Lithostratigraphy, chemostratigraphy, and vertebrate biostratigraphy of the Dockum Group (Upper Triassic), of southern Garza County, West Texas

by

Jeffrey W. Martz, M.S.

A Dissertation

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Approved

Dr. Sankar Chatterjee

Dr. Thomas M. Lehman

Dr. James E. Barrick

Dr. George B. Asquith

Dr. Calvin G. Barnes

Fred Hartmeister
Dean of the Graduate School

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ABSTRACT

The goal of this study is to establish a rigorous vertebrate biostratigraphy for the Upper Triassic Dockum Group of southern Garza County in order to test and expand upon previously postulated systems of Upper Triassic vertebrate biostratigraphy and biochronology. This proceeded by establishing a detailed lithostratigraphic framework, attempting to further subdivide it using chemostratigraphy, clarifying vertebrate systematics, and finally plotting the known occurrences of vertebrate taxa onto the lithostratigraphic framework.

The Dockum Group of southern Garza County, West Texas, consists of a basal siliceous conglomeritic sandstone (the Santa Rosa Sandstone) with pedogenic alteration at the top ("mottled beds"), which is truncated by an unconformity. The Boren Ranch sandstone and Boren Ranch beds, representing fluvial and lacustrine deposition, overly this unconformity. The overlying Cooper Canyon Formation is divided into a lower unit, middle unit, and upper unit, all deposited primarily in fluvial depositional systems, although lacustrine deposits are present in the lower part of the lower unit. The Cooper Canyon Formation is dominated by mudstone, but contains micaceous and feldspathic litharenite sandstones and intrabasinal conglomerates identical to those in the Boren Ranch sandstone and Boren Ranch beds. Several of these sandstones can be traced and mapped, allowing lithostratigraphic correlation between different localities. Sections were measured and correlated to construct a lithostratigraphic framework for chemostratigraphy and vertebrate biostratigraphy.

Physical tracing of lithologic units, particularly the lower unit and sandstones in the middle unit, indicate that the type section of the Cooper Canyon Formation correlates with the Dockum Group in the Texas Panhandle differently than had been previously thought. The lower unit correlates with the Tecovas Formation, the middle unit with the Trujillo Sandstone, and the upper unit with the Bull Canyon Formation. Gamma-ray well logs indicate that the lower unit (and possibly Boren Ranch sandstone/beds) thicken faster to the south than the middle and upper units, which suggests that the lower unit of

the Cooper Canyon Formation and the Boren Ranch Sandstone/beds correlate with the "Colorado City Member" in Howard County. Over the Midland Basin, sediments began to be derived from the Ouachita-Marathon Orogenic Belt early in the deposition of the Dockum Group, and extended further north during deposition of the middle and upper units of the Cooper Canyon Formation, Trujillo Formation, and Bull Canyon Formation. A single Tr-4 regional unconformity probably does not exist.

Chemostratigraphy, the application of bulk major and trace element geochemistry to stratigraphic subdivision of the Dockum Group, was able to identify broad geochemical differences between different lithostratigraphic units, but could not subdivide them at a fine scale. The Boren Ranch sandstone/beds and lower unit have geochemical characteristics that tend to cluster samples in both bivariate and multivariate analyses, but they also tend to have overlaps with the middle and upper units of the Cooper Canyon Formation. The middle and upper units are difficult to geochemically subdivide, or divide from each other. The Santa Rosa Sandstone can be distinguished from these samples geochemically (especially with multivariate analysis), and samples from the Tecovas Formation of the Texas Panhandle are also very distinct geochemically from the southern Garza County samples. This suggests that bulk geochemistry may be useful for distinguishing units of different lithology and provenance, although the particular discriminant plots the samples were applied to had limited success in identifying plausible tectonic environments of deposition and provenance.

The Dockum Group of southern Garza County contains a rich and diverse fauna of various fish, temnospondyls, therapsids, lepidosauromorphs, basal archosauromorphs, pseudosuchians and ornithodirans. These vertebrates are known from numerous localities scattered throughout the Boren Ranch sandstone/beds and Cooper Canyon Formation. The stratigraphic distribution of vertebrate fossils is biased by a few localities with particularly rich and diverse faunas (especially the Boren Quarry, Post Quarry, Headquarters localities, and Patricia Site), and by uneven depositional sampling of macrovertebrates and microvertebrates at these localities, and it must therefore be remembered that the known vertebrate ranges are biased and probably conservative.

The veracity of the Late Triassic Land Vertebrate Faunachrons was tested using this data. Recognizing the dependence of biochronology on biostratigraphy, and the usefulness of precise boundary definitions, the Late Triassic LVFs were treated as lowest occurrence interval biozones rather than biochrons or assemblage biozones, using the boundaries based on phytosaur first (lowest) occurrences advocated by Lucas (1998). The lowest occurrences of *Paleorhinus*, *Leptosuchus*, *Pseudopalatus*, and *Redondasaurus*-grade *Pseudopalatus* occur in the expected stratigraphic order, and were used to bound the Otischalkian, Adamanian, Revueltian, and Apachean Land Vertebrate Faunachrons. However, the distinctness of the Otischalkian and Adamanian, on the basis of either the superpositional relationships of phytosaur taxa, or overall faunal distinctiveness, is difficult to confirm in western North America.

Many of the observed biostratigraphic trends are similar to those established by previous work in eastern Arizona and New Mexico. These often involve a decline in diversity from the Adamanian through the Revueltian. For aetosaurs, *Stagonolepis* may be present in the Otischalkian?-Adamanian, *Desmatosuchus,* cf. *Rioarribasuchus, Typothorax*, and *Paratypothorax* are present in the Adamanian with only the latter two extending into the Revueltian, and only *Typothorax* is present in the Apachean. Large metoposaurs are abundant in the Otischalkian?-Adamanian but rare afterwards. "*Metoposaurus" bakeri* and the enigmatic archosauriform *Doswellia* may be restricted to the Otischalkian-Adamanian, but they have little use for correlation due to their rarity. Rauisuchids and shuvosaurids have extremely long ranges of Otischalkian-Adamanian through Apachean, although the poposauroid *Poposaurus* is restricted to the Adamanian. Dicynodonts are absent after the Adamanian, and their extinction was clearly not due to competition with herbivorous dinosaurs. Microvertebrates also show a decline and overturn in diversity, with sphenodontids, *Malerisaurus*, *Trilophosaurus*, "*Procoelosaurus*" and "*Pteromimus*" being extremely common in the Adamanian, while only drepanosaurs and leptopleurine procolophonids are common in the Revueltian. Dinosauromorphs are highly diverse in the Adamanian but undergo a decline in diversity in the Revueltian, until only theropods remain in the Apachean. The replacement of pseudosuchian archosaurs by dinosaurs in the Late Triassic may have therefore been neither fully competitive nor fully opportunistic, but a little of both. Dinosauromorphs declined along with other vertebrates, but one group (the theropods) outlasted the others and went on to ultimate success later in the Mesozoic.

CONTENTS

FIGURES

CHAPTER 1

INTRODUCTION

Following the most devastating mass extinction in the history of life on Earth at the end of the Permian, the Triassic Period witnessed one of the most extreme reorganizations of terrestrial tetrapod faunas of the Phanerozoic. These changes extended throughout the Triassic, as surviving synapsid lineages co-existed with, and were eventually almost entirely replaced by, archosauromorph diapsids. By the Late Triassic, terrestrial and freshwater vertebrate faunas worldwide were dominated by a variety of temnospondyls, derived therapsids, basal archosauromorphs, and crown-clade archosaurs, while a few other amniote groups found or maintained a toehold. Changes continued throughout the Late Triassic, including the appearance and expansion of several new groups that would continue to play important ecological roles after the Triassic, such as the dinosaurs, pterosaurs, crocodylomorphs, lissamphibians, lepidosauromorphs, turtles, and mammals. The roots of later Mesozoic and Cenozoic terrestrial ecosystems lay in the Late Triassic (Benton, 1983a, 2003; Fraser, 2006).

Major questions revolve around tetrapod evolution and extinction during the Late Triassic. Were the faunal overturns gradual, or caused by one or more sudden mass extinctions (e.g. Benton, 1986; Olsen and Sues, 1986; Lucas and Tanner, 2004)? Was the replacement of surviving synapsid groups and non-dinosaurian archosaurs by dinosaurs a gradual change due to competition, or a more rapid opportunistic replacement (e.g. Bakker, 1980, 1986; Benton, 1983a, 1993; Colbert, 1986)? What other changes involving the evolution and extinction of particular tetrapod groups took place, and how were these changes influenced by environmental change (e.g. Tucker and Benton, 1982; Parrish et al., 1986; Simms and Ruffell, 1990; Dubiel et al., 1991; Simms et al., 1994)? During what geochronologic ages did particular taxa, events, and turnovers occur, and how do they correlate globally (e.g. Lucas, 1998; Channel et al., 2003; Schultz, 2005)?

Answering these questions depends on the development of a detailed vertebrate biostratigraphy, and biochronology derived from it, such as has been pursued rigorously for North American Cenozoic Mammals. The North American Land Mammal Ages have undergone extensive development and refinement since their original formulation by Wood et al., (1941). This process has involved the detailed measurement, description, and correlation of lithostratigraphic units, the careful plotting of biostratigraphic data onto that lithostratigraphic framework, the refinement of alpha taxonomy for biostratigraphically important taxa, the recognition of local variation in faunas, the definition and correlation of biozones and biochrons using the first occurrences, last occurrences, and/or co-occurrences of taxa, the augmentation and testing of these biostratigraphic correlations using alternative sources of correlation and dating (especially magnetostratigraphy and radiometric dates), the recognition of the limitations of resolution provided by terrestrial vertebrates preserved in continental sediments, and the careful distinction between lithostratigraphic, chronostratigraphic, geochronologic, biostratigraphic, and biochronologic terms and concepts (e.g. Tedford, 1970; Savage, 1977; Woodburne, 1977; 1989, 2004; Flynn et al., 1984; Walsh, 1998, 2000).

Systems of local and global biostratigraphy and biochronology have also been pursued for Late Triassic vertebrates (e.g. Camp, 1930; Colbert and Gregory, 1957; Bonaparte, 1982; Cooper, 1982; Murry, 1982; Long and Ballew, 1985; Chatterjee, 1986a; Long and Padian, 1986; Fraser, 1988b; Ochev and Shishkin, 1989; Kutty and Sengupta, 1989; Long and Murry, 1995; Parker, 2006). Perhaps the most detailed and frequently published scheme for Late Triassic vertebrate biochronology in the last decade, the Late Triassic Land Vertebrate Faunachrons (LVFs), were devised by Spencer Lucas at the New Mexico Museum of Natural History and Science (NMMNHS) and his colleagues (e.g. Lucas and Hunt, 1993b; Lucas, 1993b, 1998; Lucas and Heckert, 1996; Lucas and Huber, 2003; Lucas et al., 2007). However, this system has not received universal endorsement and various issues have been raised, particularly regarding lithostratigraphic correlation (Lehman, 1994a, b; Lehman and Chatterjee, 2005) and tetrapod alpha taxonomy (Hungerbühler, 2001a, b; Schultz, 2005; Langer, 2005; Rayfield et al., 2005;

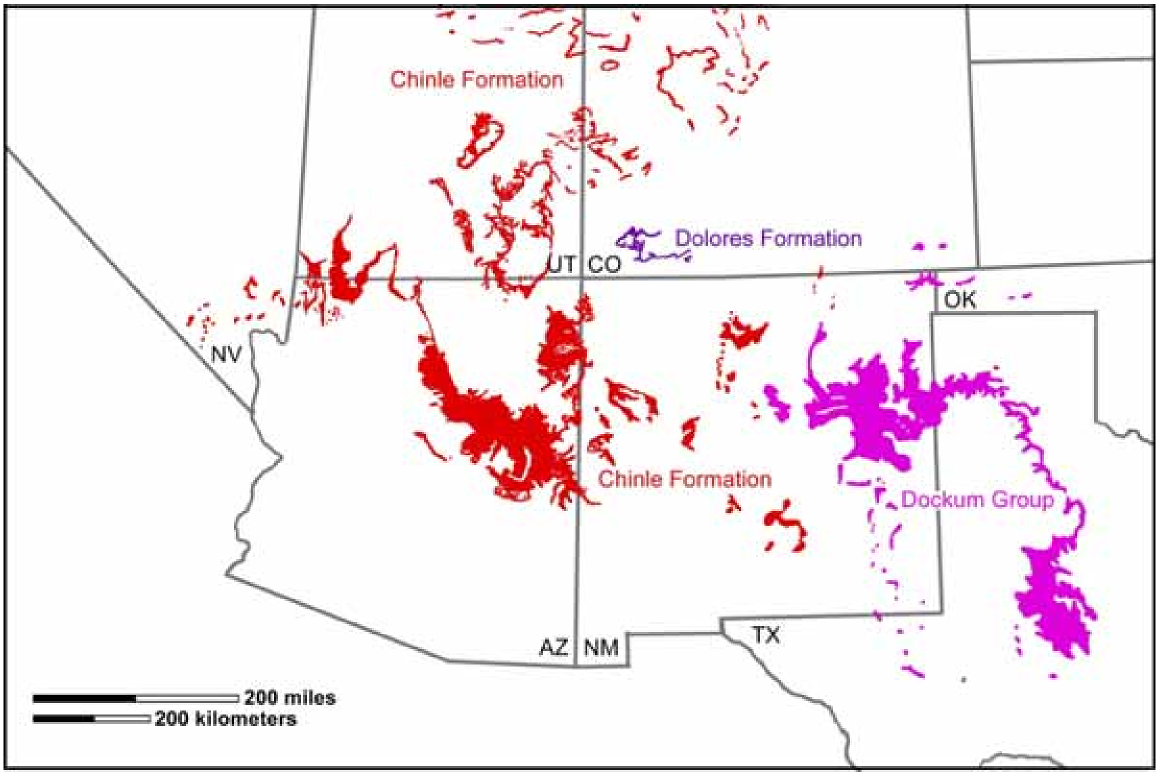


Fig.1.1. Exposures of Upper Triassic terrestrial strata in the Four Corners States, Texas, Oklahoma, and Nevada. Sources: Stewart et al. (1972) and Lehman (1994a, b).

Martz and Small, 2006) that may have implications for the system's applicability.

Some of the best known Late Triassic vertebrate faunas in the world come from the western United States. These strata, mostly representing fluvial and lacustrine depositional systems, are most extensive and best studied in the Southwest, but extend into the northern states of the Western Interior (Fig. 1.1). The Chinle Formation is exposed primarily in the Colorado Plateau region of Arizona, New Mexico, Utah, and Nevada (Stewart et al, 1972; Blakey and Gubitosa, 1983; Dubiel, 1987, 1989, 1994; Lucas et al, 1997b; Woody, 2006). Upper Triassic strata exposed around the edge of the Llano Estacado or Southern High Plains in eastern New Mexico and West Texas (Figs. 1.2-1.3) are traditionally known as the Dockum Formation or Dockum Group (Drake, 1892; McGowan et al., 1979, 1983; Lucas et al., 1985; Johns and Granata, 1987; Murry, 1986, 1989; Lucas and Hunt, 1989; Lehman, 1994a, b; Lucas et al., 1994; Lucas and

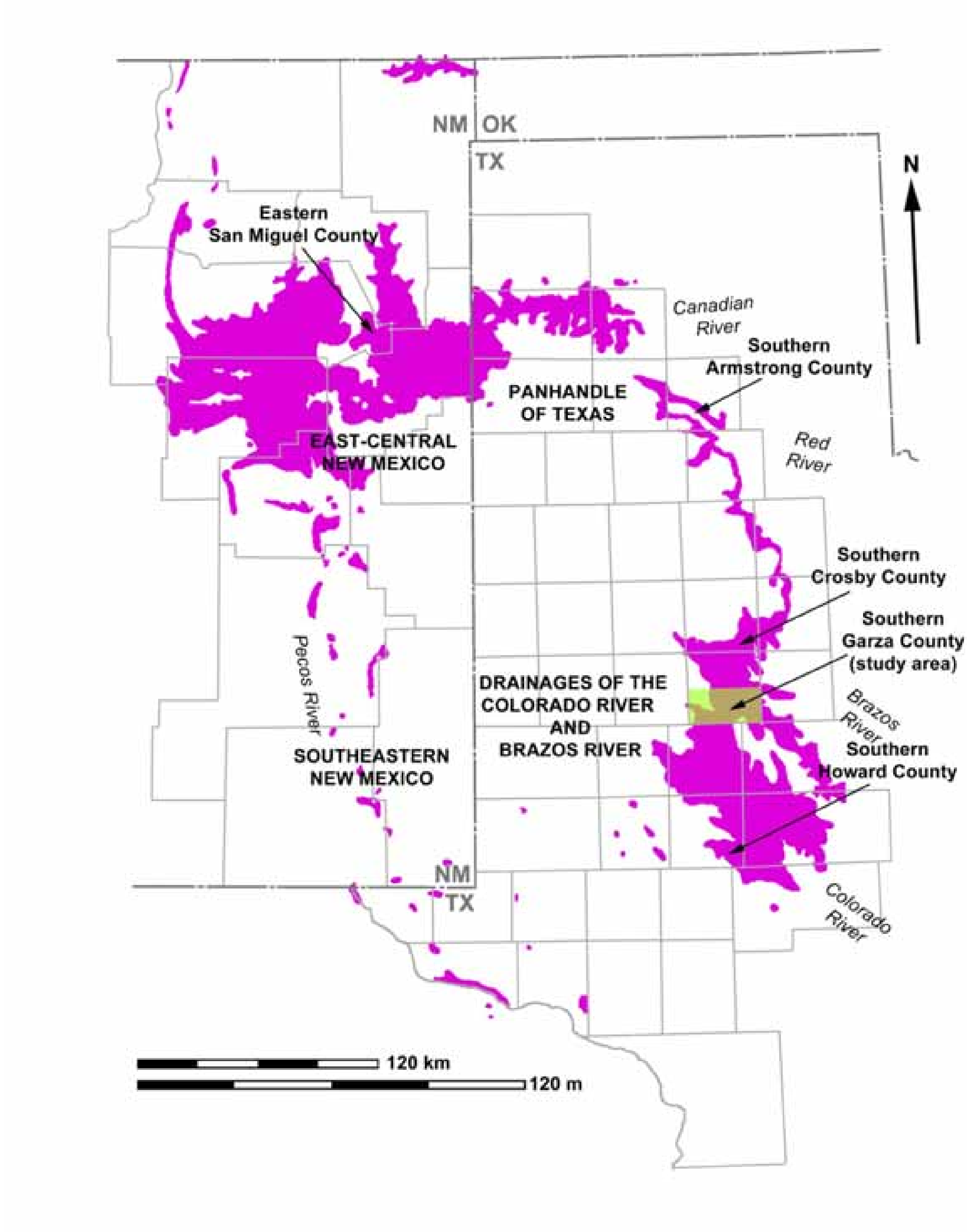


Fig. 1.2. Map of exposures of the Dockum Group around the edge of the Llano Estacado modified from Lehman and Chatterjee (2005, Fig. 2), showing study area in yellow. Locations of correlated sections used in Figs. 2.37, 2.38, and 2.40 are indicated with arrows.

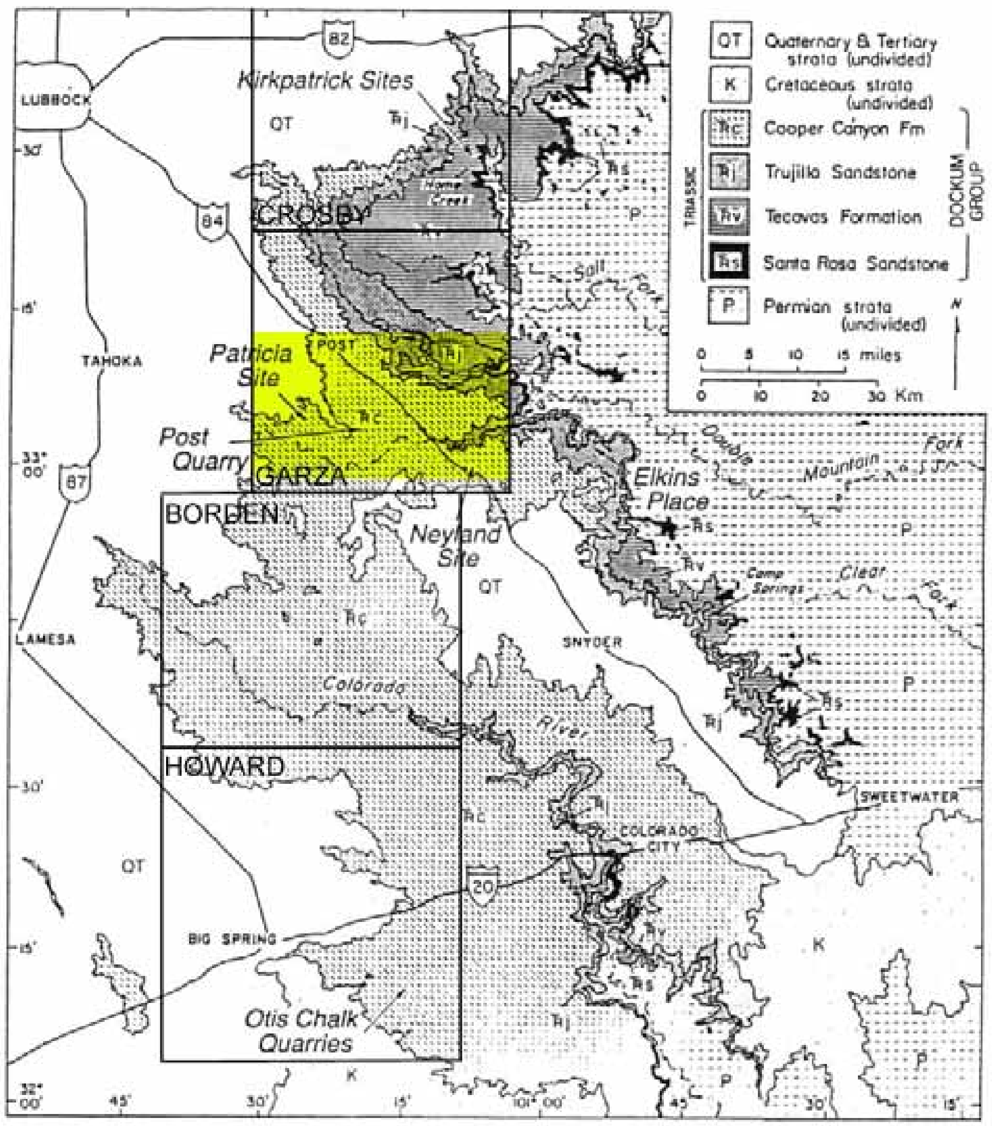


Fig. 1.3. Enlargement of Dockum Group exposures in the drainages of the Brazos River and Colorado River in Texas, including the study area in yellow. Modified from Lehman and Chatterjee (2005, fig. 4) and showing their interpretation of lithostratigraphic correlation and nomenclature.

Anderson, 1995; Lehman and Chatterjee, 2005), while coeval strata in northern Utah, Colorado, Wyoming, and Idaho are referred to the Chinle, Sananker, Dolores, Ankareh, Popo Agie, and Jelm Formations (Blodgett, 1984, 1988; Dubiel et al., 1989; Dubiel 1992; 1994; Cavaroc and Flores, 1991; Johnson, 1993).

In the last decade or so, Spencer Lucas and his colleagues have presented a somewhat revised nomenclature for Upper Triassic strata in the western United States, which abandons many traditional terms (including "Dockum"), elevates the Chinle Formation to group status, and assigns all Upper Triassic continental strata in the Western Interior to the "Chinle Group" (Lucas, 1993b, 1997; Lucas et al., 1994, 1997b). This approach has not received universal acceptance, and terms Dockum Group and Chinle Formation continue to be used (Lehman, 1994a, b; Dubiel, 1994; Carpenter, 1997; Lehman and Chatterjee, 2005; Woody, 2006; Parker, 2006). The following discussion will refer to the Upper Triassic strata in eastern New Mexico and West Texas as the Dockum Group.

The Dockum Group in southern Garza County, West Texas, is an extremely prolific source of fossil vertebrates. The localities in this area, collected almost entirely by workers at Texas Tech University, have produced a large and diverse Upper Triassic vertebrate fauna (Green, 1954; Chatterjee, 1983, 1984, 1985, 1986a, 1991, 1993; Small, 1985, 1989a, b, 1997, 2002; Davidow-Henry, 1987, 1989; Long and Murry, 1995; Simpson, 1998; McQuilkin, 1998; Edler, 1999; Bolt and Chatterjee, 2000; Atanassov, 2002; Martz, 2002; Weinbaum, 2002, 2007; Hungerbühler et al., 2003; Houle and Mueller, 2004; Lehman and Chatterjee, 2005; Lehane, 2006; Mueller and Parker, 2006). However, although the lithostratigraphy and depositional systems of the Dockum Group in southern Garza County have been discussed (Drake, 1892; Frehlier, 1987; McGowan et al., 1979; Lehman et al., 1992; Lehman, 1994a, b; Lehman and Chatterjee, 2005), its vertebrates have not been placed in a detailed and rigorous biostratigraphic framework. The objective of this study was to construct such a framework in several steps:

1. Construct a detailed lithostratigraphic framework for the Dockum Group in southern Garza County. An area including parts of 15 quadrangles (Fig. 1.4) was mapped for this purpose (although the total area covered is only equal to about 8). Mapping focused on the most prominent and traceable sandstone and mudstone-dominated

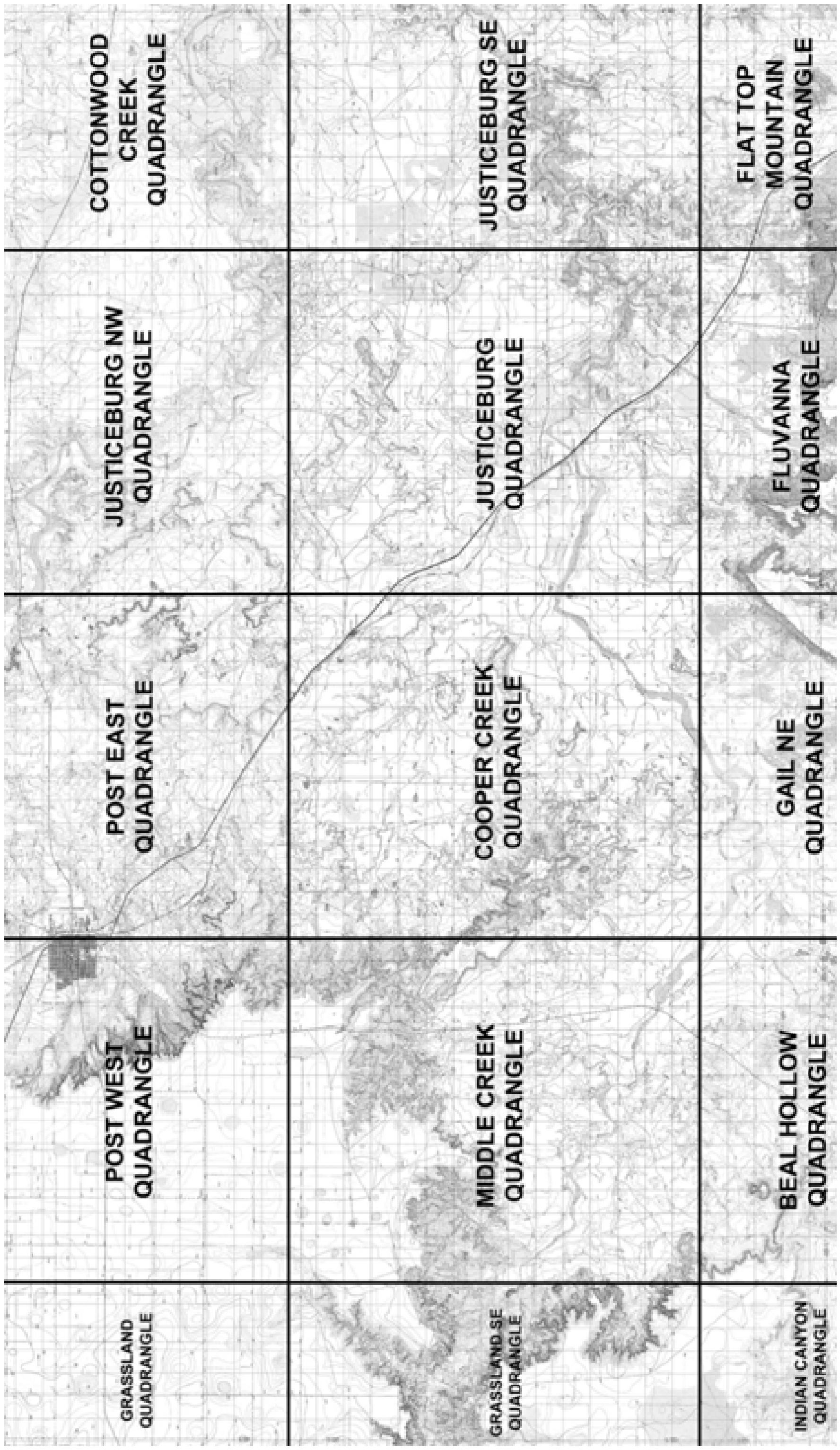


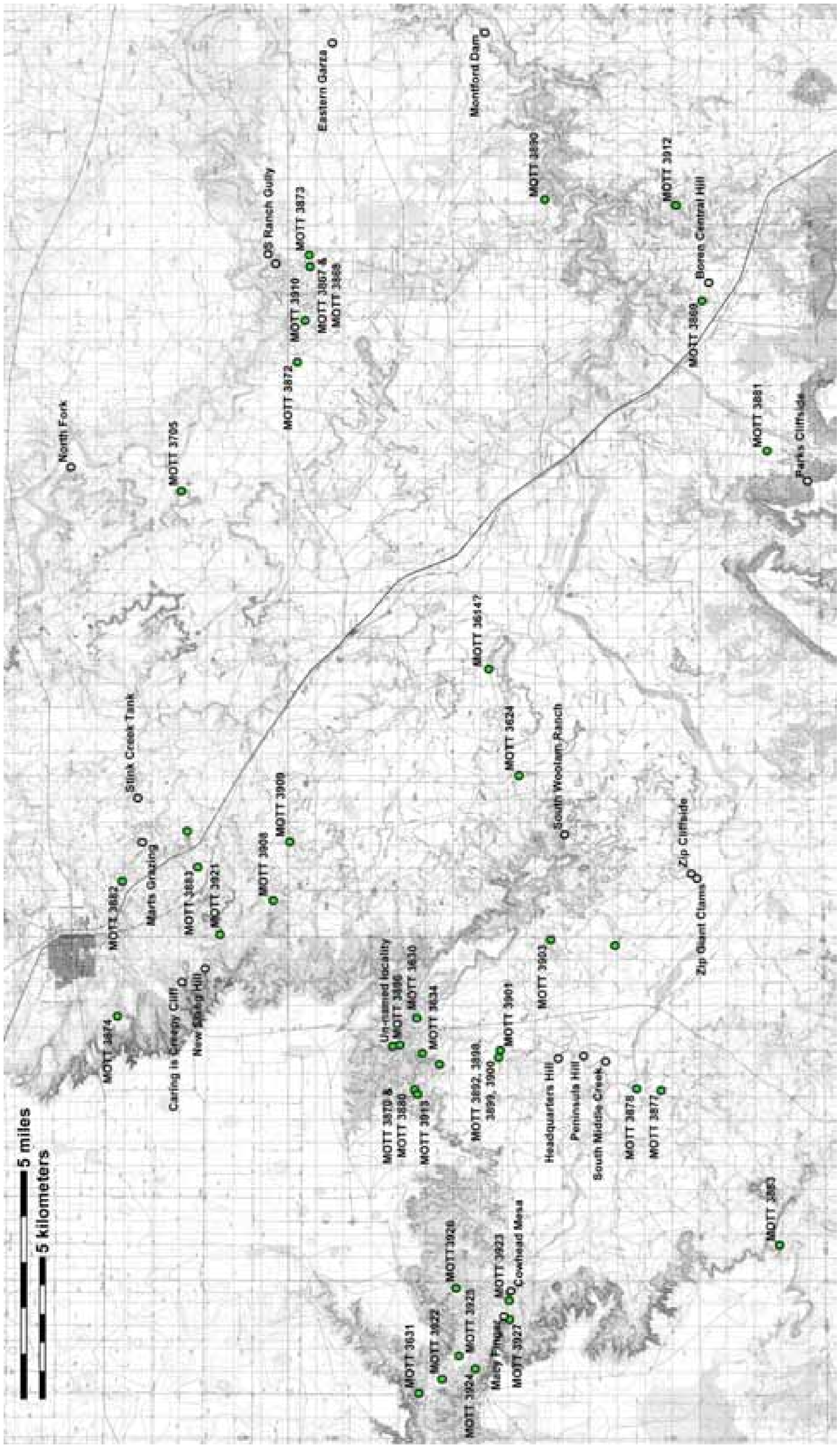
Fig. 1.4. Map showing quadrangles in southern Garza County covered by geologic mapping.

units, many of which were recognized previously (but not mapped) by Drake (1892), McGowan et al. (1979), Frehlier (1986), and Lehman et al. (1992), and measuring numerous sections at individual localities (Fig. 1.5). Additionally, surface reconnaissance and data from well logs (Fig. 1.6) was used to attempt to describe the behavior of these units in the subsurface, and to tentatively correlate them to the north and south of the study area.

2. Attempt subdivision of the Dockum Group in southern Garza County using chemostratigraphy. Mudstone samples carefully constrained by lithostratigraphy were collected and analyzed for major element weight percentages and trace element concentrations using the Inductively Coupled Plasma (ICP) lab at the Texas Tech University Department of Geosciences. Bivariate and multivariate statistical techniques were then utilized to determine if major and trace elements show stratigraphic variation that may be useful for the more precise subdivision of the Dockum Group in southern Garza County, and/or for correlating parts of the section with the Dockum Group elsewhere.
3. Plot vertebrate localities (Fig. 1.5) in the Dockum Group of southern Garza County on this lithostratigraphic framework in order to determine their relative stratigraphic positions in relation to mappable contacts between sandstone and mudstone dominated units, and construct a range chart for individual vertebrate taxa.
4. Compare this range chart with previously postulated vertebrate biostratigraphy and biochronology for the Late Triassic of western North America, particularly the Late Triassic Land Vertebrate Faunachrons of Spencer Lucas and his colleagues.

Next Pages: Fig. 1.5. Map showing locations of measured sections given in Appendix 1 (gray points) and vertebrate fossil localities (green points with MOTT locality numbers), many of which are represented by measured sections in Appendix 1.

Fig. 1.6. Map showing locations of gamma-ray well logs in southern Garza County used in this study. The two numbers beneath the name of the well log separated by a slash mark are elevations in feet above sea level; the first is the surface elevation of the well itself, the second is the elevation of the TR-3 unconformity determined from the well logs (explained in Chapter 2).


5 miles
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MOTT 3872
MOTT 3912
Boren Central Hill
MOTT 3869
MOTT 3881
Parks Cliffside
MOTT 3614?
Stink Creek Tank
MOTT 3624
South Wooten Ranch
MOTT 3909
Marts Grazing
MOTT 3882
MOTT 3883
MOTT 3921
MOTT 3908
Zip Cliffside
Zip Giant Clams
MOTT 3874
Caring is Creepy Cliff
New Spring Hill
Un-named locality
MOTT 3886
MOTT 3630
MOTT 3634
MOTT 3903
MOTT 3901
MOTT 3879 &
MOTT 3880
MOTT 3918
MOTT 3892, 3898,
3899, 3900
Headquarters Hill
Peninsula Hill
South Middle Creek
MOTT 3878
MOTT 3877
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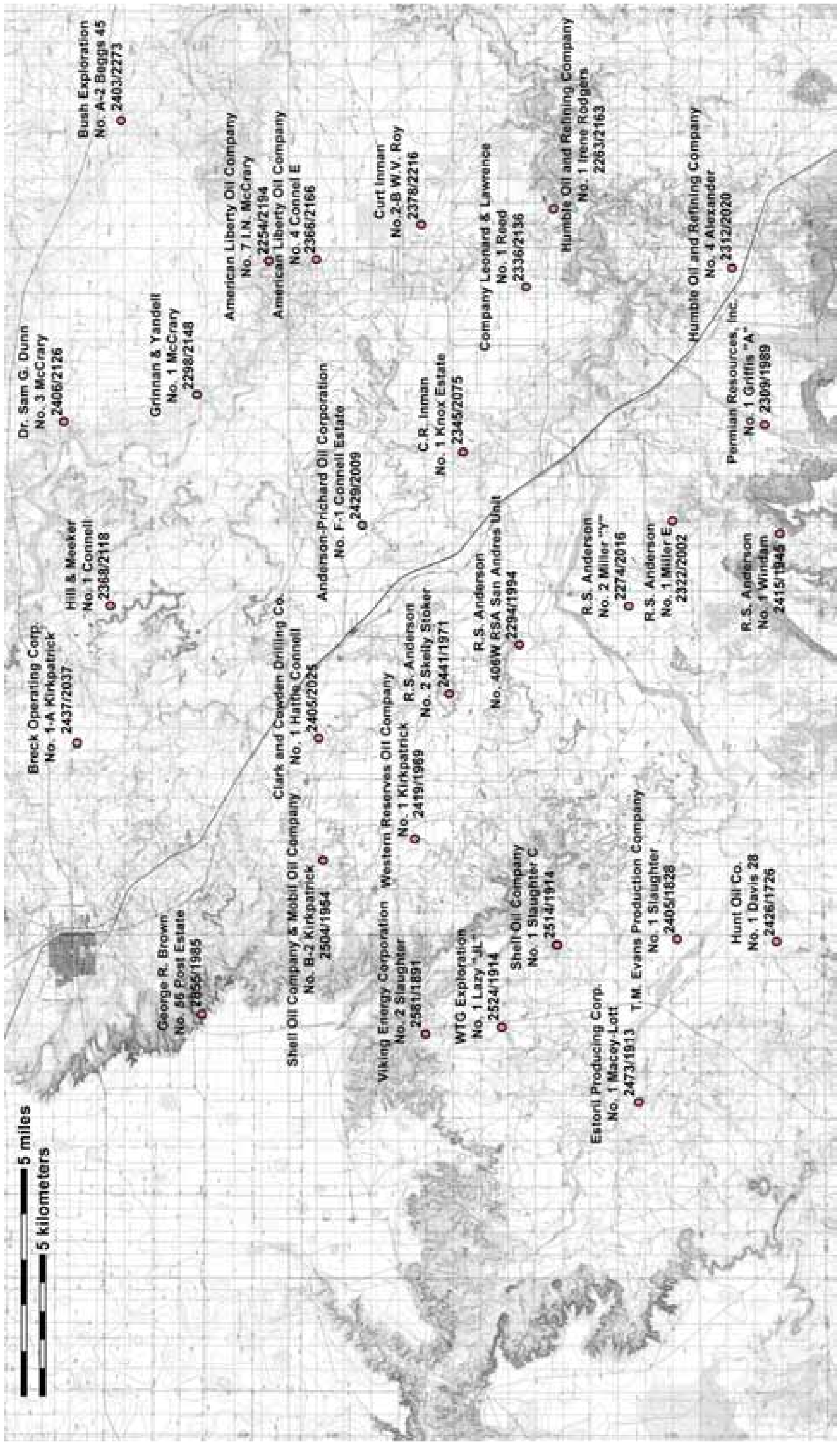
Many Fingers
MOTT 3927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Dr. Sam G. Dunn No. 3 McCrary 2406/2126
Grinnan & Yandell No. 1 McCrary 2298/2148
American Liberty Oil Company No. 7 I.N. McCrary 2254/2194
American Liberty Oil Company No. 4 Connel E 2366/2166
Curt Inman No.2-B W.V. Roy 2378/2216
Company Leonard & Lawrence No. 1 Reed 2336/2136
Humble Oil and Refining Company No. 1 Irene Rodgers 2263/2163
Humble Oil and Refining Company No. 4 Alexander 2312/2020
Permian Resources, Inc. No. 1 Griffis "A" 2309/1989
C.R. Inman No. 1 Knox Estate 2345/2075
Anderson-Prichard Oil Corporation No. F-1 Connell Estate 2429/2009
Hill & Meeker No. 1 Connell 2368/2118
Breck Operating Corp. No. 1-A Kirkpatrick 2437/2037
Clark and Cowden Drilling Co. No. 1 Hattie Connell 2405/2025
R.S. Anderson No. 2 Skelly Stoker 2441/1971
R.S. Anderson No. 406W RSA San Andres Unit 2294/1994
R.S. Anderson No. 2 Miller "Y" 2274/2016
R.S. Anderson No. 1 Miller E 2322/2002
R.S. Anderson No. 1 Windam 2415/1945
Western Reserves Oil Company No. 1 Kirkpatrick 2419/1969
Shell Oil Company & Mobil Oil Company No. B-2 Kirkpatrick 2504/1964
George R. Brown No. 86 Post Estate 2856/1985
Viking Energy Corporation No. 2 Slaughter 2581/1891
WTG Exploration No. 1 Lazy "JL" 2524/1914
Shell Oil Company No. 1 Slaughter C 2514/1914
T.M. Evans Production Company No. 1 Slaughter 2405/1828
Estoril Producing Corp. No. 1 Macey-Lott 2473/1913
Hunt Oil Co. No. 1 Davis 28 2426/1726

CHAPTER 2

LITHOSTRATIGRAPHY AND LITHOSTRATIGRAPHIC CORRELATION OF THE DOCKUM GROUP OF SOUTHERN GARZA COUNTY, WEST TEXAS

The Tectonic, Depositional, and Climatic Setting of the Dockum Group

During the Late Triassic, the Western Interior of the United States was located on the western edge of the Pangean supercontinent (Fig. 2.1), at about 5° to 15° north latitude (Dickinson, 1981; Bazard and Butler, 1991). Prior to deposition of the Dockum Group, the western margin of North America had undergone major tectonic changes during the later part of the Paleozoic and Early to Middle Triassic, including the accretion of a volcanic arc and associated sedimentary rocks to the western margin of the continent, truncation of the southwestern edge of the continent, and development of an Andean or Central American-type volcanic arc (Fig. 2.2) extending through what is now California and southwestern Arizona (Busby-Spera, 1988; Saleeby and Busby-Spera, 1992; Burchfiel et al., 1992). Further to the east, the collision of North America with South America and Africa in the Late Paleozoic produced several uplifts in western North America, especially the Ancestral Rocky Mountains and the Ouachita-Marathon Orogenic Belt, smaller uplifts such as the Matador Arch and Amarillo-Wichita Uplift, and basins associated with these orogenic events such as the Midland Basin and Palo Duro Basin (Fig. 2.2) (Kluth and Coney, 1981; Walper, 1977; Dickinson, 1981; Viele and Thomas, 1989). Southeast of the Ouachita-Marathon orogenic belt, continental rifting during the Late Triassic was beginning to open the Gulf of Mexico as Pangea began to fragment (Van der Voo et al., 1976; Salvador, 1987, 1991). These centers of Late Triassic tectonic activity and older Paleozoic structures had important influences on Late Triassic sedimentation in western North America.

The Colorado Plateau Chinle Formation was deposited in a back-arc basin associated with the magmatic arc extending through southwestern Arizona (Dickinson, 1981; Dickinson et al., 1983; Busby-Spera, 1988; Saleeby and Busby-Spera, 1992; Lawton, 1994), and derived its sediments primarily from the arc itself, or from a

Fig. 2.1. North America during the Late Triassic, showing its location in western Pangea. Fluvial systems in western North America are shaded dark brown. Map © Ron Blakey.

northeasterly sloping upland associated with the arc (the "Mogollon Slope"), as well as from the older Ancestral Rocky Mountains (Stewart et al., 1986; Bilodeau, 1986; Dubiel, 1994).

However, the Dockum Group was deposited further east. McGowan et al. (1979, 1983) noted that the Dockum Group was deposited over older Paleozoic basins associated with the Ouachita-Marathon Orogenic Belt, and suggested that the rifting of Pangea was

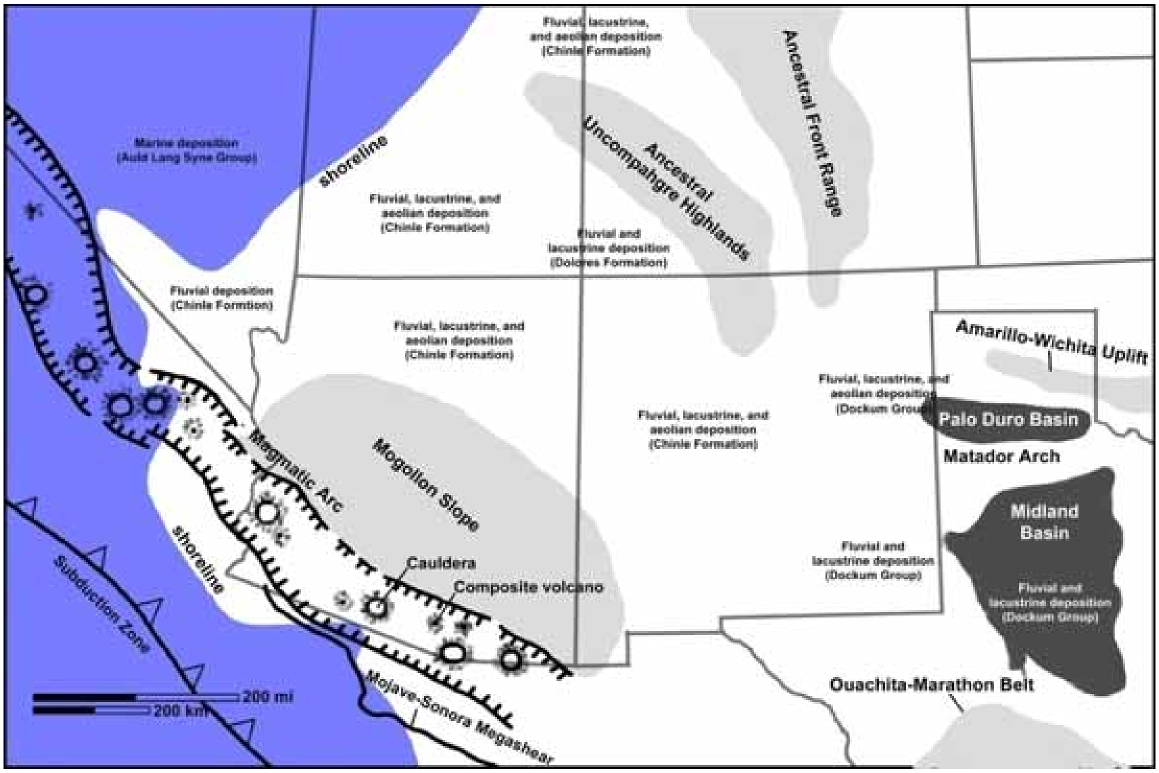

Fig. 2.2. Some structural and tectonic influences on sedimentary deposition in western North America during the Late Triassic. Highland sources of Upper Triassic continental sediment are light gray, selected basins are dark gray, area covered by eastern edge of Panthalassa blue. Sources: Stewart et al. (1972); McGowan et al. (1981); Busby-Spera (1988); Busby-Spera et al. (1990); Ewing (1991). Reconstruction of the arc as a Central American-type extensional based on the interpretation of Busby-Spera (1988).

indirectly responsible for the onset of Dockum sedimentation by reactivating subsidence of these basins, causing thermal uplift of the Ouachita-Marathon belt, and increasing precipitation along the rift zone. Lehman and Chatterjee (2005) also favored primarily tectonic influences on Dockum sedimentation, noting that sediment source areas and paleocurrent directions shifted during Late Triassic time, casting doubt on the claim by Lucas (1991) and Lucas et al. (1997b) that sedimentation was driven primarily by eustatic sea level changes, which would not be expected to so drastically alter the source or direction of fluvial transport. Dockum sediments were derived primarily from the Ouachita-Marathon Orogenic Belt and the Amarillo-Wichita Uplift (Asquith and Cramer, 1975; McGowan et al., 1979, 1983; Lehman and Chatterjee, 2005).

Interpretations of the Dockum depositional system have varied over time, although through most of the 20th century, the majority of workers have agreed that the Dockum was deposited in continental freshwater fluvial and lacustrine environments (e.g. Baker, 1915; Adams, 1929; Green, 1954; Cazeau, 1962). Several graduate studies and publications produced by workers at the Bureau of Economic Geology at the University of Texas at Austin (Seni, 1978; Boone, 1979; McGowan et al., 1979, 1983; Granata, 1981; Johns and Granata, 1987) presented a highly detailed and influential model for the Dockum Group depositional system, interpreting it as a fairly complex system of fluvial, deltaic, and lacustrine deposits. They also utilized a large volume of gamma-ray well log data to interpret Dockum sedimentation as centripetally filling a very large lake covering much of eastern New Mexico and West Texas, with rivers and deltas encroaching from around the edge of the basin. However, workers at the Texas Tech University Department of Geosciences (Asquith and Cramer, 1975; Frehlier, 1987; May, 1988; May and Lehman, 1989; Fritz, 1991; Schnable, 1994; Slaydon, 2002; Lehman and Chatterjee, 2005), as well as Lucas and Anderson (1992) and Newell (1993), have interpreted the Dockum Group as having been deposited primarily in braided and meandering river systems flowing through eastern New Mexico and West Texas rather than infilling a major lake basin, although some Dockum strata are indeed dominated by lacustrine deposition (Hester and Lucas, 2001; Lehman and Chatterjee, 2005).

Paleoclimatic interpretations of western North America have been based primarily on sedimentological and paleontological evidence from the Chinle Formation. The presence of extensive and well-vegetated lake and river systems inhabited by large reptiles and amphibians indicates that the climate was not only warm, but wetter (semiarid to subhumid) than during the Permian, with return to more arid conditions in the latest Triassic and early-middle Jurassic (e.g. Dubiel et al., 1989; Ash and Creber, 1992; Therrien and Fastovsky, 2000; Tanner, 2003). The paleoclimate of the Dockum Group has also been argued to be warm and semiarid to subhumid based on similar lines of evidence (McGowan et al., 1979; Frehlier, 1987; Lehman and Chatterjee, 2005). The climate in western North America may also have been highly seasonal, with pronounced wet and dry seasons driven by powerful “megamonsoonal” circulation across the Tethys seaway far to the east (Parrish et al., 1986; Dubiel et al., 1991; Demko et al., 1998).

Lithostratigraphy of the Upper Triassic Dockum Group in southern Garza County

Introduction

Numerous lithostratigraphic sections were measured in southern Garza County (Appendix 1). The sandstone and mudstone-dominated units represented in these sections, many recognized previously by McGowan et al. (1979), Frehlier (1987), and Lehman and Chatterjee (2005), were correlated across the study area (Fig. 2.3), combined into a composite lithostratigraphic section (Fig. 2.4a, b), and mapped (Fig. 2.4c). Names used here for units within the Dockum Group, many of which were provided by Frehlier (1987), are used informally. Consequently, the unit names are in lower case following the recommendations of the NASC (1983) even though Frehlier (1987) capitalized them; e.g. Boren Ranch sandstone vs. “Boren Ranch Sandstone” of Frehlier (1987).

The Dockum Group in southern Garza County (Figs. 2.3-2.4) is capped unconformably by the Tertiary Ogallala Formation (Barnes et al., 1993, 1994), which underlies the Llano Estacado or southern High Plains. The western part of Garza County is marked by the dramatic, mostly easterly and southerly facing cliffs of the Caprock Escarpment marking the erosional edge of the Ogallala Formation and Llano Estacado. The distinctive pinkish and tan colored sandstones, conglomerates and calcretes of the Ogallala Formation are well exposed unconformably capping the Dockum Group. The escarpment trends south and slightly southeast from just west of Post, to form a long thin finger (identified on Fig. 2.4c as the “Caprock Finger”). The escarpment then trends west to form the steep-walled gully surrounding the South Fork of the Double Mountain Fork which penetrates Lynn County, before trending south again into Borden County. In southernmost Garza County, the Lower Cretaceous coastal and shallow marine deposits of the Comanche Peak Limestone, Walnut Formation, and Antlers Sand (Barnes et al., 1993, 1994) wedge between the Ogallala Formation and Dockum Group to unconformably cap the latter. Further east, along the Borden County line near Highway

Fig. 2.5. Exposures of the Upper Permian Quartermaster Formation along the spillway for Montford Dam. The exposure is approximately 40 feet high.

84, these Cretaceous strata cap the massive cliffs (best accessible from the Fluvanna Highway), which are dramatically topped by a large wind farm. Cretaceous oysters, eroded remnants of these Cretaceous strata, are commonly found on the surface of Triassic and Quaternary strata throughout the study area. Below Montford Dam, along the cliffs and gullies in the Lake Alan Henry Wildlife Mitigation Area, and in the North Fork drainage just south of Highway 380, the base of the Dockum Group lies unconformably over the Upper Permian Quartermaster Formation (Fig. 2.5), which is composed of reddish brown mudstone densely interbedded with lighter colored and strikingly horizontal layers of fine or very fine-grained sandstone (Barnes et al., 1993, 1994).

The sedimentary geology (including lithostratigraphy and depositional systems) of the Dockum Group in southern Garza County has been described and interpreted previously by Drake (1892), McGowan et al. (1979, 1983), Chatterjee (1986a), Frehlier (1987), Lehman et al. (1992), and Lehman and Chatterjee (2005). There are two thick sequences dominated by sandstone and conglomerate at the base of the Upper Triassic section. The lower of these, capping the Quartermaster Formation unconformably, was recognized and mapped as the Santa Rosa Sandstone by Lehman (1994a, b) and Lehman and Chatterjee (2005), but has never been described in detail in southern Garza County, presumably due to its relative inaccessibility at the base of steep cliffs surrounding the North Fork and South Fork of the Double Mountain Fork of the Brazos River in the eastern part of the study area. The upper of these basal sandstones was referred to as the “Boren Ranch Sandstone” by Frehlier (1987) and the Trujillo Sandstone by Chatterjee (1986a), Lehman et al. (1992), Lehman (1994a, b) and Lehman and Chatterjee (2005), who noted the lithologic similarity of this unit, a micaceous and feldspathic litharenite rich in schistose metamorphic rock fragments, to those of the Trujillo Sandstone in the Panhandle, and in the Cooper Canyon Formation. Frehlier (1987) described the “Boren Ranch Sandstone” as having been deposited in the channel belt of a mixed-suspended load meandering river system, as he did with major sandstones in the overlying Cooper Canyon Formation.

The remainder of the Dockum Group in southern Garza County, making up the majority of the section, is a thick sequence of predominantly reddish mudstones interbedded with reddish and drab-colored sandstones and conglomerates. Drake (1892) had discussed these strata and measured two sections in southern Garza County, sections 5 and 6 of his plate V (Fig. 2.6). Section 5 was measured along the cliffs capped by the Cretaceous strata at the southern edge of the county[1], and section 6 further north, probably at the tip of the Caprock Finger. McGowan et al. (1979) and Frehlier (1987) also described these strata at several localities in southern Garza County. As already summarized, McGowan et al. (1979) interpreted these strata as being lacustrine and deltaic with associated meanderbelts, while Frehlier (1987) and Lehman and Chatterjee (2005) interpreted them as having been deposited in meandering rivers and associated overbank deposits, with lacustrine deposits forming only a relatively minor component.

Chatterjee (1986a) provided the name “Cooper Member” (in the same paper, he lowered the Dockum Group to formation rank) for this section of interbedded mudstone, sandstone, and conglomerate, measuring a 16 m thick type section at the Post Quarry

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1. Drake (1892, p. 238) claimed that section 5 was measured in northeastern Borden County, but his description of the location as being along the cliffs “about three miles south of the Double Mountain Fork of the Brazos River” indicates it was probably measured in southern Garza County.

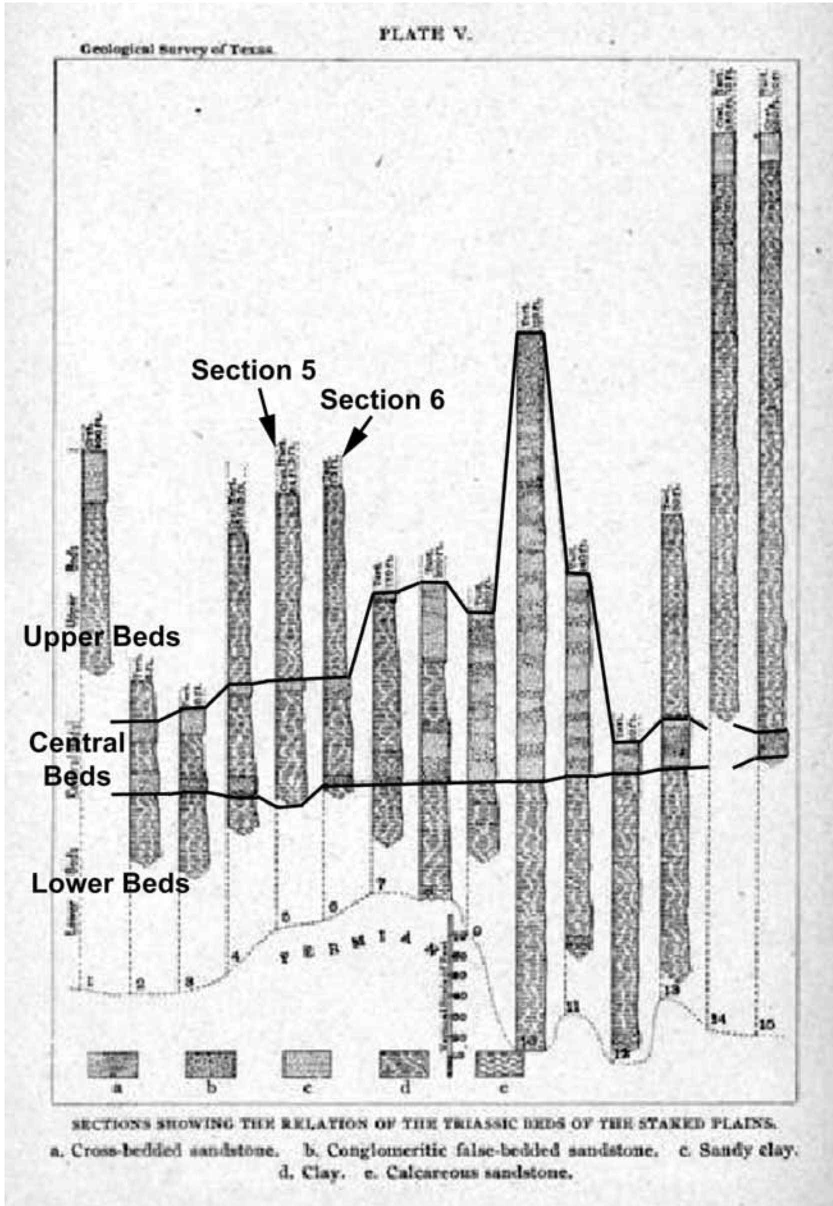

Fig. 2.6. Modified version of Drake's (1982) pl. V, showing his correlated sections of the Dockum Group from the southern Texas Panhandle (left) to east-central New Mexico (right), and his straigraphic subdivisions of the Dockum. Sections 5 and 6 are located in southern Garza County, and are probably roughly equivalent respectively to the Meyer's Hill/Parks Cliffside section and South Woolam Ranch section in Appendix 1.

fossil locality about 8 km southeast of Post, near the tip of the Caprock Finger (Fig. 2.7a). Chatterjee (1986a) considered this unit to correlate with the upper, mudstone-dominated part of the Trujillo Formation of Gould (1906, 1907) in the northern Panhandle region.

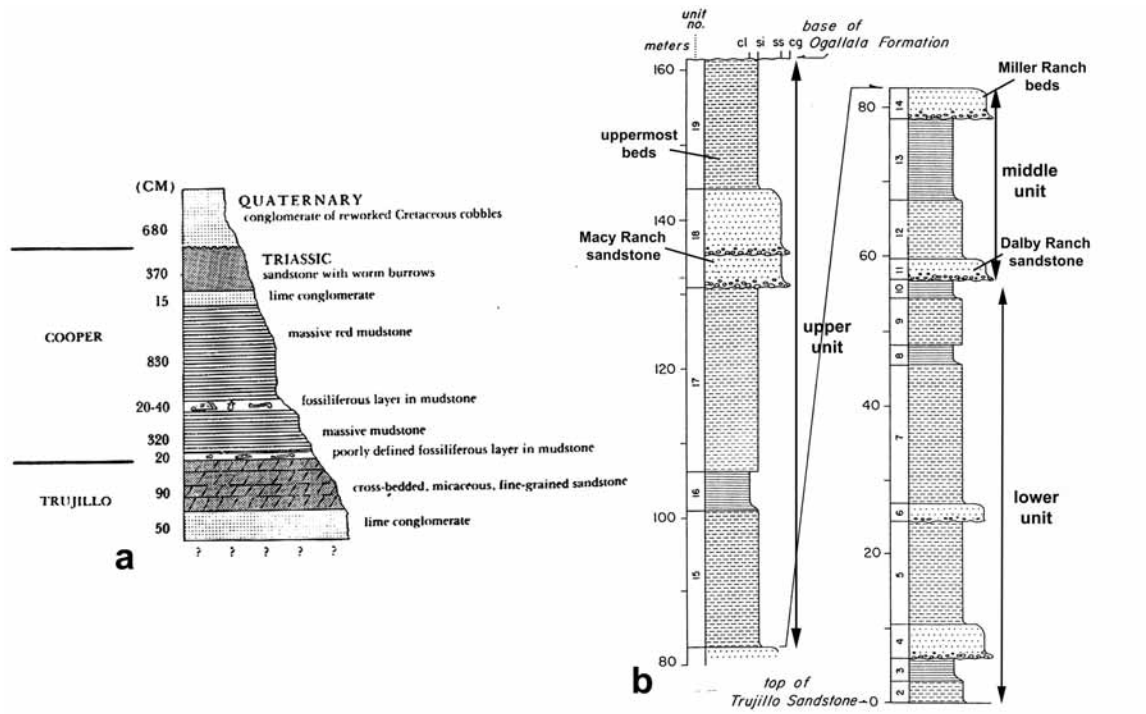

Fig. 2.7. Type sections in southern Garza County: *a*, Chatterjee's (1986) type section for the Cooper Member measured at the Post Quarry; *b*, Modified version of Lehman et al.'s (1992) revised type section for the Cooper Canyon Formation, with units named by Frehlier (1987) and here labeled. Units 9 and 10 are approximately equivalent to Chatterjee's type section.

Chatterjee (1986a, p. 142) identified a conglomeritic sandstone at the base of his type section as the Trujillo Sandstone (a name now generally restricted to the massive sandstone at the base of Gould's original Trujillo Formation, as is discussed in more detail later), but also identified the massive sandstone unit at Boren Ranch, further east near Justiceburg, as the Trujillo Sandstone. As already mentioned, this latter unit was named the "Boren Ranch Sandstone" by Frehlier (1987).

Lehman et al. (1992) agreed with Chatterjee's (1986a) identification of Frehlier's (1987) "Boren Ranch Sandstone" as the Trujillo Sandstone, but noted that the sandstone he identified at the base of his type section as being the Trujillo Sandstone was a laterally restricted sandstone which was much higher in the section than the "Boren Ranch Sandstone", and also that the top of Chatterjee's (1986a) type section did not reach to the top of the Upper Triassic section in Garza County. They therefore measured a new type section (Fig. 2.7b) as an overland transect from the top of the Boren Ranch Sandstone to the top of the Dockum Group at the Caprock Finger, with their total section being about 160 m thick. Lehman et al. (1992, p. 351) also renamed the Cooper Member the "Cooper Canyon Formation" (having re-elevated the Dockum Formation to group status) "in order to avoid confusion" with previously named lithostratigraphic units such as the Cooper Marl and Cooper Limestone. The contentious later history of the Cooper Canyon Formation and its correlation will be discussed later.

The primary objective of this study was to provide a lithostratigraphic framework on which biostratigraphic data could be plotted. This involved the identification of prominent sandstone and conglomeritic sandstones which could be traced and mapped over several miles, making it possible to determine the relative lithostratigraphic position of vertebrate fossil localities scattered throughout the study area. Although Miall (1996) cautioned against the use of channel sandstones for regional correlation due in part to their complex lateral facies changes, they were found to be fairly convenient for the current study, tending to form easily identifiable caps on mesas and cliffsides, which usually have a distinct drab coloration compared to the underlying reddish-brown mudrocks, and are therefore easy to trace.

These traceable blanket sandstones and conglomerates have been described in detail at particular localities by McGowan et al. (1979), Frehlier (1987) and Lehman and Chatterjee (2005), and were interpreted by them as channel deposits for meandering mixed-suspended load and braided bed-load rivers encased in mudstone-dominated overbank deposits. These are sometimes single-story sand bodies representing phases of channel occupation, and sometimes amalgamated deposits representing multiple phases of channel occupation. The latter of these (especially the Dalby Ranch sandstone, Route 669 Roadcut sandstone, and Macy Ranch sandstone) tend to be the more laterally extensive blanket sand bodies. Not every distinctive sandstone and conglomerate was mapped, because most do not extend laterally for more than a mile.

The basal contacts of the channel sandstones with underlying overbank deposits tend to be easier to trace and map than the upper contacts with the overlying overbank deposits, for two reasons:

1. The lower contacts are usually sharp erosional surfaces (5th and 6th order bounding surfaces, sensu Miall, 1996), which are easy to place during mapping. However, the upper surfaces with the overlying overbank deposits are more gradational (4th order bounding surfaces sensu Miall, 1988), with complexly interbedded sequences of mudstone, sandstone and conglomerate often separating the main body of the sandstone from the more mudstone dominated overbank deposits. Consequently, the upper contact of these sandstones is somewhat arbitrary, and placed approximately where the section becomes dominated by mudstone.
2. The lower contacts tend to be better exposed. Good exposures of Dockum Group strata tend to be cliffs and mesas capped by these major sandstone and conglomerate units, so the contacts with underlying overbank deposits tend to be well exposed. However, the upper contacts of these sandstone units are usually either eroded away (for the mesas), or form gently sloping topography grading into mudstone and then up to the next major sandstone unit, and are usually than covered by soil and vegetation. Consequently, upper contacts for mappable sandstones can often only be identified in well-eroded gullies on top of cliffs. For both these reasons, upper contacts for sandstones are often mapped as dashed lines, and must be taken with a grain of salt.

An additional difficulty is that several separate sandstones and/or conglomerates may be closely associated stratigraphically, rather than forming a single amalgamated sand body. For example, although the Miller Ranch sandstone usually consists of a relatively “well-behaved” single-story sandstone across much of the study area, but in places there are at least two distinct but closely associated sandstones separated by thin sections of mudstone. The same is true of the Cooper Creek beds, which consist of a package of closely associated conglomeritic sandstones, and the Boren Ranch sandstone/beds, which always consists of at least two distinct sandstone beds separated by mudstone. In these cases, the multiple sandstones or conglomeritic sandstones are mapped as a single unit. As already noted, the objective of this study is to identify the relative stratigraphic positions of vertebrate fossil localities, and a package of closely associated sandstones which can be traced over miles may serve as well for large-scale correlation as a single thick sandstone, albeit with less clearly defined boundaries. Future, finer scale mapping that is more concerned with detailed stratigraphic architecture may separate out these individual beds.

Santa Rosa Sandstone

The unit mapped by Lehman (1994a, b) and by Lehman and Chatterjee (2005) as the Santa Rosa Sandstone, extending Darton's (1922) name for this unit from New Mexico into West Texas, is the most basal unit of the Dockum Group in southern Garza County. Lucas et al. (1985), Lucas and Hunt (1987), and Lucas et al. (1994) preferred to refer to the unit in New Mexico as the Santa Rosa Formation, and Lucas and Anderson (1993a) and Lucas et al. (1994) referred to its Texas correlative as the Camp Springs Member (the Camp Springs Conglomerate of Beede and Christner, 1926). Although Lucas and Anderson (1994) and Lucas et al. (1994) described the Camp Springs Member at the type area as being predominantly arkosic and micaceous litharenite sandstones with siliceous conglomerates, Lehman (1994b) suggested they are combining two closely associated sandstones; a lower silica-rich conglomeritic sandstone he identifies as the Santa Rosa Sandstone, and an upper arkosic and micaceous litharenite sandstone with minor silica conglomerate he identified as the Trujillo Sandstone. Although I question Lehman's identification of the latter unit for reasons discussed later, his recognition of two, lithologically distinct but closely associated units at the base of the Dockum Group in Scurry County is consistent with the situation in southern Garza County.

The Santa Rosa Sandstone rests unconformably on top of the Quartermaster Formation (the TR-3 unconformity of Pipiringos and O'Sullivan, 1978) wherever its base is exposed throughout southeastern Garza County (Fig. 2.8). Just south of Highway 380

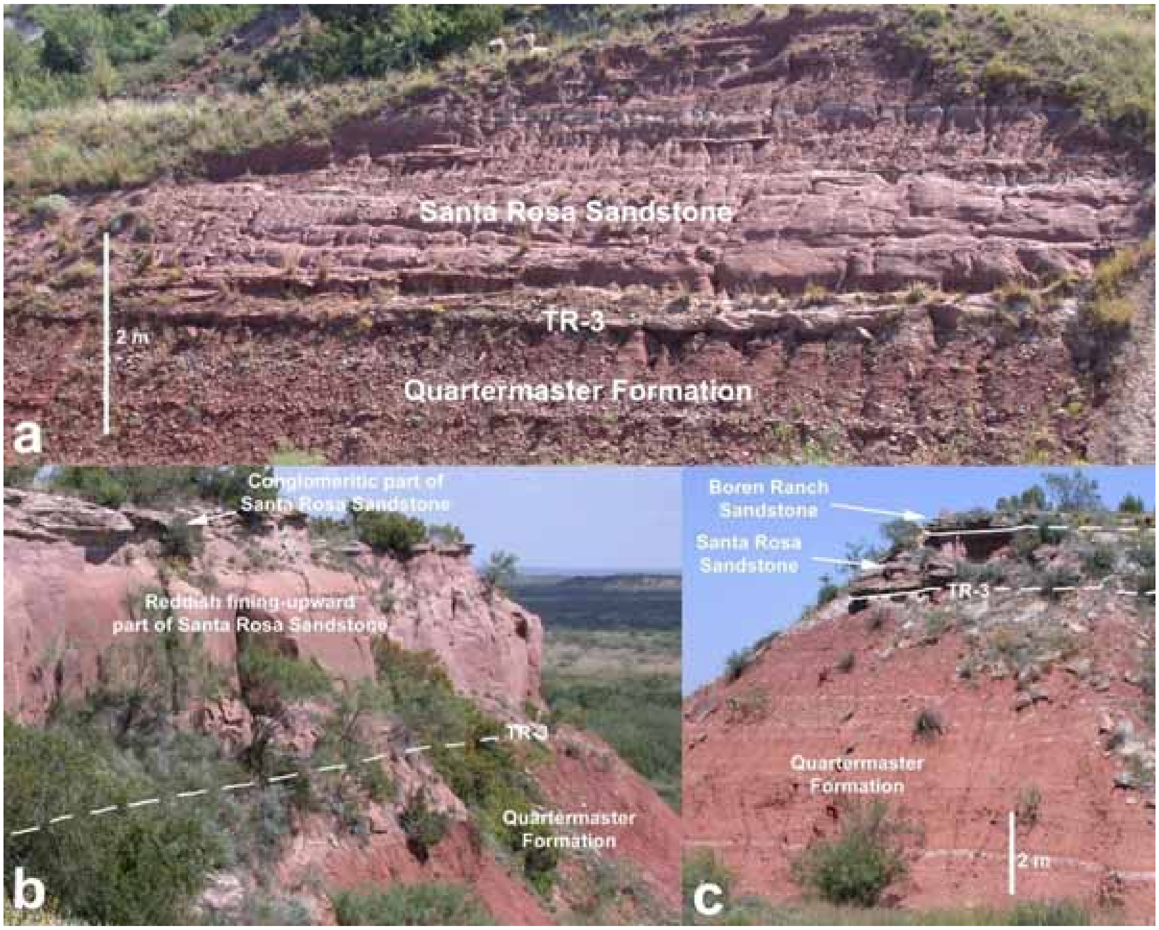

Fig. 2.8. The TR-3 unconformity and base of the Santa Rosa Sandstone in southern Garza County: *a*, contact at Montford Dam spillway at southwest edge of dam (outcrop of Quartermaster Formation shown in Fig. 2.5 is to left of photograph); *b*, contact below northeast edge of dam, (thickness of lower reddish sandstone of Santa Rosa Sandstone is about 8 meters); *c*, almost completely truncated Santa Rosa Sandstone at outcrop in Lake Alan Henry Wildlife Mitigation Area in Kent County.

along escarpments rimming the North Fork of the Double Mountain Fork of the Brazos River near the OS Ranch and extending into Kent County, only the base of the Santa Rosa Sandstone is exposed capping the Quartermaster Formation. The Santa Rosa Sandstone has a distinct southwesterly dip. Westward within the North Fork drainage, and southwards toward Lake Alan Henry, the basal contact drops about 60 feet over five miles (from an elevation of about 2270’ above sea level to disappear into the subsurface at about 2210’) to expose more of the basal Upper Triassic section. Most or all of the

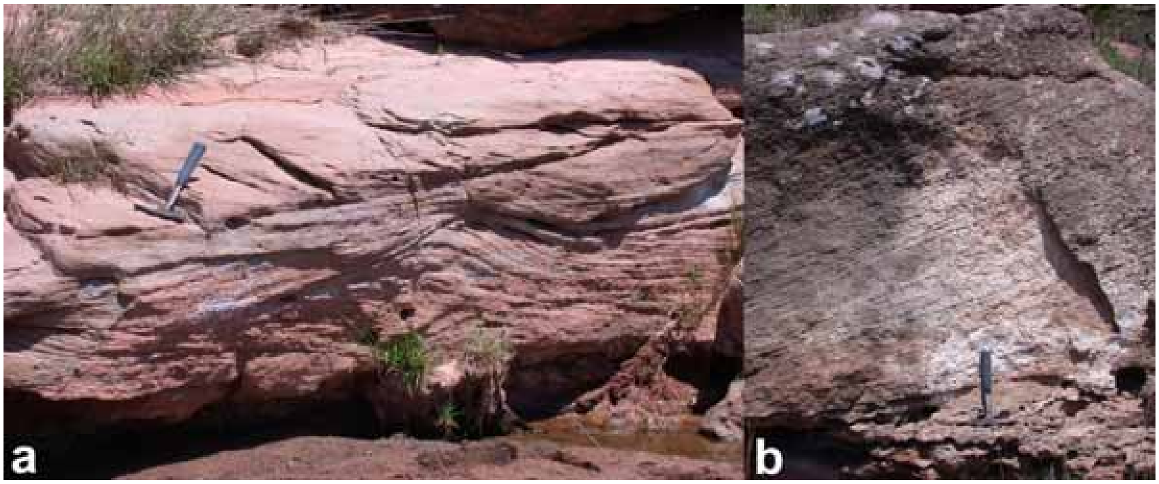

Fig. 2.9. Sedimentary structures in the Santa Rosa Sandstone at OS Ranch along North Fork of Double Mountain Fork of the Brazos River, rock hammer for scale: *a,* double trough cross bed set; *b,* gently dipping planar cross beds.

thickness of the Santa Rosa Sandstone is exposed in the vicinity of the OS Ranch localities, the Lake Alan Henry Wildlife Mitigation Area north of Montford Dam (where the contact below the dam itself is at about 2210', close to the waterline), and at the eastern end of Lake Alan Henry. The thickness of the Santa Rosa Sandstone can vary considerably. At one outcrop observed in a tributary of the North Fork drainage just south of Highway 380 it approaches 30 meters (100 feet) in thickness, while in western Kent County in the Lake Alan Henry Wildlife mitigation area, it is truncated to less than 1.5 meters (5 feet) by the Boren Ranch Sandstone (Fig. 2.8c). More typical thicknesses are usually in the range of 10-20 meters (about 30-60 feet).

The Santa Rosa Sandstone in southern Garza County compares fairly well with the unit seen elsewhere in eastern New Mexico and western Texas, where it has been interpreted as having been deposited in a bedload-dominated braided river system (e.g. Lupe, 1988; Fritz, 1991; Lucas and Hunt, 1987; Lehman and Chatterjee, 2005). The Santa Rosa Sandstone exhibits trough cross-bedding (Fig. 2.9a) and gently dipping tabular cross beds (Fig. 2.9b), with very rare ripple bedding. The sandstones are usually somewhat friable, although occasionally they are well-cemented. They are commonly reddish brown, although they may also be yellowish or grayish, and are often sculpted by erosion so that they look superficially aeolian (Fig. 2.9a-b). The sandstones are usually medium-coarse grained sand, often with subrounded to subangular chert grains scattered throughout (Fig. 2.10a). Thick conglomerate lenses (Fig. 2.10b), usually lacking any discernable sedimentary structures, are commonly interbedded in these sandstones. The clasts are usually subangular or subrounded chert and quartzite granules and pebbles, occasionally reaching cobble-size (Fig. 2.10b-c). Conglomerates containing large flattened cobble to boulder-sized sedimentary rip-up clasts, similar to those at the base of the Boren Ranch sandstone/beds, are also locally seen at the base of the Santa Rosa Sandstone (Fig. 2.10d). Mudstone is extremely rare in the Santa Rosa Sandstone, occurring primarily as small reddish or purplish pockets or lenses no more than a few centimeters thick. In the Santa Rosa Sandstone exposed around Montford Dam, predominantly grayish-purple mudstone is unusually prevalent, interbedded with sandstone and conglomerate. Vertical tendrils of sandstone extend through these thick mudstone lenses, possibly representing sandstone filling desiccation cracks in the mudstone (Fig. 2.11). Lehman and Chatterjee (2005) reported similar sedimentary structures probably representing conglomerate fills of desiccation cracks in subareally exposed lacustrine mudstones in the lower Tecovas Formation.

At Montford Dam, there is a reddish-brown, fining upward sandstone unit with gently dipping cross beds at the base of the Santa Rosa Sandstone (Fig. 2.8a-b) that is quite distinct from the upper part of the unit, which is lighter yellowish gray, highly conglomeritic, and interbedded with mudstone. It is tempting to identify this unit with the "aeolian unit" described by May (1988) at the base of the Santa Rosa along much of the northern High Plains of Texas. However, the sandstone is not very well sorted and

Next Page: Fig. 2.10. Sandstones and conglomerates in the Santa Rosa Sandstone at the OS Ranch along the North Fork of the Double Mountain Fork: *a*, coarse-grained sandstone with subangular and subrounded pebble-sized clasts scattered throughout; *b*, conglomerate lenses interbedded with sandstone; *c*, close-up of subangular and subrounded pebble-sized clasts in conglomerate lens (bone fragment in the middle of the photograph); *d*; boulder-sized, slightly rounded sedimentary rock clast at the very base of the Santa Rosa Sandstone.


a
b
c
d
HEAVY HITTER

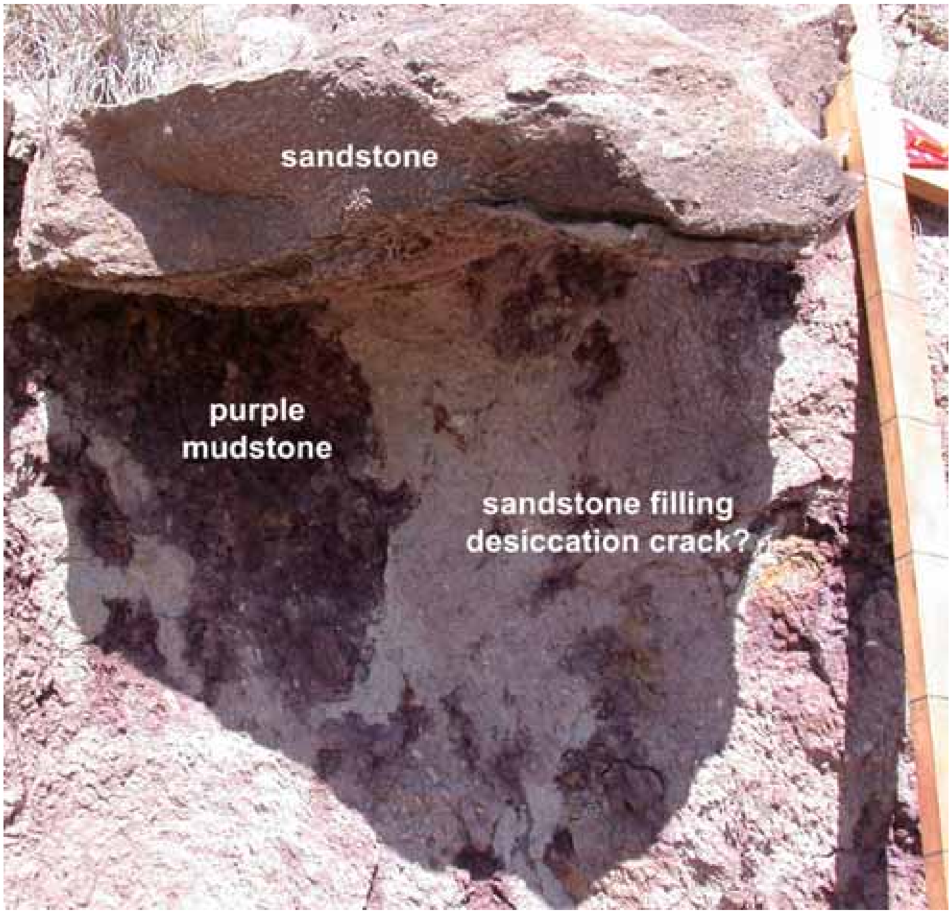

Fig. 2.11. Mudstone lens in Santa Rosa Sandstone below Montford Dam with vertical tendril of sandstone possibly representing filling of a desiccation crack (increments on Jacob's staff = 10 cm).

the base is deeply scoured into the underlying Quartermaster Formation, indicating that aeolian deposition is highly unlikely. Moreover, the Santa Rosa Sandstone in most parts of southeastern Garza County, although it contains distinctive conglomeritic lenses, is closer in color and grain size to this unit. Additionally, a few miles further north at the Eastern Garza County section, the contact between this brownish unit and the rest of the Santa Rosa can be seen to be more gradational than at the dam. Most likely, this reddish-brown unit is simply the lower part of the Santa Rosa Sandstone.[2]

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2. I agree with Lucas and Anderson (1993) that the unit in the Silverton Roadcut identified by May (1988) as being a possible aolian unit of Middle Triassic age is more likely of fluvial origin. I addition to the ripped up mudstone clasts noted by Lucas and Anderson (1993), the unit contains abundant subrounded gravel-sized clasts, often as gravelly lenses lining trough cross beds. Lucas and Anderson

Petrified wood is occasionally found in the Santa Rosa Sandstone in southern Garza County (although it is much more common in the Boren Ranch sandstone/beds). Vertebrate remains are unknown except for occasional unidentifiable scraps of bone (Fig. 2.10c). However, the Elkins Place locality (Case, 1932), located in adjacent Kent County (Houle and Mueller, 2004), which has produced abundant material of *Metoposaurus bakeri*, and the type locality of *Paleorhinus scurriensis* (Langston, 1949) in adjacent Scurry County, may both lie in the Santa Rosa Sandstone. Case's (1932, pp. 2-4) description of the Elkin's Place locality indicates that it probably lies directly on the TR-3 unconformity, at the very base of a sandstone which is "grayish and is composed dominantly of frosted grains of pure quartz…mixed with…fine clay in flakes and in localized lumps and many fragments of quartz and other material reaching a length of twenty millimeters." Langston (1949, p. 324) identified the type skull of *Paleorhinus scurriensis* as coming from the "Camp Springs Conglomerate", and may also be referring to the unit considered here to be the Santa Rosa Sandstone.

Mottled Beds

In many exposures, the top of the Santa Rosa Sandstone is a zone of intensely mottled purple, reddish brown, gray, yellow and orange (Fig. 2.12). Lithologically, there is not a clear distinction between these mottled beds and un-mottled exposures of the Santa Rosa Sandstone below; the mottled beds are usually silica-rich sandstones with minor mudstone and chert-quartzite conglomerate, almost indistinguishable in outcrop from the strata below except for their coloration. The mottled beds therefore probably represent post-depositional pedogenic alteration of the top of the Santa Rosa Sandstone. The thickness of this unit varies; although it is usually several meters thick, it is locally truncated by the base of the Boren Ranch beds at OS Ranch, and is completely absent in the Lake Alan Henry Wildlife Mitigation area, including around Montford Dam, probably also due to truncation. This colorful mottling is quite distinct from

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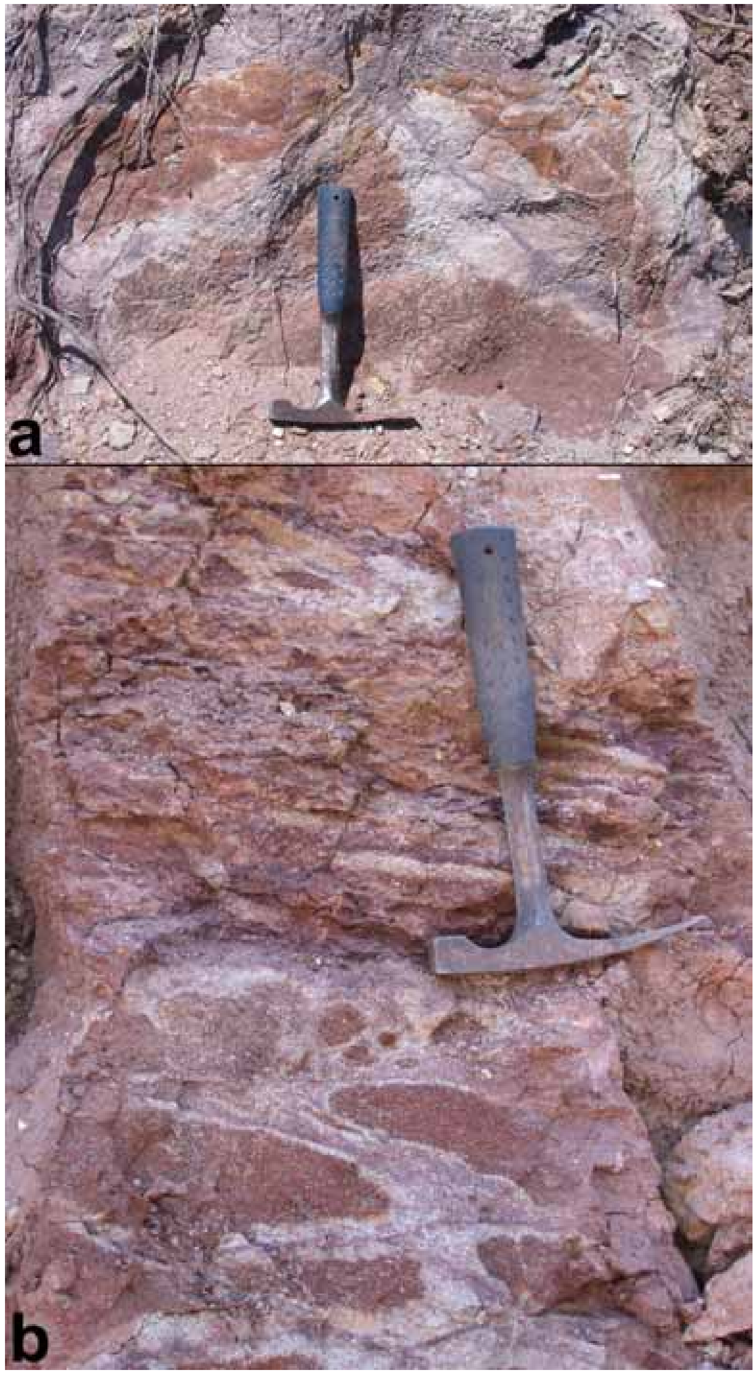
(1993) suggested it was a fluvial sandstone of Permian age, but there is nothing to preclude it from being Triassic.



Next Page: Fig. 2.12. Mottled beds at the top of the Santa Rosa Sandstone: *a*, mottled beds at OS Ranch along North Fork of the Double Mountain Fork, lithology is medium to coarse-grained silicious sandstone; *b*, mottled beds north of Lake Alan Henry Wildlife Mitigation Area, head of hammer rests at lithologic change between coarse-grained silicious sandstone with occasional pockets of claystone (below), and chert and quartzite pebble conglomerate with thin interbedded claystone lenses (above).

mottling seen higher in the Dockum Group in the Boren Ranch sandstone/beds and Cooper Canyon Formation, where it is usually confined to mudstones and is a generally a more monochrome yellowish or greenish gray caused by iron reduction (Turner, 1980; Frehlier, 1987).

Similar intensely mottled zones are commonly associated with the base of Upper Triassic strata throughout the western United States (e.g. Stewart et al., 1972; Dubiel, 1987, 1994; Dubiel et al., 1991; Lucas and Anderson, 1993a), and are produced by the aqueous remobilization and oxidation of iron (Dubiel et al., 1991; Kanhalangsy, 1997). This pedogenic mottling may occur in pre-Upper Triassic rocks immediately below the TR-3 unconformity, within basal Upper Triassic strata (often silica-rich conglomeritic sandstones), or even slightly higher within the Upper Triassic section. Examples of the latter include the mottled beds overlying the Gartra Member in the Chinle Formation of northern Colorado and Utah (Stewart et al., 1972) and the purple mottled strata between the Shinarump Member and Monitor Butte Member of the Chinle Formation in the Four Corners area (Dubiel et al., 1989, 1991).

In West Texas north of Garza County, the mottled beds usually occur at the top of the Permian Quartermaster Formation, and are capped by white quartz-rich sandstone and nodular and lamellar calcium carbonate and silica. Kanhalangsy (1997) referred to this unit at the "Palo Duro Geosol," and similar paleosols occur in the Santa Rosa and Tecovas Formations in the same region (May, 1988). Dubiel et al. (1989, 1991) claimed that mottled paleosols in the lower part of the Chinle Formation formed due to seasonally fluctuating water tables, while Kanhalangsy (1997) suggested those in the Dockum Group formed in a relatively wet climate with well-drained soils. Whatever precise climatic conditions produced them, the formation of these paleosols suggest depositional hiatuses, or at least periods of very slow sedimentation, beginning before deposition of the Upper Triassic section, and continuing into the early stages of deposition.

Fig. 2.13. The Boren Ranch Sandstone along Lake Alan Henry: *a*, reddish arkosic sandstone just east of Highway 84; *b*, reddish mudstone-dominated lens dividing Boren Ranch Sandstone further east, thickness from waterline to top of hill about 80 feet.

Boren Ranch sandstone/Boren Ranch beds

The Boren Ranch sandstone was named and briefly described by Frehlier (1987) along the banks of the South Fork of the Double Mountain Fork of the Brazos River just east of Highway 84, where it is a massive sandstone (Fig. 2.13a). This drainage is now occupied by Lake Alan Henry, but much of the Boren Ranch sandstone is still exposed. Lehman et al. (1992), who identified the unit as the Trujillo Sandstone, made the top of the unit the lower boundary of their type section for the Cooper Canyon Formation (Fig. 2.7b), beginning measurement on top of the cliffs formed by the sandstone overlooking the lake (see Fig. 1A of Lehman et al., 1992). The base of the Boren Ranch sandstone is unconformable, truncating the Santa Rosa Sandstone and mottled beds, and has a gentle southwesterly dip in the drainages of both the North Fork and South Fork of the Double Mountain Fork of the Brazos River.

Frehlier (1987) interpreted the Boren Ranch sandstone along Lake Alan Henry as an amalgamated channel sandstone formed by a mixed-load meandering fluvial system, similar to the Trujillo Sandstone and other major sandstone units higher in the Cooper Canyon Formation (Lehman et al., 1992; Lehman and Chatterjee, 2005). Frehlier (1987) gave the total thickness of the Boren Ranch sandstone near the west end of its exposure along the lake as 15 meters (50 feet), but further east along the lake the unit reaches at least 30 meters (100 feet), with the base of the unit being an uncertain distance below the water line. The unconformable basal contact with the Santa Rosa Sandstone is exposed well above the water line near Montford Dam, and becomes submerged further west. The mottled beds are not present in this area, and if they formed here they have been completely truncated by the Boren Ranch sandstone. At the western edge of the exposures along the lake, including immediately below where Lehman et al. (1992) began to measure the type section of the Cooper Canyon Formation, the Boren Ranch sandstone is a relatively thick unit dominated by sandstone and conglomerate, with almost no mudstone (Fig. 2.13a). Further east along the shores of the lake however, including the Sam Wahl Recreational Area, a predominantly reddish brown mudstone-dominated lens reaching a thickness of 6-16 meters (20-50 feet) divides the Boren Ranch Sandstone into upper and lower sandstone units, (Figs. 2.4a, 2.13b). This lens is mappable, although it is not shown on the final map.

North of the Lake Alan Henry Wildlife Mitigation Area, the nature of the Boren Ranch sandstone changes considerably, and it becomes a fairly complex system of discontinuous sandstones and conglomerates interbedded with mudstone and carbonate beds, and Boren Ranch beds is a better descriptor of the unit than Boren Ranch sandstone (Fig 2.4). At the OS Ranch localities and slightly further north in the cliffs lining the North Fork of the Double Mountain Fork of the Brazos River, discontinuous sandstone lenses resting unconformably on top of the Santa Rosa sandstone and mottled beds are

Fig. 2.14. Boren Ranch beds at the OS Ranch Gully locality. Note that the lower Boren Ranch sandstone can be seen to thin and begin to dip steeply on the left side of the photograph.

informally referred to as "lower Boren Ranch sandstones," and stratigraphically higher sandstones and conglomerates separated from the Santa Rosa Sandstone and mottled beds by mudstone are referred to as "upper Boren Ranch sandstones" (Fig. 2.14). It must be emphasized that these terms only indicate if a sandstone contacts or is separated from the lower unconformable contact with the top of the Santa Rosa Sandstone, and do not imply precise stratigraphic equivalence. The upper Boren Ranch sandstones in particular are certainly not all at precisely the same stratigraphic level, and may be several meters apart. In fact the precise relationships between these discontinuous and often steeply dipping beds are complex, and in mapping it was decided to treat the lower sandstones, upper sandstones, and interbedded strata as a single unit (Fig. 2.4a). The total thickness of the Boren Ranch beds at OS Ranch is in places at least 30 meters (100 feet) thick.

These more complexly interbedded strata at the OS Ranch have similarities to deposits in the Tecovas Formation and in the Monitor Butte Member of the Chinle Formation that have been interpreted as having formed in lacustrine and marsh

Fig. 2.15. Edge of lower Boren Ranch sandstone showing extremely steep dip, rock hammer and pack for scale. This photograph was taken just the left of the previous figure.

environments (Murry, 1989; Dubiel, 1987, 1994; Fritz, 1991; Lehman and Chatterjee, 2005). Several features of the OS Ranch strata distinguish them from the overlying Cooper Canyon Formation, and suggest lacustrine deposition:

1. The Boren Ranch sandstones and conglomerates sometimes cut sharply up section at extremely steep angles greater than 45°, well beyond the expected angle of repose. The lower Boren Ranch sandstone described at the OS Gully locality shows such geometry at its edges (Fig. 2.15). Lehman and Chatterjee (2005) described similarly steeply-dipping sandstones in the Tecovas Formation of West Texas, and interpreted them as having formed through syndepositional subsidence and deformation,

producing small lacustrine basins. The three-dimensional geometry of the steeply-dipping OS Ranch sandstones has not been examined in detail so it is unclear if they formed centripetally dipping basins, and they tend to be somewhat coarser than the relatively fine-grained sandstones described by Lehman and Chatterjee (2005). Nonetheless, their anomalously steep dip and association with other indicators of lacustrine deposition are suggestive.

2. Across most of the OS Ranch there is a thick section of reduced greenish-gray mudstone, often containing yellow or orange concretions, associated with the lower Boren Ranch sandstones. These drab-colored mudstones eventually grade up into oxidized reddish brown mudstones associated with the upper Boren Ranch sandstones (Fig. 2.16a). This differs strikingly from the reduced greenish-gray mudstones higher in the Cooper Canyon Formation, which are usually restricted to lenses within, or a reduced zone immediately below, major channel sandstones, or to reduction “haloes” in predominantly reddish overbank mudstones. Greenish gray mudstones produced by organic-rich reducing conditions are also associated with lacustrine and marsh deposits in the Tecovas Formation (Murry, 1989; Lehman and Chatterjee, 2005), the Los Esteros Member of the Santa Rosa Sandstone (Lupe, 1988; Fritz, 1991), and the Monitor Butte Member of the Chinle Formation (Dubiel 1987, 1994). The overlying reddish brown mudstones are interpreted to represent the replacement of lacustrine deposits with the well-oxidized overbank deposits which dominate the overlying Cooper Canyon Formation.
3. There are a few beds of tan-colored carbonate within the greenish gray mudstones at the main OS Ranch locality around Dicynodont Hill, one of which is a fairly distinctive and stratigraphically useful bed that can be traced locally (Figs. 2.16). They contain small dissolved voids which have been filled with recrystallized calcium carbonate. Carbonate beds have not been noted higher in the Cooper Canyon Formation, although they have also been observed and interpreted as representing lacustrine deposition in the Tecovas Formation (Lehman and Chatterjee, 2005), Los Esteros Member of the Santa Rosa Sandstone (Lupe, 1988; Fritz, 1991), and Monitor

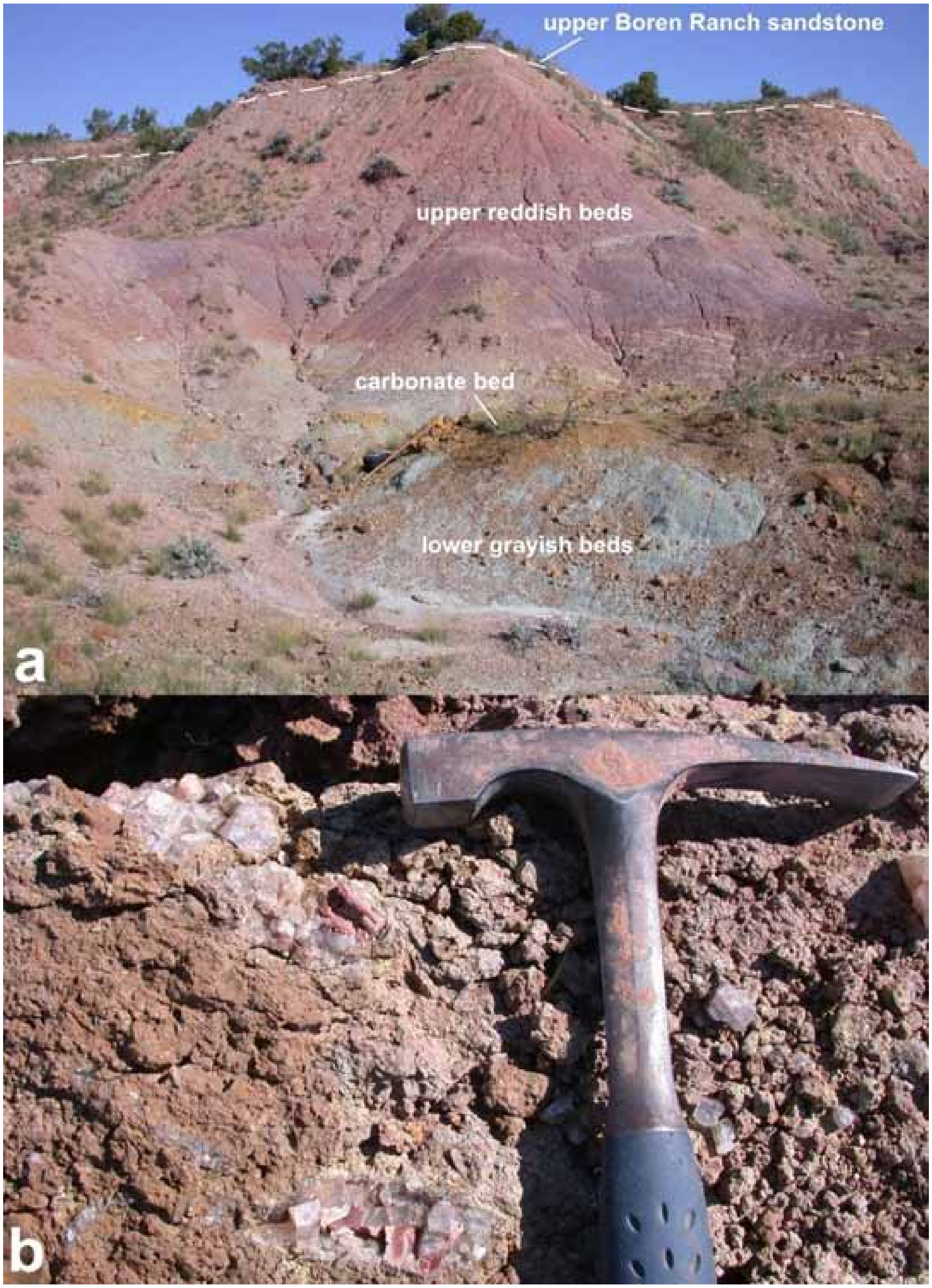


Fig. 2.16. Boren Ranch beds at OS Ranch fossil locality (MOTT 3867, Site 1): *a,* Site 1 showing transition from lower drab colored mudstone containing carbonate bed to upper reddish mudstone capped by a thin upper Boren Ranch sandstone, Jacob's staff is 1.5 m long; *b,* close up of carbonate bed showing recrystallized $CaCO_3$.

Butte Member of the Chinle Formation (Blakey and Gubitosa, 1983; Dubiel 1987, 1994). McGowan et al. (1979) reported dolomite beds from the lower part of the Dockum Group in adjacent Kent County, and they may be part of the same depositional system.

4. Plant material is unusually abundant within the Boren Ranch sandstone/beds and associated mudstones compared to within the Cooper Canyon Formation, usually in the form of petrified wood. Petrified wood is often found in the Boren Ranch sandstone along Lake Alan Henry, but is most spectacularly represented by the "petrified grove" (MOTT 3868) briefly discussed by Lehman and Chatterjee (2005, p. 333). This "grove" consists of a concentration of upright trunks (Fig. 2.17a), probably referable to *Araucarioxylon*, that are located near and just slightly down-section from the main OS Ranch localities around Dicynodont Hill. These trunks are not well preserved and are not nearly as spectacular as the abundant petrified logs known from the Chinle Formation in eastern Arizona, but represent one of the most important Upper Triassic plant localities in Texas. Other partial fossil logs have also been found in the vicinity, some in better condition (Fig. 2.17b). Petrified wood is often associated with bright yellowish limonized concretions (Fig. 2.17c). Coprolites are also unusually abundant at the OS Ranch compared to the Cooper Canyon Formation, as they are in the Tecovas Formation in Crosby County. Unusually abundant plant material and coprolites are also associated with the lacustrine deposits described by Dubiel (1987, 1994), Lupe (1988), Fritz (1991), and Lehman and Chatterjee (2005). Another unusual fossil occurrence is a black mudstone bed containing abundant conchostracans discovered by Sankar Chatterjee and John Boren in the Boren Ranch Sandstone along Lake Alan Henry. Relocating the locality has proven difficult, and it may now be submerged. Black mudstones dominated by conchostracans were also reported in the Monitor Butte Member, and interpreted as representing ephemeral pools (Dubiel, 1987, 1994).

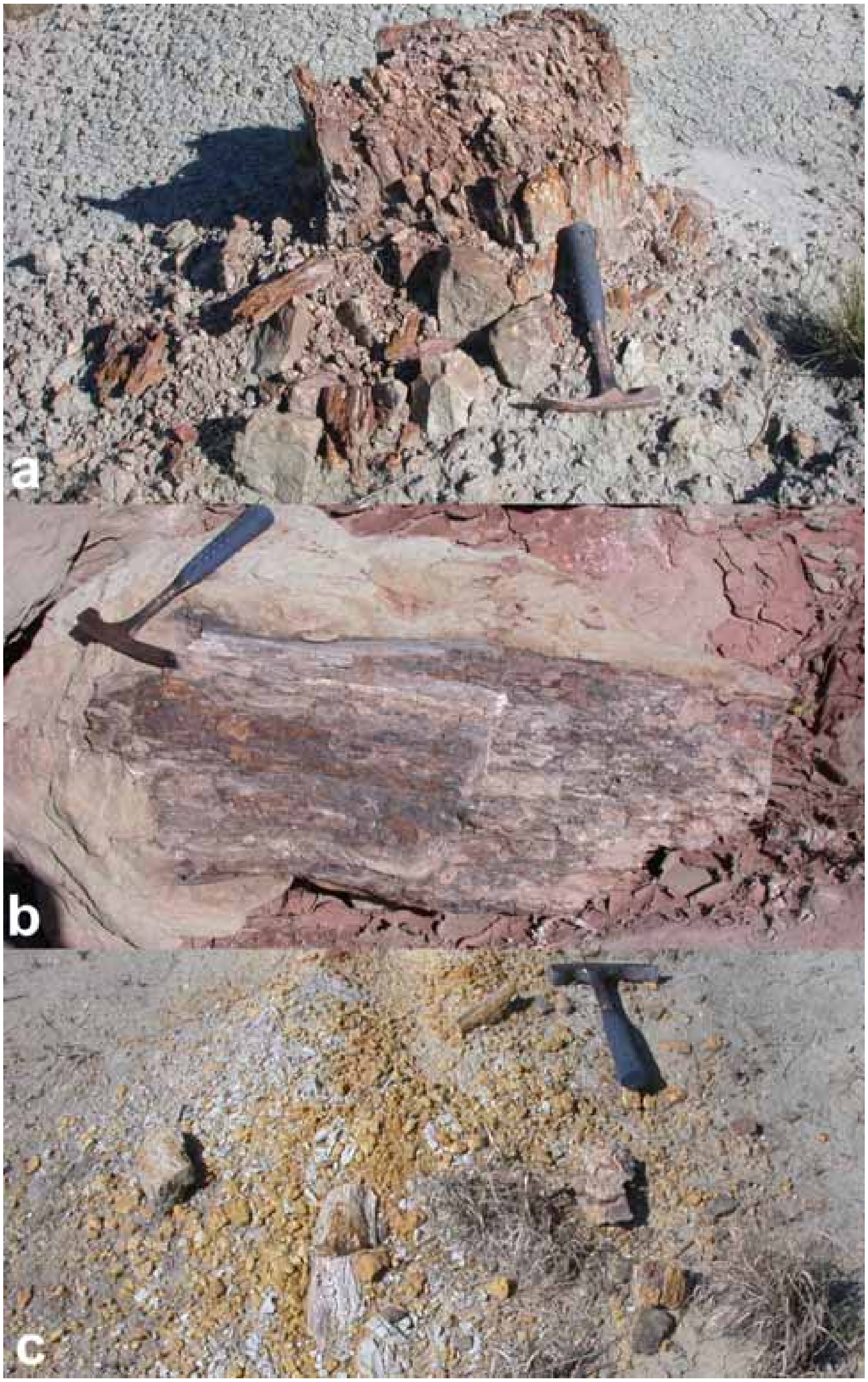


Fig. 2.17. Petrified wood in the Boren Ranch beds at OS Ranch: *a*, upright trunk at "Petrified Grove" (MOTT 3868); *b,* well-preserved log in a lower Boren Ranch sandstone near "Petrified Grove"; *c*, petrified wood preserved with limonite.

Lithologically, the sandstones of the Boren Ranch sandstone/beds are predominantly feldspathic and micaceous litharenites (Frehlier, 1987; Lehman et al., 1992), virtually identical to those in the overlying Cooper Canyon Formation, and within the Trujillo Sandstone north of the study area, which is the primary reason why Lehman et al. (1992) and Lehman (1994a, b) identified the Boren Ranch sandstone as the Trujillo Sandstone. The Boren Ranch sandstones are less siliceous than those of the Santa Rosa Sandstone, and also tend to be finer grained (mostly very fine to fine-grained rather than medium to coarse grained), and dominated by horizontal planar bedding (also as in the sandstones of the Trujillo Sandstone and Cooper Canyon Formation; Lehman and Chatterjee, 2005), although trough cross-bedding and ripple cross-lamination is also present. The Boren Ranch sandstones tend to be drab grayish or greenish-gray, although they may also be reddish (particularly when arkosic) or yellowish.

Locally, there are also conglomeritic beds, occasionally reaching several meters in thickness. Compositionally, these tend to be dominated by sedimentary rocks clasts, usually reworked pedogenic carbonate nodules, or slightly rounded rip-up clasts of sandstone or siltstone cemented with calcium carbonate (Frehlier, 1987). Again, this lithology is distinct from the conglomerates of the Santa Rosa Sandstone, where the dominant clasts are siliceous. However, silica-rich conglomerates are occasionally seen in the Boren Ranch sandstone (particularly low in the section), as they are in the Trujillo Sandstone. The base of the Boren Ranch sandstone/beds is often dominated by large (cobble-sized), flattened, sedimentary rip-up clasts (Fig. 2.18). At both the OS Ranch area and at Lake Alan Henry, the intrabasinal conglomerates seem to dominate the upper part of the Boren Ranch Sandstone/beds.

In most places where the contact can be observed, the arkosic and micaceous litharenite sandstones and intrabasinal conglomerates sit directly on the truncated upper surface of the Santa Rosa Sandstone and/or mottled beds, indicating that scouring by the channels in which the Boren Ranch sandstones were deposited is at least partly responsible for the truncation. This is certainly clear at Lake Alan Henry, but is also true

Fig. 2.18. Base of a lower Boren Ranch sandstone not far from the OS Ranch Gully section; the very base is dominantly cross-bedded sandstone, but the rest of the unit in the photograph is composed almost entirely of cobble to boulder-sized rip-up clasts of siltstone and sandstone; rock hammer for scale.

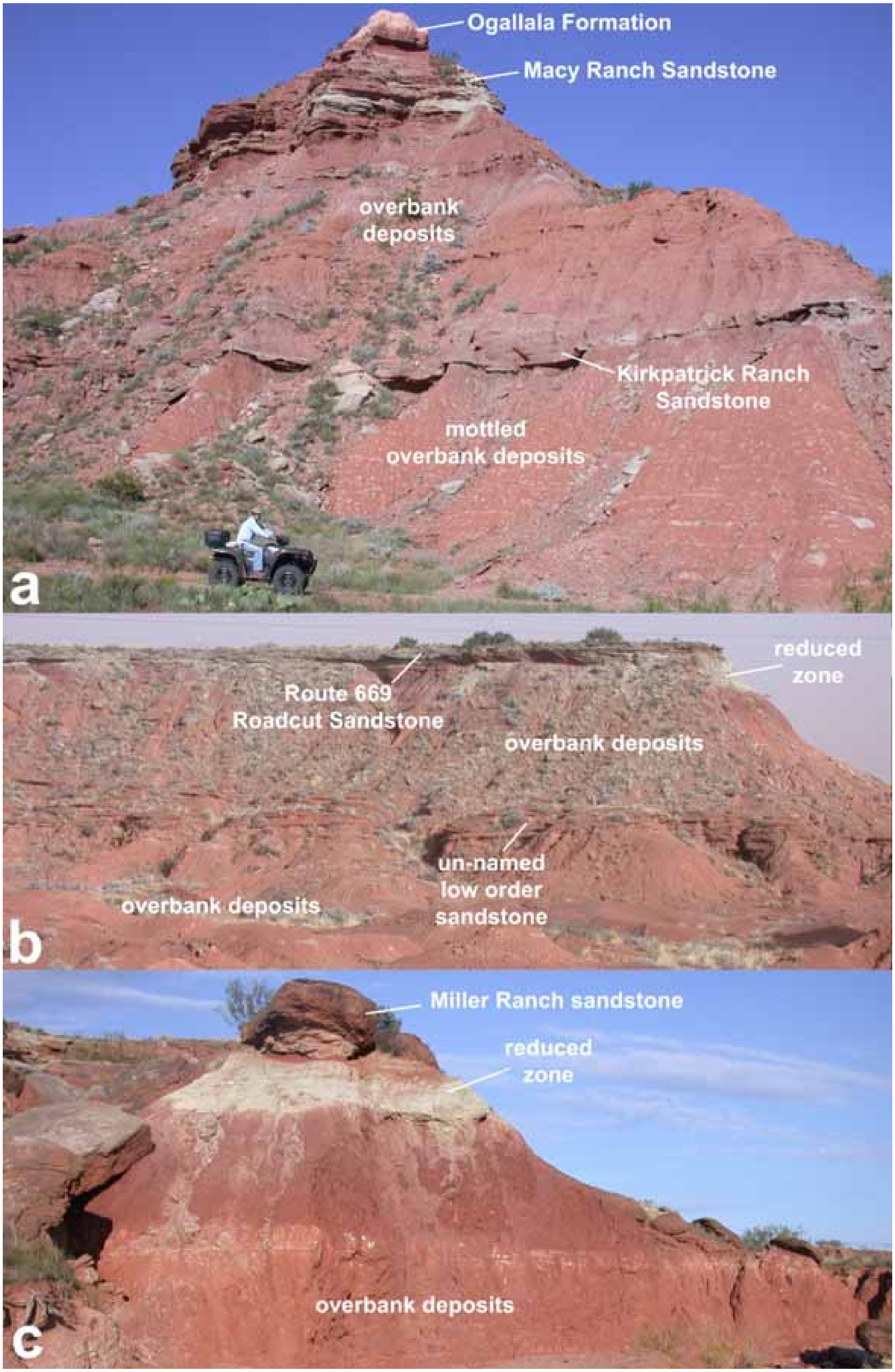
of the smaller sandstones in the North Fork drainage at OS Ranch. In the OS Ranch Gully section (Fig. 2.14) for example, the thickest part of the lower micaceous sandstone forming the base of the Boren Ranch beds completely truncates the mottled beds in the gully, but only partly truncates them to the east and west where the sandstone cuts sharply upsection before pinching out. However, in other areas, including at the Eastern Garza locality, the unconformity at the top of the mottled beds is overlain directly by reddish mudstone, with the first micaceous litharenite sandstones occurring well above the contact. This suggests that the top of the Santa Rosa Sandstone and mottled beds were being eroded prior to the deposition of the Boren Ranch sandstone/beds, and corroborates the extended depositional hiatus implied by the mottled beds themselves.

Cooper Canyon Formation

The Cooper Canyon Formation in southern Garza County is an approximately 160 meter thick unit dominated by thick sequences of reddish siltstone and claystone making up about 70%-80% of the section, interbedded with sandstones and conglomerates lithologically identical to those in the Boren Ranch sandstone/beds (Fig. 2.19) (Frehlier, 1987; Lehman et al., 1992), with which the Cooper Canyon Formation has a gradational lower contact.. The sands are highly micaceous and contain abundant reworked fragments of phyllitic metamorphic rocks derived from the Ouachita fold and thrust belt to the southwest of the Dockum depocenter (McGowan et al., 1979, 1983; Frehlier, 1987; May, 1988; Lehman et al., 1992; Long and Lehman, 1994; Lehman and Chatterjee, 2005; Lehman et al., unpublished), whereas the conglomerates tend to be almost exclusively intrabasinal reworked carbonate nodules, or clasts of siltstone cemented by carbonate (Fig. 2.20a), although siliceous conglomerates are rarely present (Fig. 2.20b). Intrabasinal clasts are derived from eroded floodplain deposits, and other locally derived clasts include vertebrate bone fragments, petrified wood, rhizoliths, coprolites, and unionid bivalve shells (Frehlier, 1987; Lehman and Chatterjee, 2005).

As already discussed, McGowan et al. (1979) considered the thick mudstones to represent lacustrine deposits, with the sandstones and conglomerates representing deltaic and associated channel deposits feeding into the lake system. However, Frehlier (1987) and Lehman and Chatterjee (2005) interpreted the Boren Ranch Sandstone and Cooper Canyon Formation to represent a single depositional sequence formed primarily by fluvial channel and overbank deposits, with lacustrine deposits being a relatively minor component (Fig. 2.21). Most of the thick and laterally extensive blanket sandstone represent the channel facies of mixed load or suspended load-dominated meandering

Next Page: Fig. 2.19. Channel and overbank deposits in the Cooper Canyon Formation in southern Garza County: a, the Lott Kirkpatrick vertebrate locality (MOTT 3634) high in the Cooper Canyon Formation; b, the Peninsula Hill locality, thickness of section in photograph about 20 meters; c, the Marts Grazing locality, thickness of section in photograph about 11 meters.


Ogallala Formation
Macy Ranch Sandstone
overbank deposits
Kirkpatrick Ranch Sandstone
mottled overbank deposits
a
reduced zone
Route 669 Roadcut Sandstone
overbank deposits
un-named low order sandstone
overbank deposits
b
Miller Ranch sandstone
reduced zone
overbank deposits
c

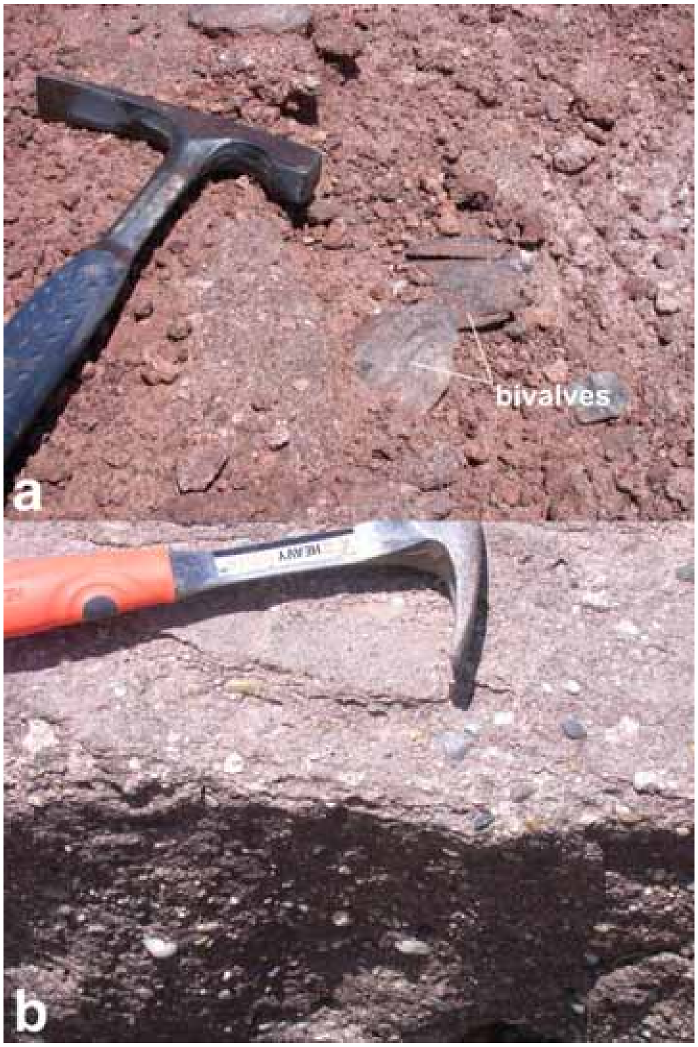


Fig. 2.20. Pebble conglomerates in the Cooper Canyon Formation: a, a fairly typical intrabasinal pebble conglomerate in a low-order channel sandstone at the Zip Giant Clams locality containing large unionid bivalves; b, unusual silicious pebble conglomerate in the Bauchier Ranch sandstone near the Lott Tree locality (MOTT 3877).

rivers, deposited in thalweg, point bar, levee, and crevasse splay environments, and the thicker and finer grained mudstones are primarily proximal overbank and floodplain deposits, interbedded sandstones and conglomerates that are generally thinner and less laterally extensive than the large blanket sandstones, representing small bed-load dominated channels and sheetfloods (Frehlier, 1987; Lehman and Chatterjee, 2005).

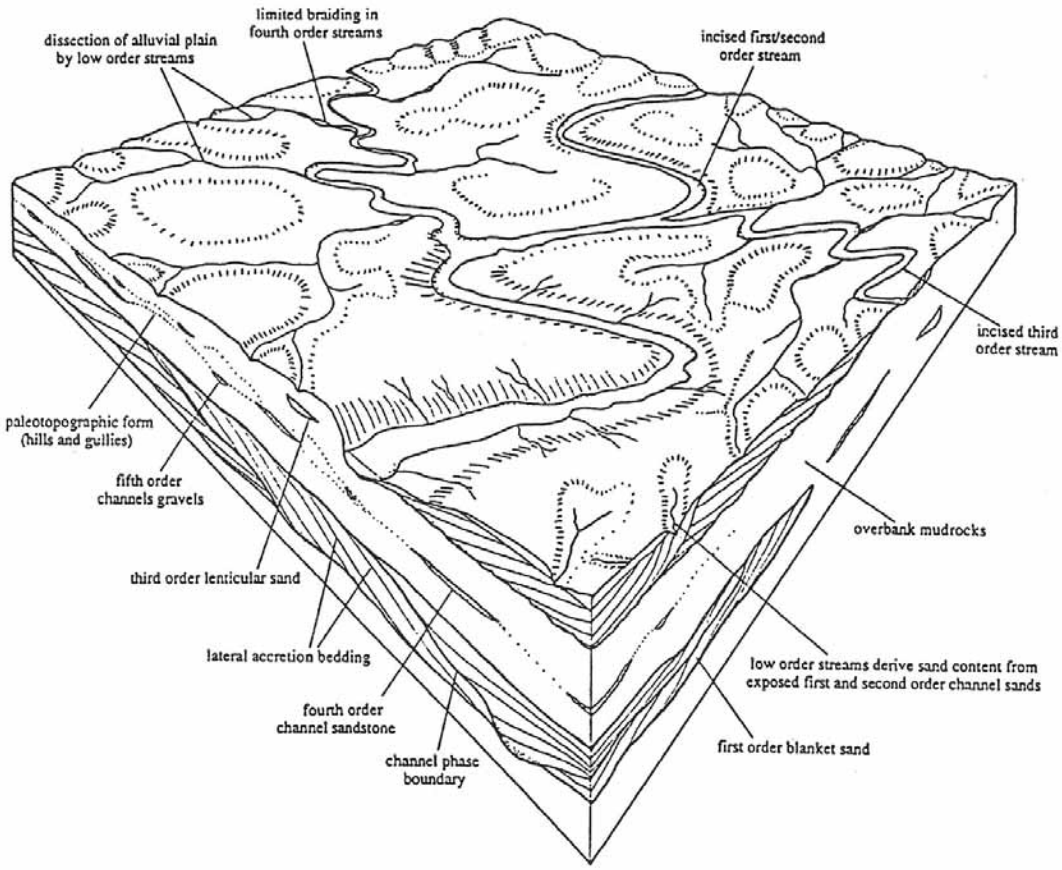


Fig. 2.21. Frehlier's (1987, fig. 8.3) interpretation of the depositional environment of the Cooper Canyon Formation of southern Garza County, during a period of floodplain degradation in which the overbank deposits are incised by both high order and low order streams.

Frehlier (1987) used the term "high order fluvial sand bodies" to describe the extensive blanket sandstones that he and Lehman and Chatterjee (2005) interpreted as being deposited by mixed load and suspended load meandering river channels (he arbitrarily divided these into "first order sandstones" and "second order sandstones," based on the thickness of the unit, size of the sedimentary structures, and calculated channel dimensions). Some of these sandstones represent single stages of channel incision, but others form thicker and usually more laterally extensive amalgamated deposits as with the Boren Ranch Sandstone along Lake Alan Henry. Thinner high order

Fig. 2.22. Cowhead Mesa. The mesa is capped by the Macy Ranch Sandstone, an amalgamated high order sandstone which reaches a thickness here of over 20 meters. The Lower Macy Ranch Sandstone, a smaller high order sandstone, outcrops at the base of the mesa. A zone of drab-colored iron reduction can be seen in the overbank mudstones immediately below both sandstones. Photo courtesy Bill Mueller.

sandstones may only be a few meters thick, though some amalgamated high order sand bodies may reach thicknesses of 15 meters or more (Fig. 2.22; Frehlier, 1987; Lehman and Chatterjee, 2005) and extend laterally for several kilometers. Using lateral accretion bedding, Frehlier (1987) calculated thalweg bankful depths of 5-13 meters, and bankfull widths of 50-195 meters, for some high order channels. High order channels tend to be the most traceable, and therefore the most useful for mapping and regional correlation within southern Garza County.

High order sandstones usually have drab coloration (usually greenish gray), which contrasts sharply with the reddish coloration of the bulk of the overbank deposits and low order sandstones and conglomerates (Figs. 2.19, 2.22). This color contrast is seen in other continental fluvial red beds, and is probably due to the relatively reducing conditions present in channels compared to the oxidizing conditions in the floodplain (Turner, 1980). A variety of interesting concretionary structures are also found in drab colored high order sandstones in the Cooper Canyon Formation, many of which appear to be small and mineralized by limonite and pyrite, whereas others are massive and

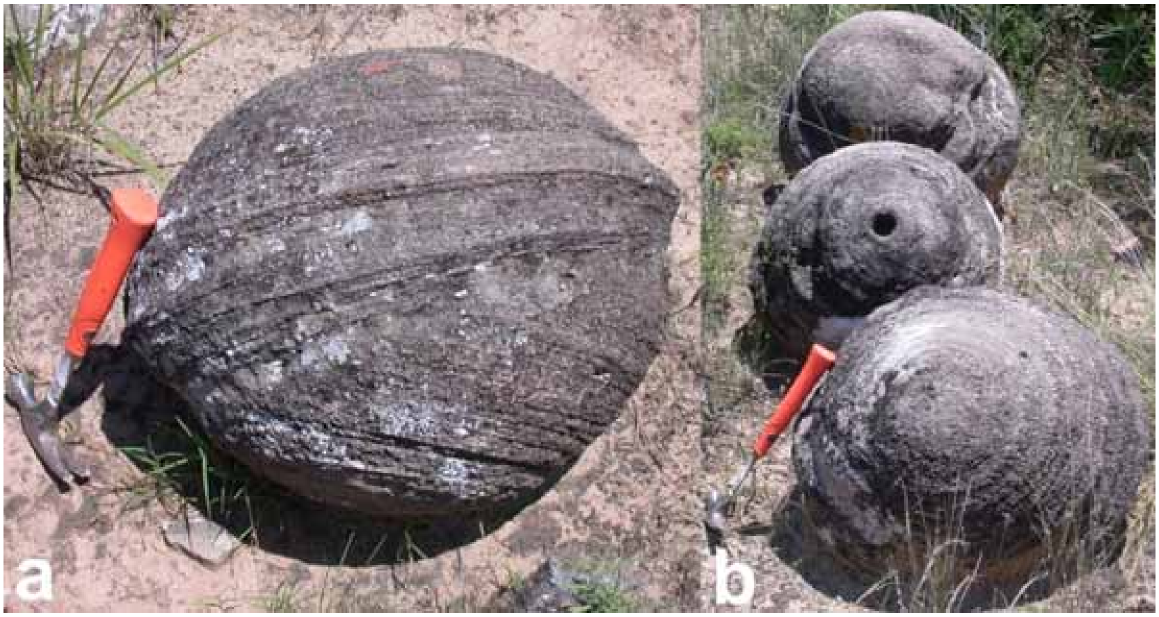


Fig. 2.23. “Basketball” concretions which have weathered out of the Bauchier Ranch Sandstone: *a,* concretion showing original cross-bedding; *b,* concretions photographed perpendicular to original bedding; the “donut hole” in the middle concretion is seen occasionally in these concretions.

spherical (Fig. 2.23). These concretions may form in a similar fashion to those found in reduced zones associated with other Permo-Triassic red beds (Harrison, 1975; Turner, 1980).

The mudstone deposits that dominate the Cooper Canyon Formation were interpreted by Frehlier (1987) and Lehman and Chatterjee (2005) as overbank sediments deposited over the floodplain during the overflow of high order channels. The lower part of an overbank sequence has a gradational lower contact with a high order sandstone and shows a generally fining upwards sequence, except when interrupted by low order conglomerates and sandstones. Except for the very top of the sequence, overbank deposits tends to be silty, somewhat micaceous, often preserve primary stratification, and are in places intensely interbedded with thin beds of conglomerate, sandstone, and siltstone. Relatively clay-rich mudstones lacking primary stratification and often containing abundant pedogenic carbonate nodules tend to form a relatively minor part of the overbank sequence, and are most commonly found high in the sequence directly below the erosional base of high order fluvial sand bodies (Frehlier, 1987; Lehman and Chatterjee, 2005). The overbank mudstones in the Cooper Canyon Formation are generally coarser-grained than seen in the Chinle Formation in the Chama Basin of New Mexico in the vicinity of Ghost Ranch, and in Petrified Forest National Park in eastern Arizona, both in that the overbank deposits are more strongly dominated by silt (or often even muddy sand) rather than clay, and are also more intensely interbedded with small channel conglomerates and sandstones. The Cooper Canyon Formation overbank deposits also tend to have more monotonous coloration than seen in the Chinle Formation.

Although overbank sediments are mostly reddish or reddish brown, drab coloration is found in thick, irregular zones directly below the bases of high order channel sandstones at the top of overbank sequences (Fig. 2.19b-c, Fig. 2.22), and were interpreted by Frehlier (1987) as having formed due to the percolation of reduced water in the channels into the underlying overbank deposits. Drab colored reduction also is found in mottled zones usually located in the lower, siltier parts of overbank sequences (Fig. 2.19a), where it mostly consists of spherical or irregularly-shaped reduction haloes and subhorizontal linear bands of reduction of the same color often associated with zones of carbonate nodules (Frehlier, 1987), or thin layers of sand and silt. Similar mottled zones are found in other continental Permian and Triassic red beds, and may be produced through the reduction of overbank sediments around patches of organic matter (Turner, 1980; Frehlier, 1987, p. 141). Lehman and Chatterjee (2005, fig. 10) also described likely lacustrine deposits within the overbank sequences at the base of the Cooper Canyon Formation, which consist of intrabasinal gravels, very fine-grained sandstone, and reddish siltstone forming centripetally dipping basins filled with lacustrine mudstone. As already noted, likely deposits possibly representing lacustrine basins also occur in the Boren Ranch beds at the OS Ranch localities.

The conglomerates and sandstones interbedded within the overbank deposits (Fig. 2.19a, b) which were described by Frehlier (1987) as “low order channel sandstones,” (arbitrarily divided into “fourth order” and “fifth order” sandstones based largely on thickness and sand content) and were interpreted by him and by Lehman and Chatterjee (2005, fig. 8) as having been formed by alternating cycles of floodplain erosion and aggradation. During periods of floodplain degradation (Fig. 2.21), gullies containing intrabasinal calcareous nodules and claystone breccia eroded from the overbank deposits were carved into the floodplain. During cycles of aggradation, when sedimentation continued, these gullies were filled with low sinuosity, bedload-dominated streams depositing conglomeritic sandstones. These units show a generally fining upward sequence, with thick layers of gravel composed of intrabasinal clasts grading up into sandstone. Unionid bivalves are locally abundant in low order conglomerates (Fig. 2.20a), sometimes forming dense accumulations, as are fragmentary vertebrate fossils.

Thinner low order sandstones (generally less than 2 meters thick) tend to be dominantly gravel, and dip at steep angles in outcrop, whereas thicker (up to five meters thick) low order sandstones have more interbedded sandstone, siltstone, and mudstone and siltstone, and may form amalgamated multi-storied sand bodies traceable over several kilometers (Frehlier, 1987). Thin deposits of sand and silt that Frehlier (1987) interpreted as sheetflood deposits are often found associated with low order sandstones, and Miall (1996) also noted such sheetfloods tend to be associated with bedload dominated streams. The Headquarters and Headquarters South vertebrate localities occur in a sheetflood which can be traced to a low order channel (Fig. 2.24). Most of the mappable sandstones that are not high order sand bodies are these larger low order sandstones, although these tend to more complex and arbitrarily bounded units closely associated with smaller low order channel gravels and sheetflood deposits, making them more difficult to map. Low order conglomeritic sandstones, unlike high order sandstones, tend to more commonly be reddish-brown in color, suggesting relatively oxidizing conditions due to a shortage of perennial water or organic material (particularly vegetation), or both.

Frehlier (1987) also identified “third order sandstones,” which in terms of lithology, stratigraphic sequence, and drab coloration, are very similar to high order

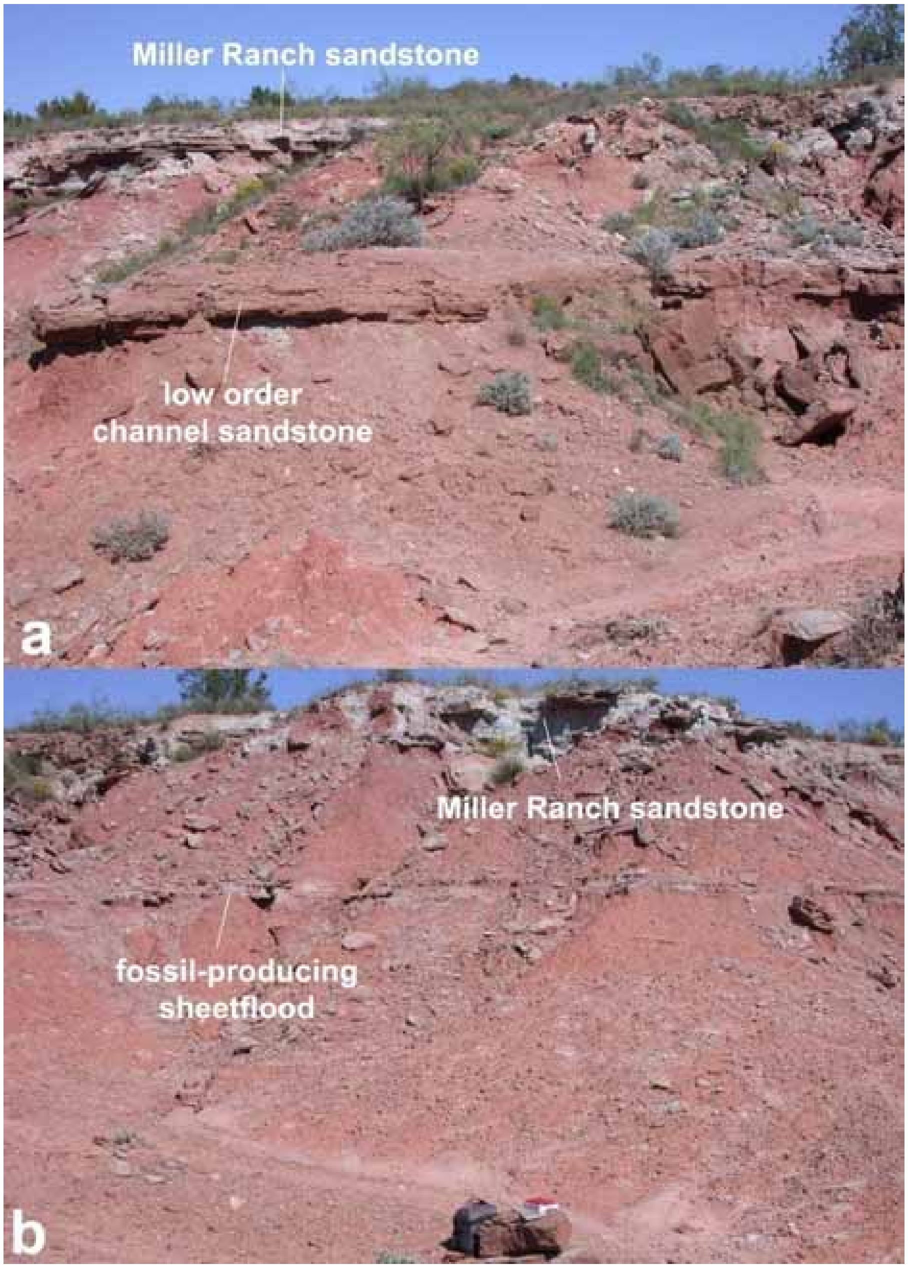


Fig. 2.24. The Headquarters vertebrate locality (MOTT 3892): *a*, low order channel sandstone immediately north of the locality, which thins laterally into a sheetflood which produces the vertebrate material; *b*, the Headquarters locality proper (MOTT 3892), immediately to the right of the first photograph, showing the sheetflood.

sandstones. However, third order sandstones represent single channel-fill ribbon sandstones lacking- lateral accretion beds, and do not form laterally extensive blanket sands (making them virtually useless for correlation). They were probably formed by relatively stable, non-migrating channels, although these channels have an asymmetric cross section indicating they probably meandered (Frehlier, 1987).

Frehlier (1987, p. 13) stated that these different ranks of sandstone body did not change in order laterally, because “each sand body order does not represent changes along a river trend, but depicts deposition by a particular type of stream.” However, is very clear that major, laterally traceable sandstone bodies of different orders may be very closely associated stratigraphically, and occur at approximately the same stratigraphic level (e.g. the Miller Ranch sandstones, also the Dalby Ranch sandstone and Cooper Creek beds; Fig. 2.4), and these were sometimes mapped as the same unit.

The Cooper Canyon Formation in southern Garza County may be divided somewhat arbitrarily into three units (Fig. 2.4). The mudstone-dominated “lower unit” forms the base of the Cooper Canyon Formation, corresponding to units 2-10 of Lehman et al.’s (1992) type section (Fig. 2.7b), and including most of Chatterjee’s (1986a) type section for the Cooper Member (Fig. 2.8a). The “middle unit” corresponds to units 11-14 In Lehman et al.’s (1992) type section, and is distinguished from the lower unit by being generally coarser-grained, containing several prominent high and low order sandstones which can be mapped for several kilometers, particularly the Dalby Ranch sandstone, Route 669 Roadcut sandstone, and Miller Ranch sandstone, as well as containing more abundant low order conglomeritic sandstones. The “upper unit” is similar to the middle unit, except that it is more dominated by overbank mudstones and has fewer prominent, laterally traceable sandstones. Drake (1892) recognized the same three part division (Fig. 2.6), with his “Lower Beds”, “Central Beds”, and “Upper Beds” corresponding approximately to the lower, middle, and upper units used here.

The Lower Unit of the Cooper Canyon Formation

The lower part of the Cooper Canyon Formation is a thick mudstone-dominated sequence usually about 30 meters (100 feet) thick (Figs. 2.3, 2.4a). Drake (1892) suggested that the “Lower Beds” were probably not more than 50 feet thick in Garza County, but the base of the lower unit is not exposed where he measured his sections. As will be explained in more detail later, this unit is probably correlative with the Tecovas Formation in the northern Texas Panhandle as suggested by Drake's (1892, pl. V) correlations. The unit is dominated by reddish brown and sometimes orangeish-colored mudstone (mostly siltstone) with greenish gray reduction mottling, and contains only few mappable sandstones and conglomerates, most of which are in the lower part of the unit, and none of which are as thick or laterally extensive as any seen in the middle or upper units. The lower contact of this unit, which is also the base of the Cooper Canyon Formation, is gradational with the Boren Ranch beds. In the area around Lake Alan Henry, this contact, although gradational, is relatively easy to identify, when exposed. The contact here varies between about 2250' and 2320' in elevation above sea level, with the lower elevations occurring to the southwest due to the regional dip of the base of the Dockum Group. In the North Fork drainage, the lower contact with the Boren Ranch beds is more difficult to place given that sandstones in the Boren Ranch beds are thinner, more discontinuous, and more complexly interbedded with mudstone. It is arbitrarily placed where the sequence becomes almost entirely monotonous mudstone, which occurs at least as high as 2380' around the OS Ranch localities, but dipping to the west and southwest to about 2300' at the base of the cliffs capped by the Dalby Ranch sandstone.

The thick sequence of overbank mudstones below the cap of the Dalby Ranch sandstone in the drainages of Salt Creek and the North Fork of the Double Mountain Fork of the Brazos River west of the OS Ranch localities is striking in having a distinctly tan or orangeish hue in the lower part of the section, which grades up into the more typical reddish-brown of Cooper Canyon Formation overbank deposits (Fig. 2.25). Remarkably large greenish-gray reduction mottles over a foot wide, surrounded by a thin halo of red, were observed in these orangeish mudstones, and autochthonous pedogenic carbonate nodules (rather than deflated or fluvially transported lag deposits of low order channels) seem to be unusually abundant as noted in this area by both McGowan et al. (1979, their figs. 15-16) and Frehlier (1986, p. 139, fig. 6.1). Some of the mudstones in the Boren Ranch beds at OS Ranch have similar coloration, which is reminiscent of the Tecovas Formation in southern Crosby County. It is possible that some slightly different

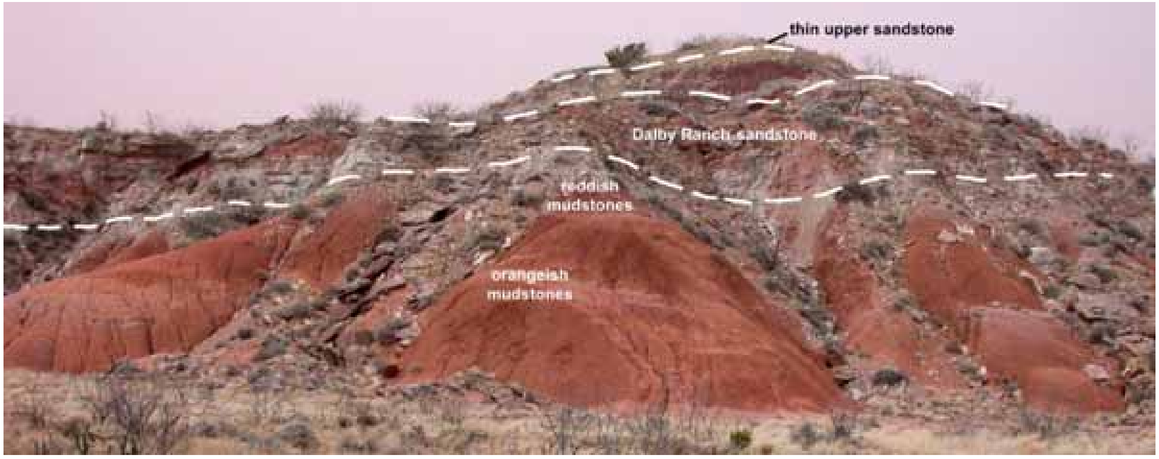


Fig. 2.25. Lower unit and Dalby Ranch sandstone at the North Fork locality, emphasizing the orangeish lower beds of lower unit.

depositional and/or diagenetic processes influenced the overbank sediments in the Tecovas Formation of Crosby County and in the lower unit of the Cooper Canyon Formation of the North Fork and Salt Creek area which were absent elsewhere in southern Garza County.

The centripetally dipping sandstones, siltstones, and claystones at the Boren (Neyland) Quarry vertebrate locality (MOTT 3869) that Lehman and Chatterjee (2005, pp. 337-338) identified as small lacustrine basins are located in the very lowermost part of the lower unit, almost directly above the top of the Boren Ranch sandstone, and the area also contains limonized petrified wood like that seen at the OS Ranch (Edler, 1999). The largely lacustrine depositional regime observed in the Boren Ranch beds at the OS Ranch seems to have continued, at least locally, into the lower unit of the Cooper Canyon Formation. There are also numerous low order conglomeritic beds and fine-grained sandstones in the lower unit immediately above the Boren Ranch sandstone near Lake Alan Henry, including at the Boren Quarry locality, and several of these channel deposits are exhumed to show a ribbon-like geometry in map view (Edler, 1999; Lehman and Chatterjee, 2005, fig. 10). Similar sandstones are present in the lower part of the lower unit throughout the region (some are distinctly visible in roadcuts along Highway 84 near the Scurry County line), and at least some are mappable.

A few other prominent sandstones and conglomerates in the lower unit have been mapped, although they are not very extensive laterally. These tend to be exposed near the base of mesas and cliff capped by the Dalby Ranch sandstone, and separated from it by thick sequences of mudstone. A low-order conglomeritic sandstone occurs near the base of the Post Quarry, where it was mistakenly identified by Chatterjee (1986a) as the Trujillo Sandstone (Frehlier, 1987: p. 76, fig. 2.16; Lehman and Chatterjee, 2005, lowermost sandstone in fig. 6B). Low order conglomeritic sandstones often contain unionid bivalves, and one particular low order conglomeritic sandstone (the “Zip Giant Clams” section, Appendix 1) contains gigantic unionids over ten centimeters wide that were not noted elsewhere in the study area (Fig. 2.20a). There are also several micaceous, drab colored sandstone bodies in the lower unit which have a ribbon-like geometry in map view, which were observed in the North Fork and Salt Fork drainages. At least some may represent Frehlier’s (1987) third-order sandstones. One thin sandstone can be traced below the Dalby Ranch sandstone just south of Highway 380 for some distance, and several prominent sandstones and conglomerates form hills and mesas in the Sand Creek drainage east of the Kirkpatrick Ranch that are distinctly lower than the Dalby Ranch sandstone capping the surrounding cliffs. Some of these minor sandstones are mapped in Fig. 2.4c.

Distinguishing sand bodies in the upper part of the lower unit of the Cooper Canyon Formation from those of the middle unit (particularly in the case of the Dalby Ranch sandstone and Cooper Creek beds) is sometimes a somewhat arbitrary exercise. Even though the base of the Dalby Ranch sandstone in particular is usually a fairly distinct and easily traced unconformity, it is possible that some sandstones mapped in the upper part of the lower unit may be approximately stratigraphically equivalent with sandstones elsewhere mapped as part of the Dalby Ranch sandstone.

The Middle and Upper Units

The combined middle and upper units of the Cooper Canyon Formation are about 80-90 meters (about 250-300 feet) thick, and contain several prominent sandstones that can be traced over several kilometers. Although these sandstones are sometimes discontinuous, pinch out within the study area, vary in thickness, show some slight variance in elevation and stratigraphic position, and sometimes consist of a package of several closely associated lenses rather than a single massive sandstone, their relative superpositional relationships seem to be consistent. For example, the Miller Ranch sandstone and the Dalby Ranch sandstone are consistently separated by a mudstone-dominated interval wherever they can be traced into the same area, even though the Miller Ranch sandstone in particular is actually a somewhat discontinuous package of two or more closely associated sandstones.

Low order conglomeritic sandstones are more common in the overbank mudstones of the middle and upper units then they are in the lower unit, and many are probably mappable. These are extremely common in the area southwest of the Caprock Finger called Big Red Mud (Fig. 2.4c) in the stratigraphic interval between the Dalby Ranch sandstone and Miller Ranch sandstone, especially between about 2460'-2500', where they often cap small hills and mesas (Fig. 2.26a). A notable low order conglomeritic sandstone occurs stratigraphically below the Route 669 Roadcut sandstone and above the Bauchier Ranch sandstone just south of the Double Mountain Fork in the southwestern part of the study area (Fig. 2.26b). Although only traceable over a few kilometers, this unit is quite well exposed in places, and an outlier forms the Lott Hill vertebrate locality, and prominent low order conglomeritic sandstones below the Route 669 Roadcut sandstone at the South Middle Creek and Peninsula Hill sections (Fig. 2.19b) may be correlative with it. The Headquarters and Simpson Ranch vertebrate localities (MOTT 3892, MOTT 3898-3900, MOTT 3874) lie in complexes of low order sandstones (Figs. 2.24 2.26c). The area just southwest from the UU Railroad Flats vertebrae locality (MOTT 3883), below the cliff capped by the UU Ranch sandstone, is intensely interbedded with steeply dipping low order conglomeritic sandstones, and these continue into exposures above the Miller Ranch sandstone in the vicinity of the Squeak Site and the K.W. Flats vertebrate localities (MOTT 3908 and 3909). The zone of distal sheetflood deposits described by Frehlier (1987, pp. 90-91, fig. 2.37) previously

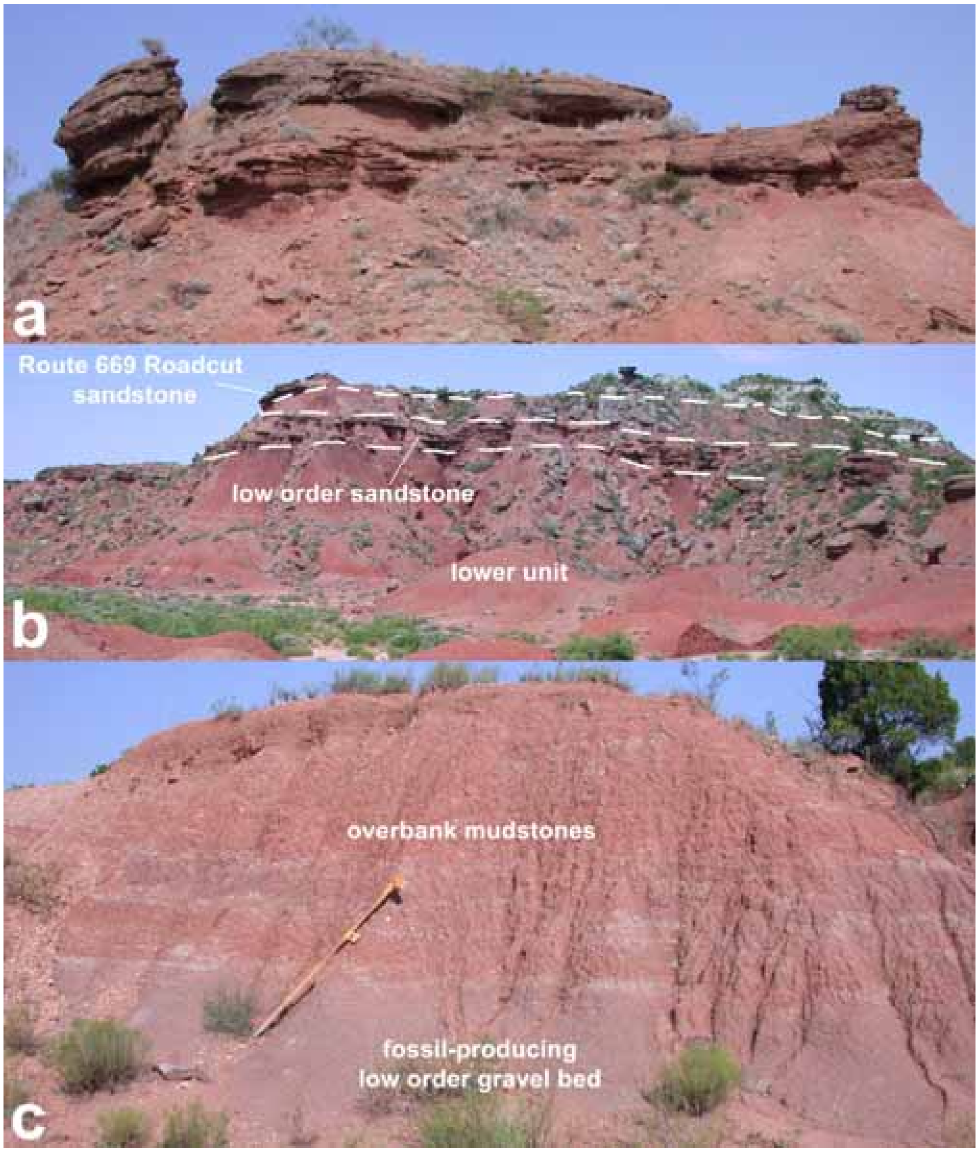


Fig. 2.26. Low order conglomeritic sandstones in the middle and upper units of the Cooper Canyon Formation: *a*, two low order sandstones at Big Red Mud; *b*, low order sandstone which can be traced to the Lott Hill vertebrate locality (MOTT 3878); *c*, low order gravel bed at the Simpson Ranch vertebrate locality (MOTT 3874), Jacob's staff is 1.5 meters long.

described by McGowan et al. (1979, fig. 22) as deltaic foreset bedding is located below the Macy Ranch sandstone at Macy Ranch.

Elsewhere, below the Miller Ranch sandstone (along the northeast edge of the Caprock Finger for example), the overbank deposits may form a fairly monotonous sequence of mudstones lacking many sandstones or conglomeritic beds. In places where the Dalby Ranch sandstone, Cooper Creek beds, and Bauchier Ranch sandstone, which all form the arbitrary lower boundary of the middle unit of the Cooper Canyon Formation (Fig. 2.4a) are absent, overbank deposits of the lower and middle units have a fairly uninterrupted gradational contact. As will be discussed later, this has significance for the postulated existence of the regional TR-4 unconformity of Lucas (1991, 1993b).

The Dalby Ranch sandstone

The Dalby Ranch sandstone, Cooper Creek beds, and Bauchier Ranch sandstone all occur with basal contacts between about 2400' and 2460' across the study area, making this an arbitrary but useful lower boundary for the middle unit of the Cooper Canyon Formation. The Dalby Ranch sandstone is the most prominent and laterally extensive of these (at least within southern Garza County), and was named and described by Frehlier (1987) south of Highway 380, several kilometers east of Post, where it forms prominent drab-colored cliffs capping the reddish mudstones of the lower unit at Dalby Ranch (Fig. 2.25). These strata were also described in the same area by McGowan et al. (1979, figs. 15-16), who interpreted the Dalby Ranch sandstone as a fluvial meanderbelt, and this interpretation was accepted by Frehlier (1987, figs. 2.12-2.14, 2.18) who described it as an amalgamated high order sandstone. The sandstone reaches up to 15 meters (about 50 feet) in thickness at Dalby Ranch Butte (Frehlier, 1987), although it is usually thinner.

The Dalby Ranch sandstone is fairly easy to trace, capping the prominent cliffs west and southwest of the North Fork of the Double Mountain Fork of the Brazos River (Figs. 2.4c, 2.25, 2.27a), and surrounding Sand Creek, between Highway 84 and Highway 380. In the Salt Creek drainage north of the Kirkpatrick Ranch, its basal contact becomes somewhat harder to trace and the sandstone may be locally absent, but it is well exposed where it forms the banks of Stink Creek Tank, and its superpositional relationship with the Miller Ranch sandstone capping the hills around the tank is clear. Highway 84 actually extends for some distance southeast of Post along a long, broad

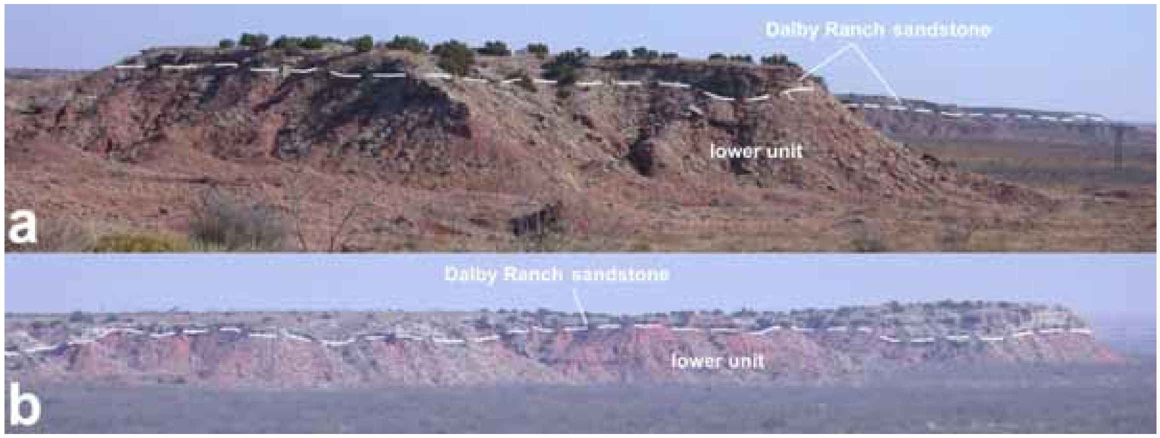


Fig. 2.27. The Dalby Ranch sandstone: *a*, immediately to the east of Highway 84, where it was identified as “unit 11” in Lehman et al.’s (1992) type section for the Cooper Canyon Formation; *b*, capping a mesa on Miller Ranch a few miles from the Post Quarry, just north of the South Fork of the Double Mountain Fork of the Brazos, photograph taken from Woolam Ranch near the tip of the Caprock Finger.

finger of the Dalby Ranch sandstone, and Lehman et al.’s (1992, fig. 1) identified the sandstone as “unit 11” of their type section near where the highway drops off of it into the lower unit (Fig. 2.7a). The Dalby Ranch sandstone continues southwest, capping cliffs and mesas around Cooper Creek, north of the South Fork of the Double Mountain Fork (Fig. 2.27b). Its exact relationship with the Cooper Creek beds is not entirely clear, though they certainly occur at roughly the same stratigraphic level, and probably interfinger slightly. The Dalby Ranch sandstone can be traced around the tip of the Cap Rock Finger into Big Red Mud, and also crosses the South Fork of the Brazos River to form the low cliffs at the base of the more massive cliffs capped by the Cretaceous strata at the south edge of Garza County, including those just above the Meyer’s Hill vertebrate locality (MOTT 3881). Drake’s (1892, pl. V) measured his section 5 not far west of Meyer’s Hill, or slightly further south in northern Borden County. His unit no. 4 at the base of his “Central Beds” probably corresponds to the Dalby Ranch sandstone, although if so Drake (1892) seems to have correlated it erroneously with the Miller Ranch sandstone across the South Fork at the tip of the Caprock Finger (unit no. 4 of pl. V, section 6; the Dalby Ranch sandstone is probably unit no. 6 of the same).

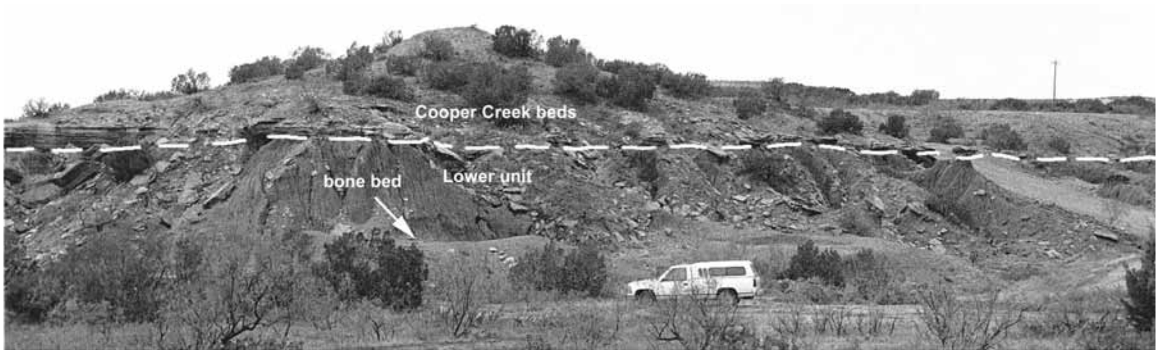


Fig. 2.28. The Post Quarry vertebrate locality (MOTT 3624).

The basal contact of the Dalby Ranch sandstone is usually between 2400’ and 2460’. It does not show the distinct southwesterly dip seen in the Santa Rosa Sandstone and Boren Ranch sandstone, and in fact shows a very slight southeasterly dip. However, determining the exact base of the Dalby Ranch sandstone, although usually easy, is complicated in areas where it separates into two or more thick sand bodies separated by thin sections of mudstone, rather than remaining a single amalgamated sand body. This occurs for example on the mesas south of Cooper Creek and Highway 84, where in places the Dalby Ranch sandstone breaks into three sand bodies dipping subtly to the east, some with basal contacts as low as 2370’; one or more of these may be equivalent to the Cooper Creek beds.

The Cooper Creek beds

Frehlier (1987) examined what he described as a single story low order sandstone at the Cooper Creek locality just east of the tip of the Caprock Finger, which he included in a large section for the Cooper Canyon Formation in that area (Frehlier, 1987, fig. 2.16, lower part of Section A). Lehman and Chatterjee’s (2005, fig. 6B) section for the Post Quarry vertebrate locality is taken from this part of Frehlier’s section, and his given location for the Cooper Creek locality (Frehlier, 1987, fig. 2.7) and elevation in his fig. 2.16 for the base of the sandstone (about 2400’), corroborates that this sandstone is probably the one capping the Post Quarry (Fig. 2.28).

Although this sandstone is at roughly the same stratigraphic level as the Dalby Ranch sandstone, and close to the mesas capped by the Dalby Ranch sandstone to the east, Frehlier (1987, p. 76) indicates that it is a single story low order sandstone rather than a high order sandstone like the Dalby Ranch. Also, other conglomeritic low order sandstones outcrop at about the same level to the south of the Post Quarry, forming a complex package of relatively thin and discontinuous sandstones and sheetfloods, rather than a single massive unit like the Dalby Ranch sandstone. Moreover, northeast of the Post Quarry, in the broad valley surrounding Cooper Creek, the Dalby Ranch sandstone seems to pinch out the east, and more discontinuous low order conglomeritic sandstones occur at about the same stratigraphic distance below the Miller Ranch sandstone. These low order conglomeritic sandstones, the Cooper Creek beds, are mapped with the Dalby Ranch sandstone (Fig. 2.5)

The Bauchier Ranch sandstone

The Bauchier Ranch sandstone is a distinctive sandstone which outcrops over a few kilometers in yet another drainage called Salt Creek just west of Highway 669 in the southwestern part of Garza County, below the Route 669 Roadcut sandstone (Figs. 2.4a-c, 2.29a). Its basal contact occurs at a slightly higher elevation (about 2450’), and probably at a slightly higher stratigraphic level, than the Dalby Ranch sandstone on the other side of the South Fork of the Double Mountain Fork of the Brazos. It is arbitrarily considered to form the base of the middle unit of the Cooper Canyon Formation where it occurs.

This sandstone is extremely unusual lithologically for the Cooper Canyon Formation, being composed primarily of highly siliceous and somewhat micaceous trough and planar cross bedded sandstone with an unusual light gray or whitish-yellowish hue. Unlike most of the sandstones and conglomerates in the Cooper Canyon Formation, the base of the unit in places is seen to be composed of silica (primarily quartzite) pebble conglomerate rather than reworked intrabasinal clasts (Fig. 2.20b). At the Lott Tree locality (MOTT 3877), this unit also produces abundant spherical soccer ball to beach

Fig. 2.29. The Route 669 Roadcut sandstone and its stratigraphic relationship to other sandstones: *a*, The Lott Hill locality (MOTT 3878), with the "basketball" concretions shown in Fig. 2.22 weathering out of the Bauchier Ranch sandstone at the base of the mesa; *b,* Headquarters Hill locality, Doug Cunningham for scale.

ball sized concretions, which strikingly preserve their original cross bedding, and have a dark gray color contrasting with the pale sandstone they weather out of (Fig. 2.23). Petrified wood is also locally abundant in this unit at the Lott Tree Locality (Bill Mueller, personal communication). The Bauchier Ranch sandstone can be traced from its lateral fringe, where it cuts sharply upsection and pinches out just south of the South Fork of the Double Mountain Fork, southeast to Highway 669. The unit has not been identified east of the highway.

The Route 669 Roadcut sandstone

Frehlier (1987) described this amalgamated high order sandstone in southwestern Garza County, where a cross section through its channel and proximal floodplain mudstones was nicely exposed by a road cut of Highway 669 as it passed on top of the sandstone. The Route 669 Roadcut sandstone is a prominent (reaching 15 meters or 50 feet thick in places, although it is usually thinner), drab-colored cliff-forming sandstone similar to the Dalby Ranch sandstone, and caps the cliffs surrounding Salt Creek east of Highway 669 along the southern edge of Garza County, continuing an uncertain distance into Borden County. It crosses the highway west and is well exposed in the Salt Creek drainage (Fig. 2.26b) including above the Bauchier Ranch sandstone (Fig. 2.29a). The sandstone follows the South Fork drainage west, becoming difficult to trace in places the land slopes above it, then returns east to become a well-exposed cliff former along Middle Creek and the next major drainage to the west (Fig 2.19b). The Route 669 Roadcut sandstone dies out almost immediately after re-crossing Highway 669 again into Big Red Mud, and is clearly absent in good exposures of overbank mudstones below the Miller Ranch sandstone a short distance to the east.

The unconformable basal contact of the Route 669 Roadcut sandstone is fairly level, at about 2500' or slightly higher throughout its exposures, and it lies slightly stratigraphically higher than the Dalby Ranch sandstone. The stratigraphic relationship between this sandstone and the Miller Ranch sandstone is well exposed at Headquarters Hill west of Middle Creek (Fig. 2.29b), where the gradational upper contact of the Route 669 Roadcut sandstone with middle unit overbank deposits can be seen, with the latter being truncated by the Miller Ranch sandstone on top of the hill. Orange-sized limonized and pyritized concretions are fairly common in places in the Route 669 Roadcut sandstone, particularly along Middle Creek.

The Miller Ranch sandstone

Frehlier (1987) described a high order sandstone at his Miller Ranch Butte locality at the tip of the Caprock Finger, which he showed as having a basal contact at about 2480' (Frehlier, 1987, section B of fig. 2.16). This drab-colored high order sandstone is an important cliff former in this area. This is probably the same sandstone identified by Drake (1892, section 6 of pl. V) in the same area at the top of his "Central Beds," and is also used here to arbitrarily mark the top of the middle unit. It probably also corresponds to unit 14 in Lehman et al.'s (1992) type section.

I refer to this unit as the Miller Ranch sandstone, but it is a particularly problematic unit to characterize as it is traced away from the Miller Ranch Butte locality for several reasons:

1. Although in places it remains a fairly "well behaved" blanket sandstone, in others it can be seen to be comprised of two or more stratigraphically closely associated sandstones, and in other places it pinches out entirely for short stretches. Even in the Miller Ranch Butte area, where Frehlier (1987, fig. 2.16) included it in his measured section as a single high order sandstone, there are actually two closely associated sandstones which vary considerably in thickness. The upper one is usually the thicker and more discontinuous of the two, but in places it is thicker than the lower sandstone. To the north, particularly as it approaches Highway 84 on the UU Ranch, there are also at least two closely associated sandstone beds. The higher of these caps the roadcuts along Highway 84 immediately southeast of Post (Fig. 2.30), and both sandstones show a noticeable degree of dip over short distances. This situation continues to the north on the UU Ranch between Highway 84 and Highway 380, where the sandstones cap hills and mesas east of Post (Fig. 2.19c), including at Stink Creek Tank. Green (1954) was probably referring to these sandstones when he referred to outcrops of the "Trujillo Sandstone" capping mesas east of Post. To the west of the Caprock Finger, the Miller Ranch sandstone continues to be an important cliff former across Big Red Mud, becomes somewhat harder to trace as it crosses

Fig. 2.30. The Miller Ranch sandstone along Highway 84, immediately southeast of Post; *a*, on the east side of the highway; *b*, on the west side of the highway. Note the thin bad of iron reduction immediately beneath the sandstone.

Highway 669, becomes an important cliff former again along Middle Creek and the east side of the next major drainage to the west (Fig. 2.25), then dies out before reaching Macy Ranch. Moreover, these sandstones certainly do not represent a single type of channel sandstone. For example, even though Frehlier (1987) identified the unit at Miller Ranch Butte as a high order sandstone, the sandstones present on the UU Ranch are highly conglomeritic, and even sand-sized clasts are of intrabasinal origin and composed primarily of reworked sedimentary rocks rather than the micaceous and phyllitic clasts which make up high order sandstones. It is most likely that the sandstones capping hills and mesas on the UU Ranch represent a complex of low-order sandstones, so the "Miller Ranch sandstone" actually includes at least two different types of sandstones.

2. The elevation of the basal contacts of these sandstones varies considerably, certainly more than other major sandstones in the Cooper Canyon Formation. North and northeast of the Caprock Finger, the basal contact of the lower and more persistent of these sandstones generally lie between 2470' and 2500'. However, after passing

around the tip of the Caprock Finger, it cuts gently upsection on Big Red Mud to an elevation of 2540’ or higher, and remains at this elevation until it dies out west of Middle Creek.

In spite of all these problems, I find it most reasonable to map these sandstones, conglomeritic sandstones, and interbedded mudstones as a single unit, the “Miller Ranch sandstone.” As already mentioned, these sandstones form a fairly consistent line of cliffs and mesas which can be traced all the way from Highway 380 to their termination west of Middle Creek. Changes in elevation of the package are fairly gentle and easy to follow. Moreover (and most importantly), these sandstones maintain a consistent superpositional relationship relative to the more well-behaved Dalby Ranch sandstone and Route 669 Roadcut sandstone (Fig. 2.29b). The complex nature of the Miller Ranch sandstone makes determining the exact relative stratigraphic positions of vertebrate localities close to it or within it difficult, but they can at least be considered to occur over a limited stratigraphic interval.

The Bull Creek beds

Frehlier’s (1987) Bull Creek locality, located in northern Borden County along Highway 669, is a section of overbank mudstone interbedded with mostly single-story low order conglomeritic sandstones, with the whole unit capped by an amalgamated low order sandstone (Frehlier, 1987, pp. 76-81, 170-183, figs. 2.30-2.32, Lehman and Chatterjee, 2005, fig. 8). Frehlier (1987) and Lehman and Chatterjee (2005) interpreted this locality as representing multiple phases of erosion and aggradation of overbank sediments, with the low order sandstones forming in incised paleogullies during periods of renewed deposition. Although most of the individual low order sandstones cannot be traced far, the complex multi-story low order sandstone capping the sequence can be traced as a cliff and mesa capping unit into southern Garza County.

The basal contact of this unit is at about 2580’ at Frehlier’s Bull Creek locality, and it can be traced fairly constantly northwest of Highway 669 at least a few kilometers.

Northeast of Highway 669, the sandstone becomes difficult to trace a few miles into southern Garza County, slightly lower conglomeritic sandstones with a basal contact at about 2550’, representing either the same sandstone or (more likely) a closely associated one, continues to form cliffs and mesas before dying out several kilometers southeast of Cowhead Mesa. Given their close stratigraphic association, these sandstones are mapped together as “Bull Creek beds.” They occur about the same stratigraphic distance above the Route 669 Roadcut sandstone as the Miller Ranch sandstone along Middle Creek, and are probably roughly stratigraphically equivalent, and are also use to arbitrarily bound the top of the middle unit.

The Lower Macy Ranch sandstone

The sandstone was identified and named by Frehlier (1987, pp. 112-113, fig. 2.7) as a high order sandstone outcropping about 30-35 meters (about 100-115 feet) below the Macy Ranch sandstone. This drab-colored sandstone unit is fairly easy to identify and map, as it caps a low line of cliffs and mesas in the drainage of the South Fork of the Double Mountain Fork of the Brazos River on Macy Ranch, with a basal contact a little above 2600’. The unit appears a couple kilometers east of Cowhead Mesa on the north side of the South Fork, and can be traced west across the South Fork, after which it turns south, wedging out a few kilometers south of Cowhead Mesa. Cowhead Mesa itself is one of the best places to observe the Lower Macy Ranch sandstone and its stratigraphic relationship to the Macy Ranch sandstone, as it forms a prominent cliff at the base of the mesa (Fig. 2.22).

The Kirkpatrick Ranch sandstone

Frehlier (1987, pp. 72, figs. 2.7, 2.28, 2.36) described a low order sandstone with associated sheetflood deposits at his “Middle Creek Draw” locality, just west of Highway 669 after it comes down off the Caprock Escarpment southwest of Post, not far from the Patricia Site (MOTT 3870). He was probably referring to a fairly persistent reddish-brown ledge-forming sandstone which outcrops below the Macy Ranch sandstone near Highway 669, where the basal contact is at about 2620'. This unit, which I refer to as the "Kirkpatrick Ranch sandstone", is extremely variable in thickness. It reaches a thickness of 10 meters (30 feet) or more immediately east if the highway on Little Red Mud, and can be traced west onto the Cycle Ranch, where it is a fairly persistent cap on low cliffs and mesas. In other places, it thins to a couple meters thick or less (Fig. 2.19a), in which case it tends to occur as a part of steeper slopes leading up to the Macy Ranch sandstone rather than forming an erosive cap of its own. Where I examined it, the Kirkpatrick Ranch sandstone is usually composed dominantly of sandstone and siltstone, with intrabasinal conglomerate forming only a minor component. The sandstone sometimes occurs as discontinuous lenses, and tends to weather into smooth-surfaced outcrops that look superficially aeolian. The sandstone is not drab-colored like most of the mappable sandstones in southern Garza County, and so usually harder to distinguish from a distance from the reddish overbank mudstones, especially when it is too thin to form an erosive cap.

As the unit traces further west into Macy Ranch and east to the Caprock Finger, it becomes an extremely thin band less than a couple meters thick, which can barely be discerned from the surrounding overbank mudstones on cliffsides below the Caprock Escarpment by its slight purplish hue. On Macy Ranch, the unit rises several meters (to about 2640'), and terminates in a complex of low order conglomeritic sandstones below the Macy Ranch sandstone, just a few kilometers east and a little higher stratigraphically from where the Lower Macy Ranch sandstone appears. On Little Red Mud, along the southwest edge of the Caprock Finger, the unit also seems to die out to the southeast along the Caprock Finger. North of the Caprock Finger, the sandstone appears intermittently as a fairly thick unit about the same distance below the Macy Ranch sandstone, although exposures are much poorer than near Highway 669. Some thick low order sandstones at Problematic Hill and to the west look very similar to the Kirkpatrick Ranch sandstone, and may be correlative.

Fig. 2.31. The UU Ranch sandstone just east of the Problematic Hill vertebrate locality (MOTT 3908), with a second sandstone probably representing the Macy Ranch sandstone occurring just above it.

The UU Ranch sandstone

This sandstone, which reaches at least 15 meters thick or so, caps a prominent cliff (Fig. 2.32) just east of the Problematic Hill vertebrate locality (MOTT 3921). It can be traced only for a few kilometers west of the cliff before being truncated by the Ogalalla Formation, and an equally short distance south, with a probable outlying cap lying not far from the K.W. Flats vertebrate locality (MOTT 3908). It is tempting to identify this massive drab-colored sandstone as the Macy Ranch sandstone, which is well-exposed to the south and west. However, the Macy Ranch sandstone is a relatively level unit with a basal contact that remains close to 2700' throughout the study area as far as it can be traced, and the base of the UU Ranch sandstone remains below 2640'. This sandstone is considered here to be an extremely localized unit lying immediately below the Macy Ranch sandstone. A sandstone locally resting slightly above it is interpreted as a fragment of the true Macy Ranch sandstone (Fig. 2.31). Frehlier's (1987, fig. 2.6) map of the Macy Ranch sandstone also does not seem to consider the UU Ranch sandstone to be part of it.

The Macy Ranch sandstone

The Macy Ranch sandstone is a massive amalgamated high order sandstone that is also the stratigraphically highest major sandstone unit in the Dockum Group of southern Garza County (Frehlier, 1987), and represents “unit 18” in Lehman et al.’s (1992) type section. The basal contact of the unit is close to 2700’ at Macy Ranch (Fig. 2.22), south of Macy Ranch toward Borden County, and east of Macy Ranch across Highway 669 onto the Caprock Finger. Further north in the direction of Post, the basal contact is generally somewhat lower, dipping as low as 2660’. The Macy Ranch sandstone was the high order sandstone that Frehlier (1986) devoted the most attention to, and the only unit that he traced (Frehlier, 1987, fig. 2.6). Most of the areas where Frehlier (1987) examined the Macy Ranch sandstone in detail lie on Macy Ranch itself, where the sandstone forms fairly massive drab-colored cliffs slightly lower than the Caprock Escarpment proper surrounding the South Fork of the Double Mountain Fork of the Brazos River. Here, the base of the Ogallala Sandstone rises to almost 2800’, so it is the only area where the full thickness of the Macy Ranch sandstone, and overlying overbank deposits of the uppermost Cooper Canyon Formation, are exposed (see Frehlier, 1987, fig. 2.10). To the east and northeast, the base of the Ogallala Formation cuts down section to about 2700’, and partially (Fig. 2.19a) or even completely truncates the Macy Ranch sandstone. To the south, the basal contact of the Ogallala Formation remains high, but the Cretaceous strata wedge between it and the Cooper Canyon Formation, and rests on or partially truncates the Macy Ranch sandstone instead. Frehlier’s (1987, fig. 2.6) map showing the extent of the Macy Ranch sandstone stops at Highway 669 southwest of Post, but scraps of it continue further north, including in a road cut of Highway 380 due west of Post, shortly before the highway climbs onto the Ogallala Formation.

Frehlier’s (1987) maximum thickness for the Macy Ranch sandstone of 20 meters is for Cowhead Mesa and other areas on Macy Ranch, and his average of 13 meters for the unit is for elsewhere where the unit is partially truncated. Drake’s section 6 (1892, p. 238, pl. V), probably measured at the tip of Caprock Finger, is capped by a three foot thick layer of “blue clay containing a three inch layer of ferruginous conglomerate” that is probably the Macy Ranch sandstone (see the South Woolam Ranch section in Appendix 1). In contrast, Frehlier’s (1987, fig. 2.18, section B) Miller Ranch Mesa section, measured in the same area, errs in showing 17 meters of overbank deposits above a 12 m thick Macy Ranch sandstone. Lehman et al.’s (1992) type section repeats the error; their map indicates that the top of their type section for the Cooper Canyon Formation was measured there (“location C” of Lehman et al., 1992, fig. 1). Lehman and Chatterjee’s (2005, fig. 5B) section through a channel sandstone is the Macy Ranch sandstone from Frehlier’s (1987, 2.13 Section B) section from his Macy Finger locality.

In addition to being an important stratigraphic marker, the Macy Ranch sandstone is an extremely important unit because of several important vertebrate localities within it, especially the Patricia Site (MOTT 3870) and associated localities. Most of the vertebrate producing layers at the Patricia Site itself lie in a sequence representing an abandoned channel fill (oxbow lake) sequence (Lehman and Chatterjee, 2005, fig. 6A). Phytosaur material in particular is fantastically abundant in the Macy Ranch sandstone in this area (Cunningham et al., 2002; Lehman and Chatterjee, 2005), and at least fragmentary vertebrate fossils are otherwise unknown from the unit elsewhere in southern Garza County, as well as fossils logs, carbonized plant fossils, coprolites (Frehlier, 1987), orange-sized limonized concretions, and bizarre “bowling ball” concretions similar to those described from the Bauchier Ranch sandstone.

The uppermost beds

Cooper Canyon Formation strata overlying the Macy Ranch sandstone and forming the uppermost Upper Triassic strata in southern Garza County, are exposed only on Macy Ranch, and some distance to the south and east. On Macy Ranch itself, the post-Macy Ranch sandstone section is about 20 meters (about 65’) thick (see section B of Frehlier, 1987, fig. 2.10), and just west of Highway 669, several meters remain in places. Where examined, this section appears to be composed primarily of reddish mudstone and muddy sandstone, interbedded with sheet sands and low order conglomeritic sandstones, as with overbank deposits observed lower in the Cooper Canyon Formation. At least one of the low order conglomerates (probably the one shown at about 45 m in section B of Frehlier, 1987, fig. 2.10) is probably mappable across Macy Ranch. Exposures of the post-Macy Ranch sandstone section have not been explored in detail at Macy Ranch, primarily because exposures are mostly fairly steep slopes high on the cliffsides which are often difficult to reach. However, these strata represent the highest strata in the Dockum Group in southern Garza County. In fact, as the top of the Cooper Canyon Formation is truncated to the north (Lehman, 1994b) and south (Lucas et al., 1994), they may represent the highest Upper Triassic strata in West Texas.

The Dockum Group in the Subsurface of Southern Garza County

Following the previous work of McGowan et al. (1979), gamma-ray well logs were used to attempt to track lithostratigraphic components of the Dockum Group (particularly the basal contact), into the subsurface in southern Garza County. This proved somewhat problematic. Mudstones generally show a higher gamma-ray response compared to sandstones due to generally higher concentrations of uranium, thorium, and potassium, so in strata dominated by clastic sedimentary rocks, high gamma-ray responses are usually taken to indicate mudstones, and lower ones sandstones and conglomerates. However, micaceous and feldspathic sandstones, as well as those composed largely of clay clasts, may also produce a high gamma ray response due to the presence of these same elements (e.g. Asquith and Gibson, 1982; Miall, 1996, pp. 273-276).

Although both the sandstones and conglomerates making up the Santa Rosa Sandstone are highly siliceous and should give a relatively low gamma-ray response, the Trujillo Sandstone, Boren Ranch sandstone/beds, and sandstones within the Cooper Canyon Formation are, as already discussed, arkosic, micaceous, and contain clasts of reworked sedimentary rocks, all of which might be expected to give the coarse-grained clastics an unusually high gamma-ray response. McGowan et al. (1979), comparing well cuttings with gamma ray well logs (though they did not specify from which strata within the Dockum Group), noted that the mudstones do tend to emit a stronger gamma ray response than sandstones and siltstones, but that the siltstones and sandstones are difficult to distinguish from each other. This provides an additional problem as even overbank deposits in the Cooper Canyon Formation of southern Garza County tend to be extremely silty and sandy.

The basal contact of the Santa Rosa Sandstone and the thickness of the Dockum Group in southern Garza County

McGowan et al. (1979) used a well log from Upton County in the southern Texas Panhandle to illustrate their placement of the basal contact of the Dockum Group with underlying Permian strata (Fig. 2.32a). The sequence they illustrate starts with a low and very jagged gamma-ray response which they interpreted as evaporates, followed by a somewhat higher and more uniform gamma ray response they interpreted as siltstone at the top of the Permian. What they interpreted as basal Dockum Group sediments give a somewhat jagged gamma ray response, followed by a highly positive gamma ray response they interpreted as a fining upward sequence of sand grading into mudstone, followed by a strong negative gamma ray response they interpreted as a thick sequence of sandstones.

As already discussed, the Upper Permian-Upper Triassic contact is marked by the TR-3 unconformity, which is well exposed in southeastern Garza County, and several logs come from wells close enough to these exposures of this contact that it can be identified. A sequence very similar to that shown by McGowan et al. (1979) can be identified in well logs from near exposures of this contact (Fig. 2.32b-d), and this same sequence can be identified in well logs throughout southern Garza County. The sequence shows a strongly negative and jagged gamma-ray response (evaporites?) becoming increasingly positive over a thickness of about 200’ (fining upward sequence of sandstone or siltstone grading into mudstones), with a strongly negative-gamma ray response near the top (sandstone). However, this sequence is not as thick as the one illustrated by McGowan et al. (1979), so it may therefore only represent a similar

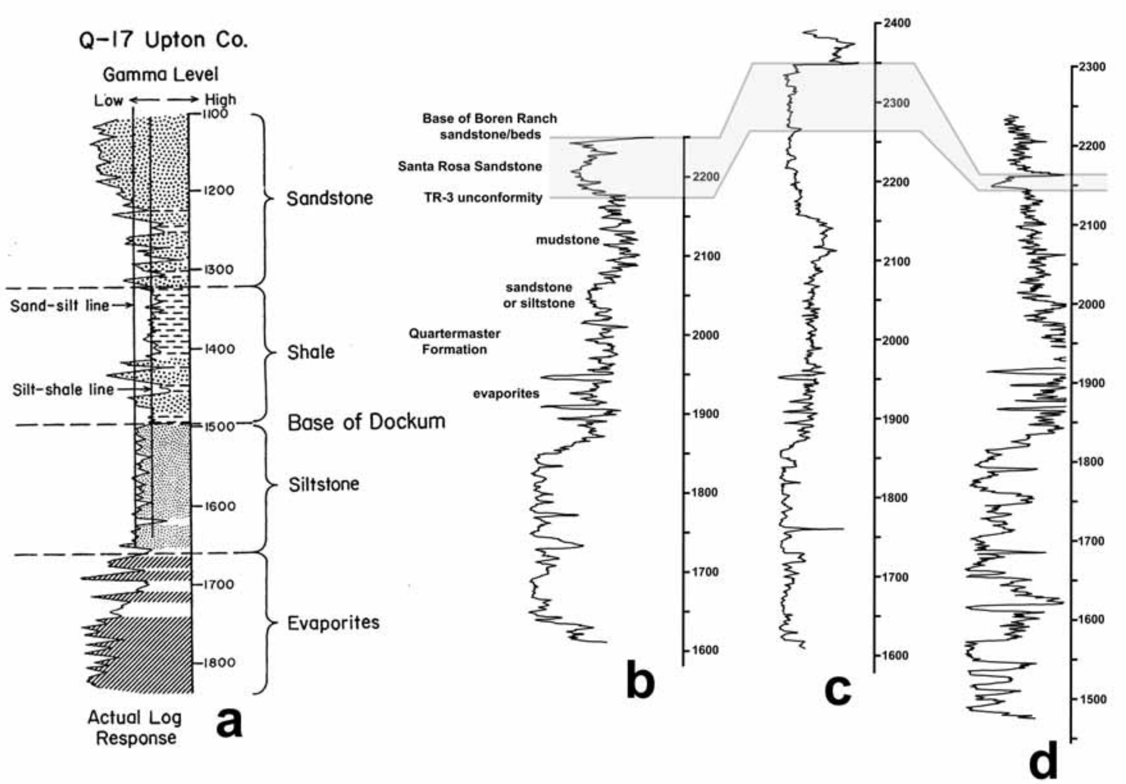


Fig. 2.32. The base of the Dockum Group in gamma-ray well logs: *a,* McGowan et al.'s (1979, fig. 32) identification of the base of the Dockum Group; *b-d* gamma-ray well logs in southern Garza County showing interpreted TR-3 unconformity, Santa Rosa Sandstone, and base of Boren Ranch Sandstone/beds; *b,* America Liberty Oil Company No. 7 I.N. McCrary; c, Bush Exploration No. A-2 Beggs 45; *d,* Humble Oil and Refining Company No. 1 Irene Rodgers.

sequence. Moreover, even if the sequence is the same, my placement of the TR-3 unconformity is several hundred feet higher than indicated by McGowan et al. (1979).

American Liberty Oil Company No. 7 I.N. McCrary (Fig. 2.32b) is from very near the OS Ranch Gully locality (Figs. 1.5-1.6) and rests on the Santa Rosa sandstone itself. The base of the Santa Rosa Sandstone descends in a westerly direction along the North Fork of the Double Mountain Fork of the Brazos, and dives into the subsurface at about 2210' a short distance to the northeast, and the TR-3 unconformity is interpreted in the well log as falling at the base of the strong negative gamma-ray response at about 2170', and the negative response itself is interpreted to represent the Santa Rosa

Sandstone. The strong positive gamma-ray response below it is interpreted to represent the uppermost Permian Quartermaster Formation, which in this area is composed of mudstones interbedded with very thin siltstones and sandstones; I have not observed any significant evaporate beds in exposures of the uppermost Quartermaster Formation in southern Garza County, as expected from the well logs, which suggest that they begin about 200' below the TR-3 unconformity (Fig. 2.32b-d).

Around the drainage of the North Fork of the Double Mountain Fork of the Brazos River, the TR-3 unconformity/base of the Santa Rosa Sandstone is placed at about 2270' for well Bush Exploration No. A-2 Beggs 45 (Fig. 2.32c), which is located just south of Highway 380 (Fig. 1.6), as exposures of the contact along the North Fork not far south of this well show it is at this elevation. However, this places the base of the Santa Rosa *within* the strong negative gamma-ray sequence, which is particularly thick (about 200' thick) in this well, for reasons that are not clear. If the placement of the TR-3 unconformity is correct, than the Santa Rosa Sandstone should be about 100' thick, which is only about half of the strongly negative gamma-ray response but far thicker than most places it was observed in outcrop. However, in a gully north of the North Fork not far from the well, the Santa Rosa Sandstone does indeed reach about 30 meters (100') feet in thickness, so it may be that the TR-3 unconformity does indeed fall within the negative response, at least in this area.

Further south, logs are available from wells near Lake Alan Henry, which are located close to where the basal contact of the Dockum Group is submerged. This requires that the contact falls at least below 2210' (low water level for the lake), and the well log for Humble Oil and Refining Company No. 1 Irene Rodgers, located near Cedar Hill (Figs. 1.5 and 1.6) shows the recognizable gamma ray sequence identified in the OS Ranch well logs (Fig. 2.32d) shortly below that elevation. I placed the contact here (and most places) at the base of the strong negative response as I did with the well near the OS Ranch Gully locality, and for No. 1 Irene Rodgers this is at about 2150'. The negative gamma ray response is very thin here, possibly indicating the Santa Rosa Sandstone is

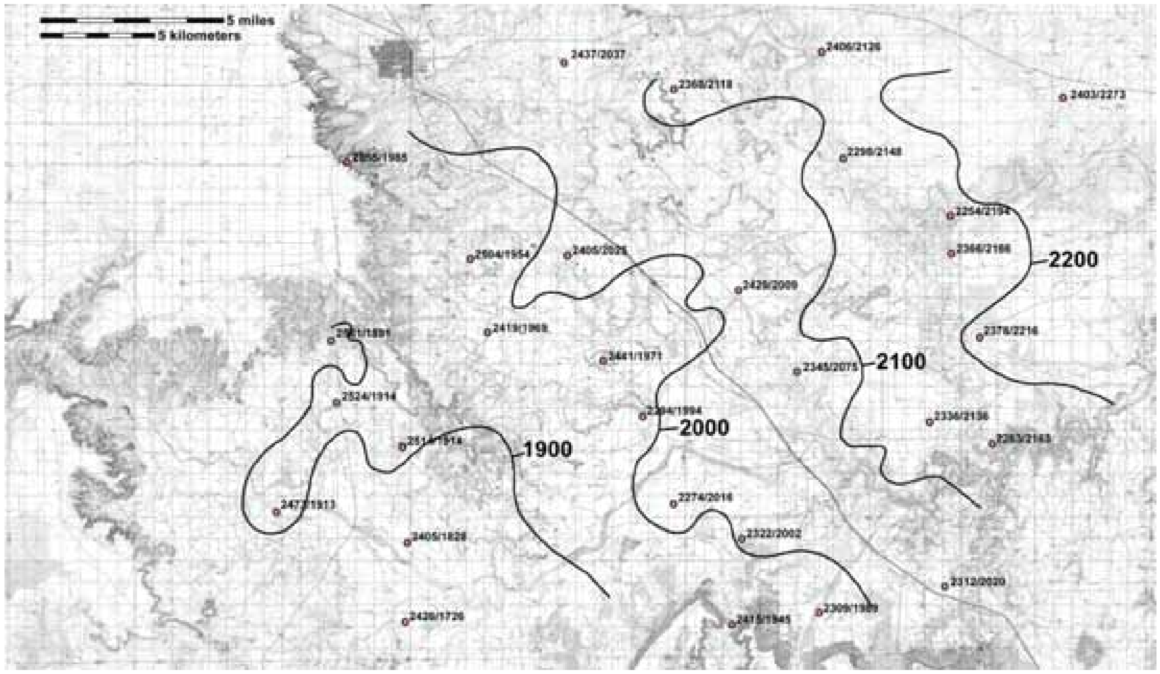


Fig. 2.33. Structure map for the Dockum Group in southern Garza County showing the elevation of the TR-3 unconformity in feet above sea level.

locally thinning; most gamma rays show this strong negative response being about 40’-60’ thick, while the No. 1 Irene Rodgers well log gives it at about 20’.

This basal contact of the Santa Rosa Sandstone can be traced in well logs across southern Garza County, and shows an unmistakable southwesterly dip, diving below 1900’ as can be seen in both a rough structure map (Fig. 2.33) and cross sections across southern Garza County (Figs. 2.4d-h). That the base of the Dockum Group dips centripetally into the Midland Basin under the Llano Estacado is not a new observation (e.g. McGowan et al., 1979; Lehman, 1994b), although it is useful to reemphasize this fact for reasons that will become clear when I later attempt correlation of the Dockum Group from southern Garza County south into Borden County and Howard County.

It is also important to consider this southwesterly dip when discussing the total thickness of the Dockum Group (Fig. 2.34). Consider the case of southern Garza County, in which base of the Dockum Group dips in a southwesterly westerly direction, and the surface exposures of the Dockum Group cut upsection to the west (see cross sections A-A’ and B-B’ of Fig. 2.4d-f). As most of the strata *above* the lower unit of the Cooper

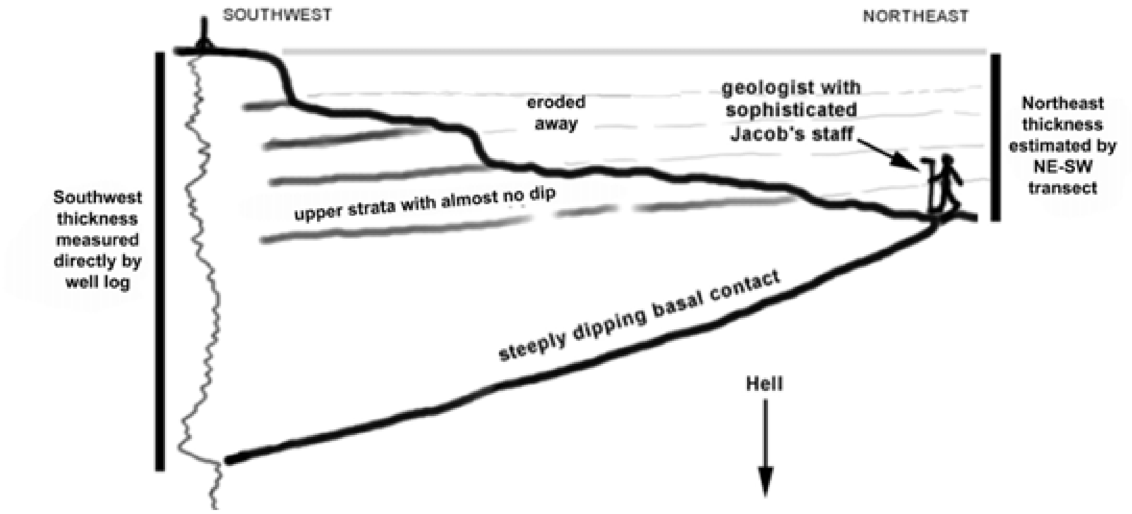


Fig. 2.34. Measuring the thickness of southwesterly dipping strata with easterly facing exposures, in which the basal contact dips more steeply than strata higher in the section. The Jacob's staff bearing geologist measuring the section by overland traverse from northeast to southwest will observe relatively shallow dip across most of the traverse, and consequently measure a thickness close to the change in elevation from where he/she began measurement and the top of the section. However, due to the steeper dip of the base of the unit, a well log drilled vertically to the base of the section in the southwest part of the outcrop area will give a much greater total thickness.

Canyon Formation do not dip strongly, and in any case not to the southwest, the thickness of a section estimated by an overland traverse will be much less then thickness measured directly from a well log in the western part of the study area. It is important to keep in mind that the former thickness estimated thickness is for the northeastern area, where most of the section has been eroded away, whereas the latter thickness is for the southeastern area (Fig. 2.34), but that both measurements are valid.

Lehman et al.'s (1992) thickness for the type section of the Cooper Canyon Formation of about 160 m (about 520') was measured in an overland traverse. If unit 19 and most of unit 18 is removed from their type section to account for its truncation at the tip of the Caprock Finger, and their traverse is extended to where the base of the Santa Rosa Sandstone is exposed below Montford Dam to include the lower part of the Dockum Group, this still gives a total thickness for the Dockum Group of about 160 m.

However, the TR-3 unconformity can be placed in the well log for Estoril Producing Corporation No. 1 Macy-Lott (the second to last well log in the C-C’ cross section in Fig. 2.4g), located much further west, at about 1900’ elevation, which, if the upper contact of the Dockum Group at over 2700’ a short distance to the west is taken into account, gives a total thickness of at least 250 m (830’), and the total subsurface thickness of the Dockum Group at the southwestern corner of Garza County may be in excess of 300 meters (almost 1,000’). Thus it is important to specify, when giving the thickness for a unit, if it was measured in an overland traverse, or vertically using well logs or an estimate based on the dip of the base of the unit, as the latter will tend to be thicker (Fig. 2.34).

The basal contact of the Boren Ranch Sandstone/beds and sandstones within the Cooper Canyon Formation

The strong negative gamma-ray response interpreted as representing the Santa Rosa Sandstone is terminated by a strong positive gamma-ray response, which is usually quite abrupt, and this is interpreted as representing the unconformable base of the Boren Ranch sandstone/beds (Fig. 2.32). Although the Santa Rosa sandstone, with its sand and gravel-sized clasts being siliceous, shows the expected negative gamma-ray response for a sandstone, the Boren Ranch Sandstone/beds (and overlying Cooper Canyon Formation sandstones) are arkosic and micaceous, with gravel-sized clasts being predominantly reworked overbank deposits. For reasons already discussed, these may give an unusually strong positive gamma-ray response, and create the impression to one unfamiliar with the lithology of the deposits that the Santa Rosa Sandstone is capped directly by mudstone.

Identifying sandstones higher in the Cooper Canyon Formation using gamma-ray well logs is extremely difficult. This base of the Dalby Ranch sandstone may be indicated by a negative gamma-ray response at about 2430’ in the well log for R.S. Anderson No. 2 Shelly Stoker (Fig. 2.35a), and at about 2400’ in the well log Anderson Prichard Oil Corporation No. F-1 Connell Estates (Fig. 2.35b), both of which sit on outcrops of the Dalby Ranch sandstone with the basal contact at about those elevations. The well log for Shell Oil Company and Mobil Oil Company No. B-2 Kirkpatrick (Fig.

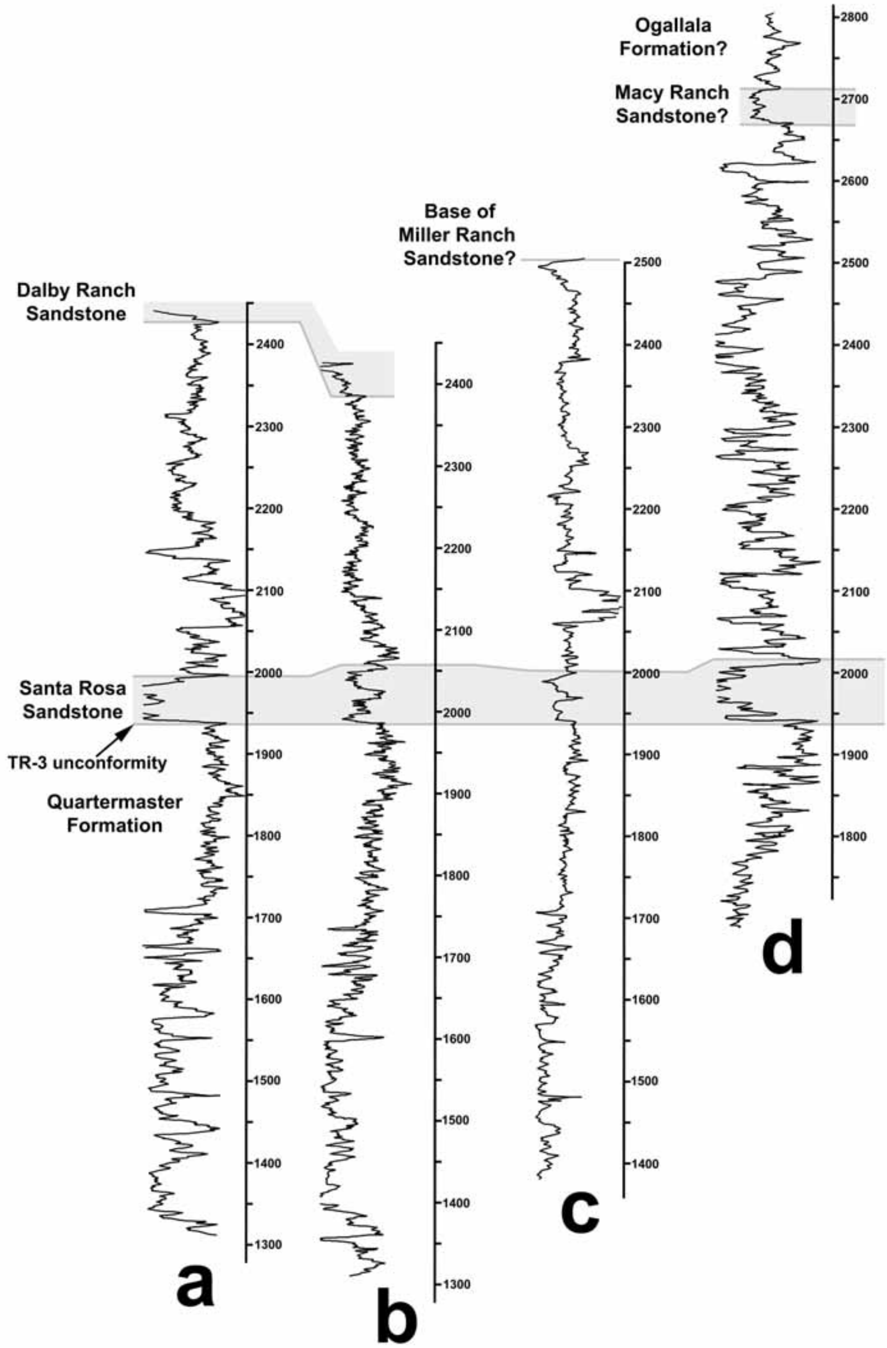


Fig. 2.35. Gamma-ray well logs in southern Garza County showing possible basal contacts of sandstones in the Cooper Canyon Formation; *a,* R.S. Anderson No. 2 Shelly Stoker; *b,* Anderson-Prichard Oil Corporation No. F-1 Connell Estates; *c,* Shell Oil Company and Mobil Oil Company No. B-2 Kirkpatrick; *d,* George R. Brown No. 56 Post Estate.

2.35c), which probably rests above the Miller Ranch sandstone, shows a sharp negative deflection at about 2500’ which may represent the base of that unit. The well log for George R. Brown No. 56 Post Estate (Fig. 2.35d), the only well log I examined which shows the entire thickness of the Dockum Group in southern Garza County, shows a very strong negative deflection at 2685’ probably representing the base of the Macy Ranch sandstone. However, most of the Cooper Canyon Formation shows a highly variable gamma-ray response. This may reflect variations in lithology, with lower gamma ray responses reflecting higher silt and sand content in overbank mudstones, or low order sandstones, but this is not clear. In fact, much of the Cooper Canyon Formation shows a gamma ray response almost as strongly negative, or more so, than the Santa Rosa Sandstone. It seems likely that using gamma-ray well logs to correlate units in the Boren Ranch sandstone/beds and Cooper Canyon Formation may be extremely difficult, if not impossible.

If the base of the Dockum Group is dipping southwest, but the upper part of the Dockum Group is not, then it stands to reason that *the lower part of the Dockum Group is thickening faster to the south and west than the upper part of the Dockum Group*. This is supported by looking at well logs in which the stratigraphic distance between the base of the Dalby Ranch and the base of the Santa Rosa Sandstone can be determined (Fig. 2.36). The well log for Hill and Meeker No. 1 Connell (Fig. 2.36a), located just south of Highway 38, has the TR-3 unconformity placed at about 2090’. This well is located stratigraphically just below the Dalby Ranch sandstone, which has an exposed basal contact there at about 2450’, giving a total thickness below the Dalby Ranch sandstone (including the lower unit of the Cooper Canyon Formation, Boren Ranch beds, and Santa Rosa Sandstone) of about 110 m (360’). The well logs for Anderson-Prichard Oil Corporation No. F-1 Connell Estates (Fig. 2.36b) and Clark and Cowden Drilling Company No. 1 Hattie Connell (Fig. 2.36c) are located several miles south and rest almost on the base of the Dalby Ranch sandstone, giving a thickness for the Dockum Group below the contact of about 400’. The well log for R.S. Anderson No. 2 Shelly

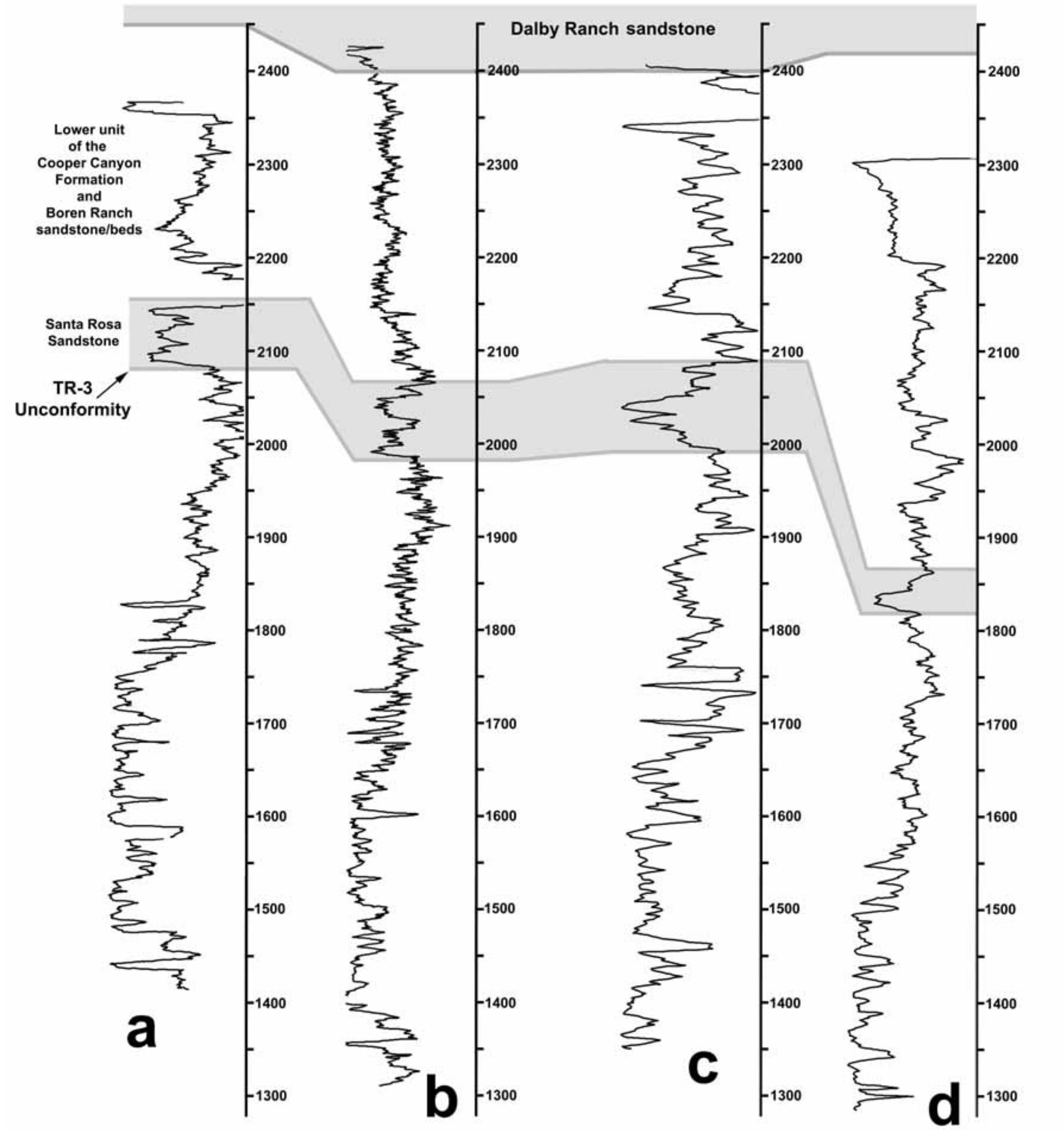


Fig. 2.36. Thickening of the Dockum Group beneath the Dalby Ranch Sandstone north to south (approximately left to right) in southern Garza County; *a,* Hill and Meeker No. 1 Connell; *b,* Anderson-Prichard Oil Corporation No. F-1 Connell Estates; *c,* Clark and Cowden Drilling Company No. 1 Hattie Connell; *d,* T.M. Evans Production Company No. 1 Slaughter.

Stoker (Fig. 2.36a), located on a butte capped by the Dalby Ranch sandstone in the Cooper Creek drainage further south, gives a thickness below the Dalby Ranch sandstone of 460’, and the well log for T.M. Evans Production Company No. 1 Slaughter (Fig. 2.36d) from Big Red Mud shows the TR-3 unconformity about 500’ below the base of the Dalby Ranch sandstone in that area. As will be discussed shortly, this southerly thickening of the Dockum Group below the middle unit of the Cooper Canyon Formation, which is probably taking place almost entirely in the lower unit, has special significance to regional correlation within the Dockum Group.

Lithostratigraphic Correlation of the Dockum Group

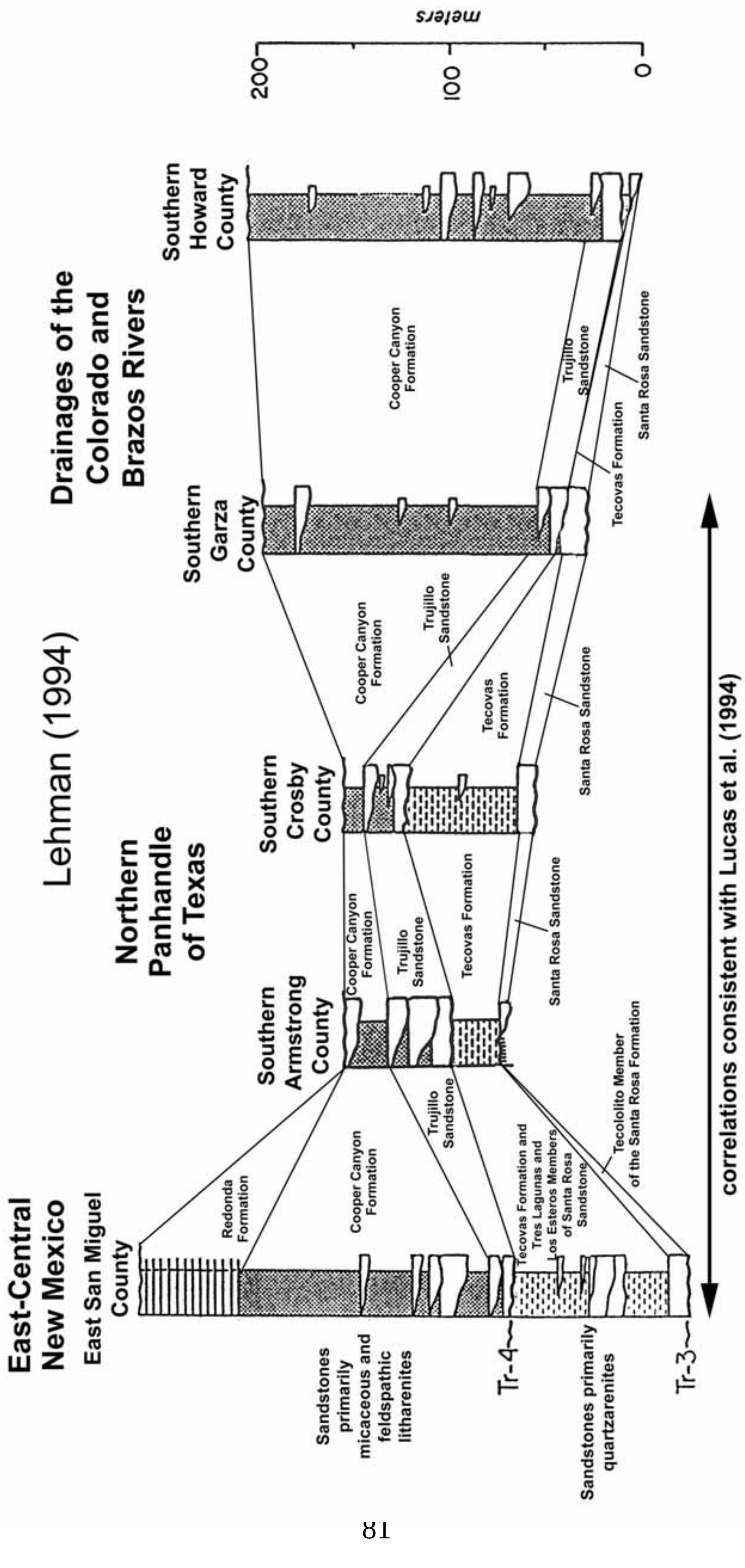
Lithostratigraphic Correlation of the Dockum Group Between East-Central New Mexico and the Texas Panhandle

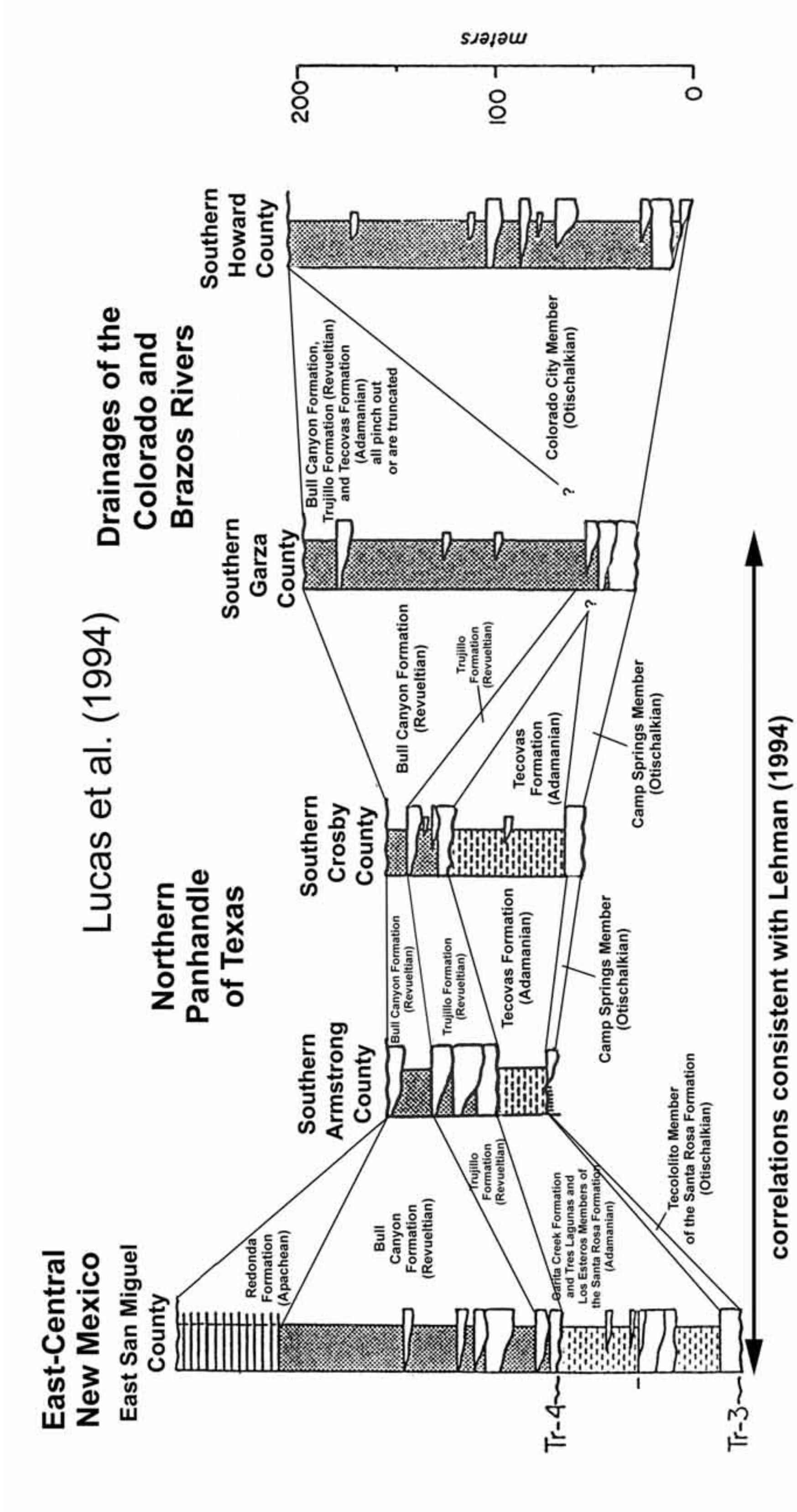
Reviews of the history of Dockum lithostratigraphic nomenclature and correlation in eastern New Mexico and western Texas have been provided previously by Green (1954), Lucas et al. (1985), and Lehman (1994a), and will not be repeated in full here. However, the debate between Lehman (1994a) and Lucas et al. (1994) is of particular importance to the current study. These authors generally agree on the correlations (although not as much on the nomenclature) between East-Central New Mexico and the Texas Panhandle; that is, between Dockum strata exposed around the northern rim of the Llano Estacado in the drainages of the Red River, Canadian River, and the northern Pecos River (Figs. 1.2, 2.37-2.38). As will be discussed later, how these northern Dockum Group strata correlate with strata in southeastern New Mexico and around the southeastern rim of the Llano Estacado, in the drainages of the Brazos River, Colorado River, and the southern Pecos River, is much more contentious (Fig. 2.37-2.38).

The base of the Dockum Group in eastern New Mexico is a silica-rich

Next Pages: Fig. 2.37. Lehman’s (1994) correlations of units within the Dockum Group. Modified from Lehman and Chatterjee (2005, fig. 3) and Lehman et al. (unpublished). Location of sections given in Fig. 1.2.

Fig. 2.38. Lucas et al.’s (1994) correlations of units within the Dockum Group. Modified from Lehman and Chatterjee (2005, fig. 3) and Lehman et al. (unpublished). Location of sections given in Fig. 1.2.


Lehman (1994)
East-Central New Mexico
East San Miguel County
Northern Panhandle of Texas
Southern Armstrong County
Southern Crosby County
Drainages of the Colorado and Brazos Rivers
Southern Garza County
Southern Howard County
Redonda Formation
Cooper Canyon Formation
Trujillo Sandstone
Tecovas Formation
Santa Rosa Sandstone
Tecovas Formation and Tres Lagunas and Los Esteros Members of Santa Rosa Sandstone
Tecolotito Member of the Santa Rosa Formation
Sandstones primarily micaceous and feldspathic litharenites
Sandstones primarily quartzarenites
Tr-4
Tr-3
correlations consistent with Lucas et al. (1994)
200
100
0
meters


Lucas et al. (1994)
East-Central New Mexico
East San Miguel County
Northern Panhandle of Texas
Southern Armstrong County
Southern Crosby County
Drainages of the Colorado and Brazos Rivers
Southern Garza County
Southern Howard County
Redonda Formation (Apachean)
Bull Canyon Formation (Revueltian)
Trujillo Formation (Revueltian)
Garita Creek Formation and Tres Lagunas and Los Esteros Members of the Santa Rosa Formation (Adamanian)
Tecolotito Member of the Santa Rosa Formation (Otischalkian)
Bull Canyon Formation (Revueltian)
Trujillo Formation (Revueltian)
Tecovas Formation (Adamanian)
Camp Springs Member (Otischalkian)
Bull Canyon Formation (Revueltian)
Trujillo Formation (Revueltian)
Tecovas Formation (Adamanian)
Camp Springs Member (Otischalkian)
Bull Canyon Formation, Trujillo Formation (Revueltian) and Tecovas Formation (Adamanian) all pinch out or are truncated
Colorado City Member (Otischalkian)
?
Tr-4
Tr-3
correlations consistent with Lehman (1994)
200
100
0
meters

conglomeritic sandstone named the Santa Rosa Sandstone (Rich, 1921; Darton, 1922), a name Lucas et al. (1985) suggested changing to Santa Rosa Formation due to the presence of interbedded conglomerate and mudstone. The Santa Rosa Sandstone in New Mexico was divided into four members by Gorman and Robeck (1946). Their "lower sandstone member" is now named the Anton Chico Formation (Lucas and Hunt, 1987). It is now recognized to be Middle Triassic in age, and no longer considered part of the Santa Rosa Sandstone/Formation (Lucas et al., 1985). The remaining members of Gorman and Robeck (1946) were named the Tecololito Member (formerly the "middle sandstone member"), Los Esteros Member ("mudstone member"), and Tres Lagunas Member ("upper sandstone member") by Lucas and Hunt (1987). In West Texas, a siliceous conglomeritic sandstone is also present at the base of the Dockum Group as was recognized originally by Cummins (1890). Lehman (1994a, b) and Lehman and Chatterjee (2005) extend the term Santa Rosa Sandstone from New Mexico into Texas, but Lucas and his colleagues (Lucas and Anderson, 1992, 1993a; Lucas et al., 1994) use the term "Camp Springs Member", the type area of which is in Scurry County in the Brazos River valley, further south (Beede and Christner, 1926), for the basal silica-rich conglomeritic sandstone in Texas, which they allege has lithologic differences from the Santa Rosa Sandstone in New Mexico. Despite these nomenclatural disagreements, these authors agree that the "Camp Springs Member" in the northern Texas Panhandle and the Tecololito Member of the Santa Rosa Sandstone/Formation in East-Central New Mexico are correlative units (Figs. 2.37-2.38; Lehman, 1994a; Lucas et al., 1994).

Above the Santa Rosa Sandstone is a mudstone-dominated unit named the Tecovas Formation in the northern Texas Panhandle by Gould (1906, 1907). Lucas and Hunt (1989) provided the name Garita Creek Formation for the equivalent unit in New Mexico previously referred to as the "lower shale member" (e.g. Kelley, 1972; Granata, 1981; McGowan et al., 1983; Broadhead, 1984; Lucas et al., 1985). Lucas et al. (1994, p. 113), and cited "lithologic and thickness changes" to distinguish it from the Tecovas Formation, which Lehman (1994a) found unconvincing. Again, regardless of the nomenclatural dispute, these authors agree that the Los Esteros and Tres Lagunas

Members of the Santa Rosa Sandstone in New Mexico correlate with the lower Tecovas Formation in Texas, and that the Garita Creek Formation correlates with the upper part of the Tecovas Formation in Texas (Figs. 2.37-2.38; Lucas et al., 1985, 1994; Lehman, 1994a).

Gould (1907) named the Trujillo Formation in the northern Texas Panhandle for a series of conglomeritic sandstones interbedded with mudstones about the Tecovas Formation. It has since become customary for the lowermost sandstone, which Gould (1907) referred to as the "lower member of the Trujillo Formation," to be referred to exclusively as the Trujillo Formation (Adams, 1929; Green, 1954; Spielgel, 1972; Lucas et al., 1994), Trujillo Member (Chatterjee, 1986a), or Trujillo Sandstone (Lehman, 1994a), with the upper, mudstone-dominated part of the section receiving a different name. The extension of the term "Trujillo" into east-central New Mexico is generally accepted (Figs. 2.37-2.38), and is one of the few areas where both correlation and nomenclature are agreed upon by most workers (e.g. Spiegal, 1972; Finch et al., 1976; Finch and Wright, 1983; Hunt and Lucas, 1989; Lucas et al., 1994; Lehman, 1994a).

The upper, mudstone-dominated part of Gould's (1906, 1907) Trujillo Formation has had a more contentious taxonomic history that must be reviewed in some detail. As previously discussed, Chatterjee (1986a) identified a massive sandstone located in southeastern Garza County (the "Boren Ranch Sandstone" of Frehlier, 1987), as the Trujillo Sandstone, and provided the name "Cooper Member of the Dockum Formation" for the mudstone dominated strata above it. Lehman et al. (1992) emended both Chatterjee's type section and his name for the unit, re-naming it the Cooper Canyon Formation (Fig. 2.7). However, shortly after Chatterjee's (1986a) naming of the Cooper Member but before Lehman et al.'s (1992) modifications, Lucas and Hunt (1989) gave the name Bull Canyon Formation to the upper mudstone-dominated unit above the Trujillo in east-central New Mexico. This is perhaps a puzzling move, given that the equivalence of this unit with Chatterjee's (1986a) Cooper Member was clearly accepted by Lucas et al. (1985), Hunt and Lucas (1990, fig. 4), and Lucas (1993b).

Lehman et al. (1992) claimed, as Lucas et al. (1985), Hunt and Lucas (1990), and Lucas and Anderson (1992) had previously indicated, that the Cooper Canyon Formation was correlative with the Bull Canyon Formation of New Mexico, and suggested the latter term was redundant be should be abandoned. Lucas and Anderson (1993a, p. 60) agreed that a single name should encompass the same strata in both states, but countered that the term Bull Canyon Formation had priority over Cooper Canyon Formation as the Cooper Member had been an “ill-defined and improperly used name.” Lucas and Anderson (1994, fig. 1) emphasized the use of the name Bull Canyon Formation in West Texas. This debate came to a head with the exchange between Lehman (1994a) and Lucas et al. (1994), in which the relative validity of the terms Cooper Canyon Formation and Bull Canyon Formation were debated at length. Carpenter (1997) sided with Lehman et al. (1994) regarding the priority of the name “Cooper Canyon Formation.” It is important to emphasize that these arguments are strictly nomenclatural and based on interpretive readings of letter and spirit of the North American Stratigraphic Code (NACSN, 1983). Lehman (1994a) and Lucas et al. (1994) always considered the Bull Canyon Formation and Cooper Canyon Formation to represent *equivalent stratigraphic units* (Figs. 2.37-2.38), a conclusion that will be questioned below.

Capping the Bull Canyon Formation and representing the uppermost strata of the Dockum Group in East-Central New Mexico is the Redonda Formation (Dobrovolny et al., 1946; Lucas et al., 1985; Lucas and Hunt, 1989). This unit is a thick sequence of interbedded mudstone, siltstone, sandstone, and limestone representing lacustrine deposition in a large lake system restricted to eastern New Mexico (e.g. Hester and Lucas, 2001; Lehman and Chatterjee, 2005).

Lithostratigraphic Correlation of the Dockum Group Between the Texas Panhandle and Southern Garza County

The Dockum Group of southern Crosby County is the southernmost region where lithostratigraphic correlation within the Dockum is generally agreed upon by Lehman (1994a, b) and Lucas et al. (1994), and will be used as an “anchor” for correlation further

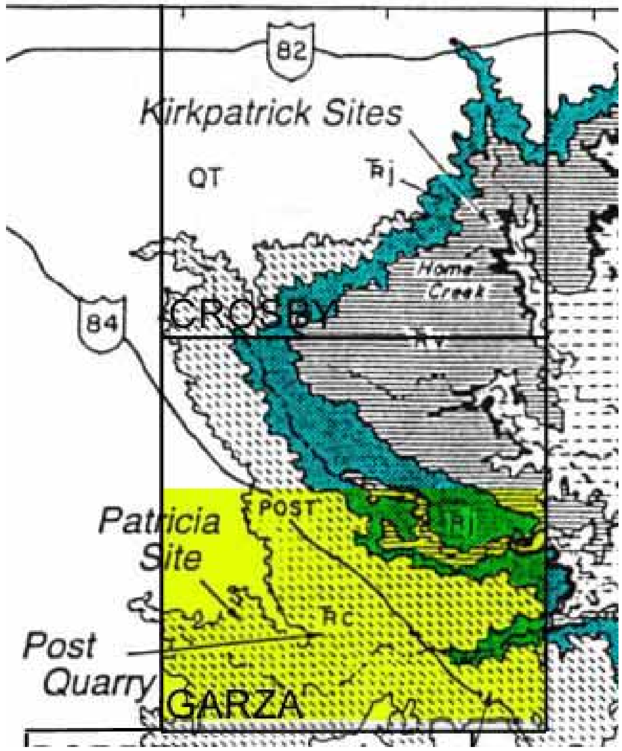


Fig. 2.39. Lehman's (1994a) mapping of the Trujillo Sandstone (blue) from southern Crosby County into the study area in southern Garza County (yellow). Modified from Lehman (1994a, fig. 4)

south. Lucas et al. (1994, sections 7 and 8 of fig. 3) and Lehman (1994a, fig. 4) both identify the mudstone-dominated strata above White River Reservoir, including those containing the Kalgary and Home Creek vertebrate localities (also see Murry, 1989 and Heckert, 2004), as lying within the Tecovas Formation/Member, and the sandstone capping Cedar Hill and Negro Hill to the west as being the Trujillo Sandstone/Member. As the Trujillo Sandstone is a fairly prominent sandstone unit and represents the stratigraphic "middle" of the Dockum Group, as well as an important eustatic (Lucas et al., 1994) or tectonic (Lehman and Chatterjee, 2005) transition, it makes a useful marker unit to attempt to trace south.

The geologic map (Figs. 1.3, 2.39) presented by Lehman (1994a, fig. 4) and Lehman and Chatterjee (2005, fig. 4) shows the Trujillo Sandstone extending into southern Garza County around the edge of the split drainages for Sand Creek and the North Fork of the Double Mountain Fork of the Brazos River due east Post, and continuing to border the North Fork drainage eastward all the way into Kent County. Here, it trends southwest more or less parallel to Highway 84, except for a tendril extending westward again up the South Fork of the Double Mountain Fork drainage to contact Highway 84, a stretch occupied by Lake Alan Henry. The implication of this mapping is that the mudstones exposed within the Sand Creek and North Fork drainages, mapped as the Tecovas Formation, all *underlie* a single sandstone-dominated unit that can be traced along the walls of these drainages to Kent County, and that this same mudstone unit therefore lies stratigraphically *below* the sandstone occupying the South Fork of the Double Mountain Fork drainage.

However, more detailed mapping in southern Garza County (Figs. 2.4c) indicates that this is not the case. The Trujillo Sandstone as mapped by Lehman (1994a, fig. 4) and Lehman and Chatterjee (2005, fig. 4) actually consists of two lithologically similar (Frehlier, 1987) but stratigraphically distinct sandstone units separated by about 30 meters (100 feet) of mudstone with minor interbedded sandstone and conglomerate, named here the lower unit of the Cooper Canyon Formation (e.g. Fig. 2.4c; cross section A-A' in Fig. 2.4e). The upper sandstone is the cliff former along the split Sand Creek and North Fork drainages due east of Post and called the Dalby Ranch sandstone, and the lower sandstone forming the cliffs along the North Fork drainage further east, and in the South Fork of the Double Mountain Fork drainage occupied by Lake Alan Henry and contacting Highway 84, is the Boren Ranch sandstone. Lehman et al.'s (1992) type section for the Cooper Canyon Formation in fact recognized these units as stratigraphically distinct. The Boren Ranch sandstone outcropping along Lake Alan Henry was identified as the Trujillo Sandstone, and the Dalby Ranch sandstone as "unit 11" *within* the Cooper Canyon Formation. Lehman et al. (1992) noted the latter was a fairly prominent cliff-forming sandstone that crosses Highway 84 several miles northwest of Lake Alan Henry (Fig. 2.27a). The mudstone dominated strata in the Sand Creek and North Fork drainages east of Post actually *overlies* the Boren Ranch Sandstone, and this places some strata mapped by Lehman (1994) and Lehman and Chatterjee (2006) as the Trujillo Sandstone and Tecovas Formation *within* the type section of the Cooper Canyon Formation measured by Lehman et al. (1992).

Which of these two sandstone units, the Dalby Ranch sandstone or the Boren Ranch sandstone (if either), is properly correlated with the Trujillo Sandstone of southern Crosby County? This is a deceptively simple question. The Trujillo Formation of the Texas Panhandle, as originally recognized by Gould (1907), consists of interbedded channel sandstones and overbank mudstones (Lehman, 1994a; Lehman and Chatterjee, 2005). The lower part of the sequence, what is now usually referred to as the Trujillo Sandstone (e.g. Lehman, 1994a; Lehman and Chatterjee, 2005) or Trujillo Formation (e.g. Lucas et al., 1994), is dominated by channel sandstones, usually stacked in multi-storied sandstones formed by multiple phases of channel migration, incision, and aggradation (May, 1988; Newell, 1993; Lehman and Chatterjee, 2005). The upper part of Gould's (1907) Trujillo Formation, is now generally referred to in the Panhandle as the Bull Canyon Formation (Lucas et al., 1994a) or Cooper Canyon Formation (Lehman, 1994a, b). The sandstones of the Trujillo Sandstone and Bull Canyon/Cooper Canyon Formation are lithologically indistinguishable (May, 1988; Lehman, 1994a; Lehman and Chatterjee, 2005), and the division between these formations is therefore somewhat arbitrary, with the lowest multistoried sand body in a given area usually being referred to as the Trujillo Sandstone. Moreover, the fluvial sandstones pinch out laterally, and it is doubtful that the sandstone unit identified as the Trujillo Sandstone in, for example, Palo Duro Canyon, is precisely the same sandstone unit or units identified as the Trujillo southward along the High Plains, although they are closely associated stratigraphically (May, 1988). For these reasons, May (1988) preferred to retain Gould's (1907) Trujillo Formation in its original sense and trace individual sandstones within it, rather than distinguishing the upper mudstone-dominated and lower sandstone-dominated parts as separate formations.

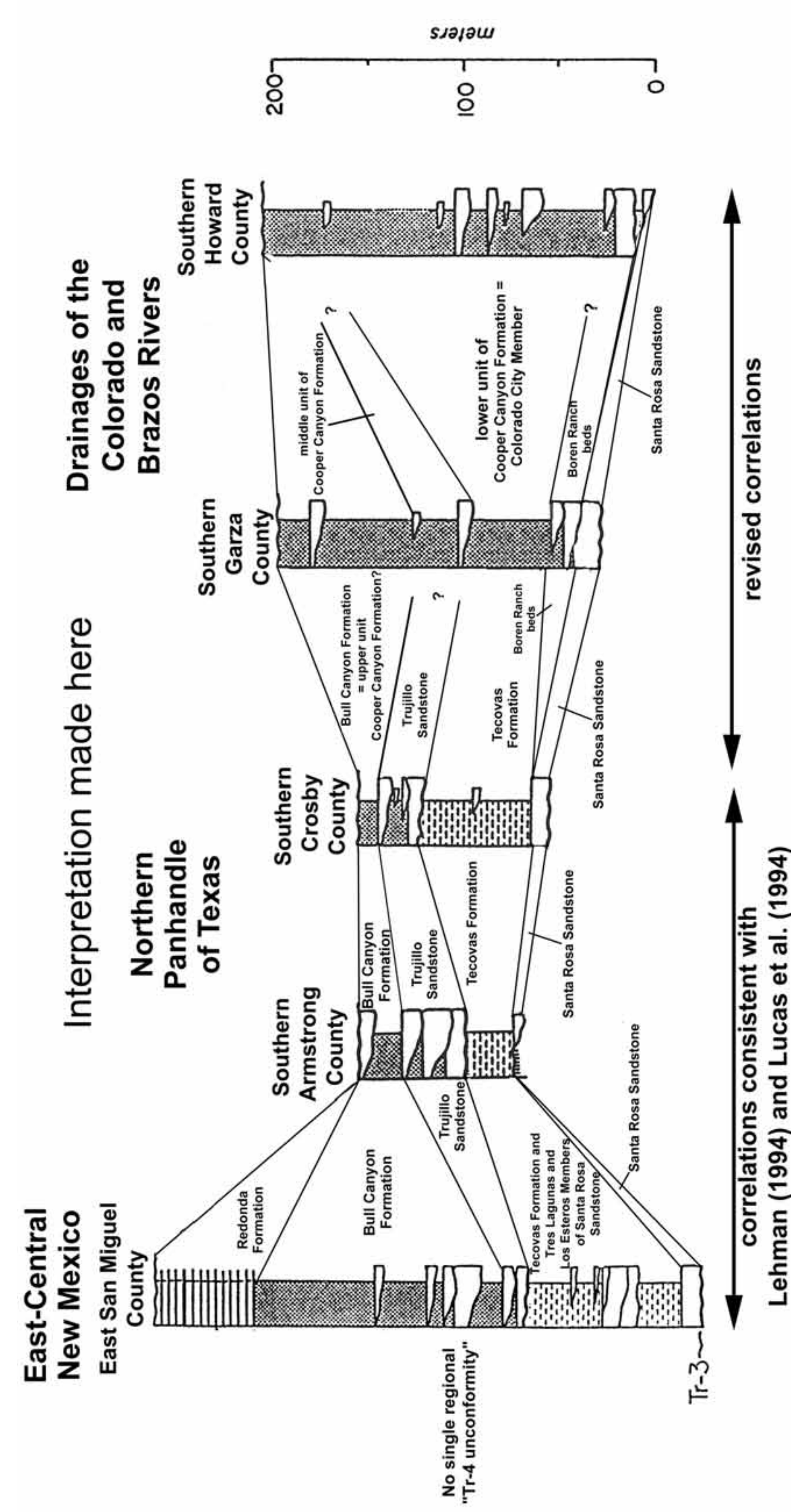
May (1988, fig. 2.15) traced the most prominent of the sandstones making up the Trujillo Sandstone south along the edge of the High Plains from Palo Duro Canyon into

Garza County. He shows the lowest of these sandstones he associates with the Trujillo Sandstone entering Garza County with the basal contact at an elevation of 2400’, the elevation at which the Dalby Ranch sandstone outcrops in the southern part of the county. The next two sandstones in May’s (1988) figure, outcrop above 2500’ and 2700’, and may represent respectively the Miller Ranch sandstone and Macy Ranch sandstone, though it is not clear how far May (1988) traced these units south in Garza County. May (1988, fig. 2.15) showed the 2400’ sandstone (Dalby Ranch sandstone?) it pinching out not far to the north of Garza County, and identified the overlying sandstone at 2500’ (Miller Ranch sandstone?) as being equivalent to the Trujillo Sandstone in Crosby County and Dickens County.

Although the mapping presented here was restricted to southern Garza County, reconnaissance of northern Garza County and southern Crosby County by myself, Bill Mueller, and Tom Lehman, seems to support May’s (1988) correlations, although these must be considered tentative until the area is mapped in detail. The sandstone capping Cedar Hill and Negro Hill in Crosby County, generally accepted as representing the Trujillo Sandstone there (Lehman, 1994a; Lucas et al., 1994; Long and Murry, 1995), is therefore probably equivalent to the Miller Ranch sandstone, or possibly the Dalby Ranch sandstone, in southern Garza County (Fig. 2.40), and either way is well above the Boren Ranch sandstone. As already discussed, Drake (1892) also seems to have identified the Miller Ranch and Dalby Ranch sandstones in Garza County with his “Central Beds”, and he correlated this unit with the Trujillo Sandstone in the Panhandle (e.g. Baker, 1915). Moreover, Green (1954, p. 35) identified the Trujillo Sandstone in Garza County as “small outliers composed of a capping sandstone or conglomerate protecting underlying clay and shale [that] are numerous…east of the town of Post…” These “outliers” probably refer to the many small mesas capped by the Miller Ranch sandstone east of Post.

The North American Stratigraphic Code (Article 22) specifies that a

Next Page: Fig. 2.40. Revised correlations of units within the Dockum Group. Modified from Lehman and Chatterjee (2005, fig. 3) and Lehman et al. (unpublished). Location of sections given in Fig. 1.2.


Interpretation made here
East-Central New Mexico
East San Miguel County
Northern Panhandle of Texas
Southern Armstrong County
Southern Crosby County
Drainages of the Colorado and Brazos Rivers
Southern Garza County
Southern Howard County
meters
200
100
0
Redonda Formation
Bull Canyon Formation
Trujillo Sandstone
Tecovas Formation and Tres Lagunas and Los Esteros Members of Santa Rosa Sandstone
Santa Rosa Sandstone
Tecovas Formation
Bull Canyon Formation = upper unit Cooper Canyon Formation?
Tecovas Formation
Boren Ranch beds
middle unit of Cooper Canyon Formation
lower unit of Cooper Canyon Formation = Colorado City Member
No single regional "Tr-4 unconformity"
Tr-3
correlations consistent with Lehman (1994) and Lucas et al. (1994)
revised correlations

lithostratigraphic unit is “distinguished and delimited on the basis of lithic characteristics *and stratigraphic position*” [my emphasis]. Although the lithology of the Boren Ranch sandstone and the Trujillo Sandstone further north may be indistinguishable, the thickness of 30 meters of mudstone between them exceeds the relatively thin tongues of mudstone separating the interbedded sandstones forming the Trujillo Sandstone (May, 1988). Given their drastically different stratigraphic positions, the Trujillo Sandstone and Boren Ranch sandstone should be considered distinct units.

Moreover, until the Dalby Ranch sandstone and Miller Ranch sandstone can be mapped further north to more firmly establish their precise relationships with the Trujillo Sandstone in southern Crosby County, I prefer to continue using their local names in southern Garza County rather than assigning one or both to the Trujillo Sandstone/Formation.

This possible correlation of the middle unit of the Cooper Canyon Formation with the Trujillo Sandstone means that the lower unit is probably correlative with the Tecovas Formation (Fig. 2.40), and if so future mapping through northern Garza County should demonstrate that the two mudstone-dominated units grade into each other laterally. Moreover, the Santa Rosa Sandstone exposed at White River Reservoir is strongly siliceous as it is further north (e.g. May, 1988), and there is no report of an arkosic or micaceous litharenite capping it as in southern Garza County. The Boren Ranch beds must therefore wedge out somewhere in northern Garza County or southern Crosby County. The relatively thin and patchy nature of the micaceous sandstones in the Boren Ranch beds at OS Ranch (in the northern part of the study area) compared to the massive nature of the Boren Ranch sandstone at Lake Alan Henry (further south) indicates this may already be beginning in Garza County. However, we have traced the Trujillo Sandstone from Cedar Hill in Crosby County several kilometers southwest to where it forms a cap on a cliff above County Road 238, and a micaceous sandstone outcrops in places about 20 meters below the Trujillo Sandstone along the road. This indicates that even in southern Crosby County just a short distance south of the reservoir, at least one micaceous sandstone still occurs stratigraphically below the Trujillo Sandstone, although it is not clear if this is precisely equivalent with the Boren Ranch Sandstone/beds.

Should the lower unit of the Cooper Canyon Formation simply be referred to as the Tecovas Formation? At least superficial similarities between these units in southern Garza and southern Crosby County, and with the Boren Ranch beds at OS Ranch, have already been discussed, including similarities in tan or orangeish coloration and the possible prevalence of lacustrine deposition, which distinguish these beds from the more distinctly reddish overbank deposits of the Cooper Canyon Formation higher in the section. However, these similarities may represent similarities in depositional and diagenetic history, but not necessarily lithologic similarity, and the presence of micaceous litharenites below the lower unit of the Cooper Canyon Formation absent below the Tecovas Formation suggests that the lithology of the mudstones may also be quite distinct. This is supported by analysis of the major and trace element content of these mudstone samples from the lower unit and the Tecovas Formation of Palo Duro Canyon (discussed in Chapter 3). Pending more detailed studies of the lithology of the lower Dockum Group, I retain the lower unit of the Cooper Canyon Formation as a unit correlative with, but distinct from, the Tecovas Formation. As a final speculation regarding the relationship between these two units, it may be that the "Tecovas Formation" of Crosby County has lithologically more in common with the lower unit in Garza County, suggested by superficial similarities in color (specifically the orangeish color of the lower part of both units), than with the Tecovas Formation further north in the Panhandle, in which the lower beds are more strongly variegated. If there is a lithologic change in the lower mudstones of the Dockum Group between the Brazos River drainage and the Panhandle, it may roughly coincide with the northern edge of the Midland Basin (Fig. 2.2). Testing these speculations will again have to await a more detailed mapping and lithologic studies of these mudstones.

This revised correlation of the Trujillo Sandstone also indicates that the type sections of the Bull Canyon Formation in New Mexico (Lucas and Hunt, 1989) and Cooper Canyon Formation in southern Garza County (Lehman et al., 1992) do not in fact refer to equivalent stratigraphic units. The Bull Canyon Formation type section may actually be lithostratigraphically correlative only with the upper unit of the Cooper Canyon Formation. This may render the debate between Lucas et al. (1994) and Lehman (1994a, b) about the relative priority of these terms somewhat moot.

The “Tr-4 Unconformity”

These correlations, and the mapping of sandstones in the middle unit of the Cooper Canyon Formation in southern Garza County, also raise doubts about the reality of the “Tr-4 unconformity” of Lucas (1991, 1993b; Heckert and Lucas, 1996b). Lithostratigraphic correlations of Upper Triassic strata throughout the western United States, based largely on vertebrate biochronology, suggested to Lucas (1993b) the presence of a regional unconformity at the base of strata containing his “faunachron C” (renamed the “Revueltian” by Lucas and Hunt, 1993). This unconformity is marked by a distinct change in lithology, usually from mudstone-dominated to sandstone-dominated strata. Following the scheme of Pipiringos and O’Sullivan (1978), Lucas (1991) referred to this erosional surface as the Tr-4 unconformity, and interpreted it, and the Tr-3 unconformity at the base of the Upper Triassic section, as having formed during eustatic drops in sea level which caused periods of regional erosion across the western United States. In the Dockum Group, the unit resting directly above the alleged Tr-4 unconformity is the Trujillo Sandstone (Lucas et al., 1994); in Petrified Forest National Park, it is the Sonsela Member (e.g. Heckert and Lucas, 2002).

However, Woody (2006) traced the Sonsela Member throughout Petrified Forest National Park, and determined that the base of the unit consists of a series of discontinuous sheet sandstones that individually incise the underlying Blue Mesa Member, but do not rest on a single regional erosional unconformity. Woody (2006, p. 29) concluded that “the Tr-4 unconformity must either be limited in distribution to areas north and west of PEFO, or is not a regionally significant surface.” May’s (1988, fig. 2.15) tracing of the Trujillo Sandstone along the eastern edge of the High Plains of West Texas also demonstrated that the unit consisted of a series of laterally extensive but discontinuous blanket sandstones, in which the boundary between the Tecovas Formation and mudstones interbedded with the Trujillo blanket sandstones is often gradational. The same is true of the Dalby Ranch sandstone and Miller Ranch sandstone in southern Garza County. The Dalby Ranch sandstone pinches out along the southwest side of the Caprock Finger, and between where this occurs and where the Route 669 Roadcut sandstone first appears further west, the transition between overbank mudstones in the lower and middle units of the Cooper Canyon Formation appears to be gradational.

There may be a stratigraphic interval, deposited more or less contemporaneously in Upper Triassic strata across the western United States, in which the amalgamated channel blanket sandstones making up units such as the Sonsela Member, Trujillo Sandstone, and Dalby Ranch sandstone, began to be deposited in high density due to a regional eustatic (e.g. Lucas, 1991) or tectonic (e.g. Lehman and Chatterjee, 2005) episode. However, unconformities are restricted to the bases of these individual discontinuous blanket sandstones and do not form a single regional unconformity, so the TR-4 unconformity (*sensu* Lucas 1993b) probably does not exist.

Controversies in the Lithostratigraphic Correlation of the Dockum Group in Texas Between the Panhandle and the Colorado River Valley

Drake (1892) presented the first major regional study of the Dockum Group, and his study is impressive both in its scope and in the confidence of his correlations. Drake recognized that exposures of the Dockum Group extended along the edge of the southern High Plains and through the Canadian River Valley well into New Mexico. Moreover, Drake (1892) recognized three units: a lower mudstone dominated unit, a middle unit with abundant sandstone and conglomerate, and an upper unit with mudstone and sandstone, all three of which he correlated over this entire region. Drake’s three units are generally accepted (at least in the northern Panhandle and east-central New Mexico, following Baker, 1915) to correspond to the Tecovas Formation/Garita Creek Formation, the Trujillo Formation, and Bull Canyon Formation/Cooper Canyon Formation. However, correlation of the Dockum Group between the northern exposures and those in southeastern New Mexico and around the southeastern edge of the Llano Estacado was problematic for later workers. As discussed by Lehman (1994a), the formal stratigraphic nomenclature that developed for the Dockum Group in the century after Drake (1892) became considerably more provincial, with some workers (e.g. Murry, 1986, 1989; McGowan et al., 1979, 1983) being reluctant to correlate *any* formally named lithostratigraphic units, such as Gould's (1906, 1907) Tecovas and Trujillo Formations, outside their type areas.

Both Lehman (1994a) and Lucas et al. (1994) make correlations between the Texas Panhandle and southern Texan exposures of the Dockum Group, but these correlations differ in fundamentally important ways (Figs. 1.5, 2.37-2.38), with Lehman's (1994a) correlations being based on lithostratigraphy and Lucas et al.'s (1994) being based on vertebrate biostratigraphy. As in the northern Dockum exposures, Lucas et al. (1994) and Lucas and Anderson (1993a, 1994) make a nomenclatural division at the Texas-New Mexico state line, and identify the basal unit of the Dockum Group in the southeastern New Mexico as the Santa Rosa Formation and in the southern Texas Panhandle as the Camp Springs Member, which they claim are correlative but lithologically distinct. Lucas and Anderson (1993a, b) and Lucas et al. (1994) named the strata overlying the Santa Rosa Formation in southeastern New Mexico the San Pedro Arroyo Formation, and those overlying the Camp Springs Member in the southern Texas Panhandle, particularly in Howard County, as the Iatan Member, a name later emended by Lucas et al. (1994) to the Colorado City Member. They assigned the uppermost part of Dockum Group above the Colorado City Member to the Tecovas Formation and the Trujillo Sandstone.

These correlations for the Colorado City Member were based primarily on vertebrate biostratigraphy. The Otis Chalk vertebrate localities in Howard County, which lie in the Colorado City Member, form the type assemblage for the "Otischalkian land vertebrate faunachron" of Lucas and Hunt (1993), which is considered (e.g. Lucas, 1998) to also encompass the vertebrates of the Tecololito Member of the Santa Rosa Formation in New Mexico and the Camp Springs Member in Texas. As the Tecovas Formation is considered to contain a younger "Adamanian" fauna, and the Trujillo Sandstone and Bull Canyon Formation even younger "Revueltian" faunas, the Colorado City Member must therefore (in Lucas and Anderson's view) be lower, hence their identification of the uppermost Upper Triassic strata above the Colorado City Member as the Tecovas Formation and Trujillo Sandstone (Fig. 2.38). Lucas and Anderson's (1993a, b) identification of at least the lower part of the San Pedro Arroyo Formation as being correlative to the Colorado City Member was apparently based entirely on its stratigraphic position directly above the Camp Springs Member.

However, Lehman (1994a, b) identified *two* lithologically distinct sandstone units at the base of the Dockum in the southern exposures, including at the type locality of the Camp Springs Conglomerate of Beede and Christner (1926) and Lucas and Anderson (1994). Lehman identified the lower one as the Santa Rosa Sandstone, and the upper one as the Trujillo Sandstone, due to lithologic similarity with these units in the Texas Panhandle. Lehman claimed the Trujillo Sandstone had truncated most or all of the Tecovas Formation and rests almost directly on top of the Santa Rosa Sandstone, or even locally on the Permian Quartermaster Formation. Lehman (1994a, b) therefore assigned most or all of the San Pedro Arroyo and Colorado City Members to the Cooper Canyon Formation, based on both the superpositional relationship of these strata to the sandstone he identified as the Trujillo Sandstone, and the lithologic similarity of the sandstones in the strata to those in the Cooper Canyon Formation (also see Lehman and Chatterjee, 2005, fig. 3, to illustrate Lehman's proposed correlations from the Panhandle to the Colorado River Valley in more detail).

This is contrary to Lucas et al.'s (1994) claim that these units were lithologically distinct, and would also make the "Colorado City Member" and "San Pedro Arroyo Member" much younger than indicated by Lucas and his colleagues. Lehman (1994a, p. 43) indicates that "in many areas, erosion *prior to the deposition* of the Trujillo Sandstone removed much or all of the intervening Tecovas Formation…" [emphasis mine] indicating that the Tecovas was originally deposited in the southern High Plains, and that Cooper Canyon Formation/San Pedro Arroyo Member/Colorado City Member strata in the southern Panhandle were deposited *after* the Tecovas Formation to the north. Lehman and Chatterjee's (2006, p. 347) interpretation of vertebrate biochronology in the Dockum Group enforces this age interpretation, indicating that faunas in the Colorado City Member and Cooper Canyon Formation to the north are "…*co-eval* on the basis of lithostratigraphic correlation." [emphasis mine].

There is then some manner of change in the depositional pattern of the Dockum Group that occurs between the Panhandle and southern exposures in Texas. In the interpretation of Lehman (1994a) and Lehman and Chatterjee (2005, fig. 3), this involves the truncation of the Tecovas Formation and/or Santa Rosa Sandstone, and massive thickening of the Cooper Canyon Formation as one travels from the north to the south, with nearly the *entire* section in the south being roughly equivalent (both lithologically and chronologically) to the upper part of the section in the north (Fig. 2.37). In the interpretation of Lucas and Anderson (1994) and Lucas et al. (1994), the bulk of the section in the south represents strata co-eval with the lowermost Dockum Group to the north, even though it is far thicker and differs lithologically from any other Dockum strata deposited prior to the Trujillo Sandstone/Formation (Fig. 2.38).

Lithostratigraphic Correlation of the Dockum Group between Southern Garza County and the Colorado River Valley

The basic lithostratigraphy of Dockum Group in southern Garza County is essentially that described by Lehman (1994a) and Lehman and Chatterjee (2005) for the Dockum Group in Borden and Howard Counties in the drainage of the Colorado River, with micaceous lithic sandstones rich in metamorphic rock fragments being found throughout almost the entire section, the lowest such sandstone being identified by those authors as the Trujillo Sandstone and occurring only a short distance stratigraphically above the siliceous sandstone at the base of the section they identify as the Santa Rosa Sandstone (Fig. 2.37; see also Lehman and Chatterjee, 2005, fig. 3, sections 1-5). Lucas and Anderson (1994, p. 7), describing a type section for the Camp Springs Member of Beede and Christner (1926) in Scurry County, described the sandstones in the type section as "'granite wash' matrix of micas and feldspars with minor quartz…Conglomerate clasts are of mudstone or siltstone pebbles derived from underlying Permian strata or of extrabasinal reddish cherts." This lithology is more reminiscent of the Boren Ranch sandstone/beds in southern Garza County than the Santa Rosa Sandstone there, and it may be that the Boren Ranch sandstone and Camp Springs Member (*sensu* Lucas and Anderson, 1994) are equivalent. However, as Lehman (1994a) noted, the siliceous Santa Rosa Sandstone is present below the micaceous and feldspathic sandstones near Camp Springs that Lucas and Anderson (1994) apparently used for their type section, and in fact Beede and Christner's (1926, pp. 16-17) original description of the Camp Springs Conglomerate as "coarse conglomerate exhibiting brownish color wherever exposed, due mainly to the preponderance of brown quartz and chert pebbles" suggests that the Camp Springs Conglomerate (*sensu* Beede and Christner, 1926) may actually be the same unit identified in southern Garza County as the Santa Rosa Sandstone.

In any case, the fact that the section from Garza County south into Howard County is dominated by mudstone interbedded with micaceous and feldspathic sandstones, with the lowest occurring almost directly above a siliceous sandstone at the base of the Upper Triassic section, supports Lehman (1994a) and Lehman and Chatterjee's (2005) claim that the "Colorado City Member" of Lucas et al. (1994) is correlative with the Cooper Canyon Formation. However, as already discussed, the Trujillo Sandstone of southern Crosby County correlates with sandstones in southern Garza County well *within* the type section of the Cooper Canyon Formation, and demonstrates that thick micaceous and arkosic litharenites (the Boren Ranch sandstone, possibly the "Camp Springs Member" *sensu* Lucas and Anderson, 1994) occur in southern Garza County in strata correlative with the *lower* Tecovas Formation, well down section from the Trujillo Sandstone. This eliminates Lehman's (1994a) main argument that the lowermost micaceous sandstones in Howard County must be correlative with the Trujillo Sandstone, and therefore that the Colorado City Member may be syndepositional not only with the lower unit of the Cooper Canyon Formation and Boren Ranch sandstone/beds in southern Garza County, but with the Tecovas Formation in the Panhandle. Ironically, Lucas et al.'s (1994) claim that the Bull Canyon Formation and Colorado City Member are *distinct* units, and Lehman's (1994a, b) claim that the Cooper Canyon Formation and Colorado City Member are *equivalent*, may therefore actually both be compatible and accurate statements. The Bull Canyon Formation may be correlative with the upper unit and part of the middle unit of the Cooper Canyon Formation, and the Colorado City Member may be correlative with the lower unit of the Cooper Canyon Formation (Fig. 2.40).

However, Lehman (1994a) had another objection to the "Colorado City Member" in Howard County being syndepositional with pre-Tecovas Formation strata to the north, and this was the enormous thickness of the "Colorado City Member" below the Otis Chalk quarries. Lehman (1994a, p. 45, fig. 5) indicated that these quarries lie "at least 60 m" (or about 200') above what he identified in the southern Panhandle as the base of the Cooper Canyon Formation, and his cross section from Mitchell to Howard Counties, taking regional dip into account, places it about twice that vertical distance.

Lucas and Anderson (1994, 1995, p. 9, fig. 5) presented a considerably more confusing argument for the thickness of the Dockum Group in Howard and Mitchell Counties. They claimed that the total thickness of the Dockum was no more than 100 meters (about 327 feet), but on the same page claimed that the thickness for the Colorado City Member *alone* was 130 meters (400 feet) in that area, and presented a well log (well 28-47603 from near Westbrook near the Howard-Mitchell County line) with contacts identified giving the total Dockum Group a thickness of about *275 meters (900 feet)*. This is even more puzzling given that on the same page they criticize Lehman for his supposedly excessive thickness for the entire Dockum Group of 250 meters. Comparing Lehman's (1994a, fig. 5) cross section showing the location of the Westbrook well with Lucas and Anderson's (1994, 1995, fig. 5) cross section using the actual well log makes clear that Lehman actually places the base of the Dockum Group about where Lehman and Anderson place the base of the Trujillo Sandstone, giving a subsurface thickness about 450' *thinner* than Lucas and Anderson. Lucas and Anderson (1995, p. 9) also criticize Lehman (1994b, fig. 4) for supposedly basing his thickness for the Dockum Group on an overly steep estimate of westerly dip of about 30° for the base of the Dockum Group, which they apparently measured directly off his *vertically exaggerated* (200X) cross section, even though Lehman (1994a, p.50) clearly states that the unexaggerated southwestern dip of the Dockum Group here is “less than 1°.”

I attempted to correlate the Tr-3 unconformity and Santa Rosa Sandstone from southern Garza County to the Otis Chalk localities using gamma-ray well logs (Figs. 2.41-2.42). The distinctive negative gamma-ray response interpreted to represent the Santa Rosa Sandstone, and the equally distinctive Upper Permian sequence beneath it (Fig. 2.32) can be traced with some success south through eastern Borden County (well logs a-i in Figs. 2.41-2.42), although the response changes gradually in character, and the inferred Permian-Triassic contact drops almost 300’ in elevation, as predicted from the southwestern dip seen in southern Garza County. However, problems arise around the Borden-Howard County line, after which the base of the Dockum Group seems to rise again in elevation by over 200’, and correlations particularly between wells i and j, l and m, and o and p in Fig. 2.42, are questionable. The Tr-3 unconformity is tentatively traced to an elevation of about 1900’ at the gamma-ray log for well Wood, McShane, and Thams No. 12 G.O. Chalk (well log p in Figs. 2.41-2.42), which is within a few miles of the Otis Chalk localities. This is close the elevation where Lehman’s (1994a, fig. 5) cross-section places it. As the Otis Chalk localities generally lie between about 2300’-2350’ elevation (Lucas et al., 1993, fig. 2), this places them above at least 130 meters (400’) above the basal contact of the Dockum Group.

Part of the confusion regarding the thickness of the Dockum Group in southern Howard County probably has to do with how the section was measured (Fig. 2.34). Lucas and Anderson’s (1994, 1995) claim that the thickness of the Dockum Group was less than 100 meters was estimated by a 40-km overland traverse east to west from Mitchell County into Howard County (Lucas and Anderson, 1993a, p. 233), and may represent the pre-erosional thickness in Mitchell County. Their much greater (and probably excessive) thickness of 275 meters shown in the log for well 28-47-603 (Lucas

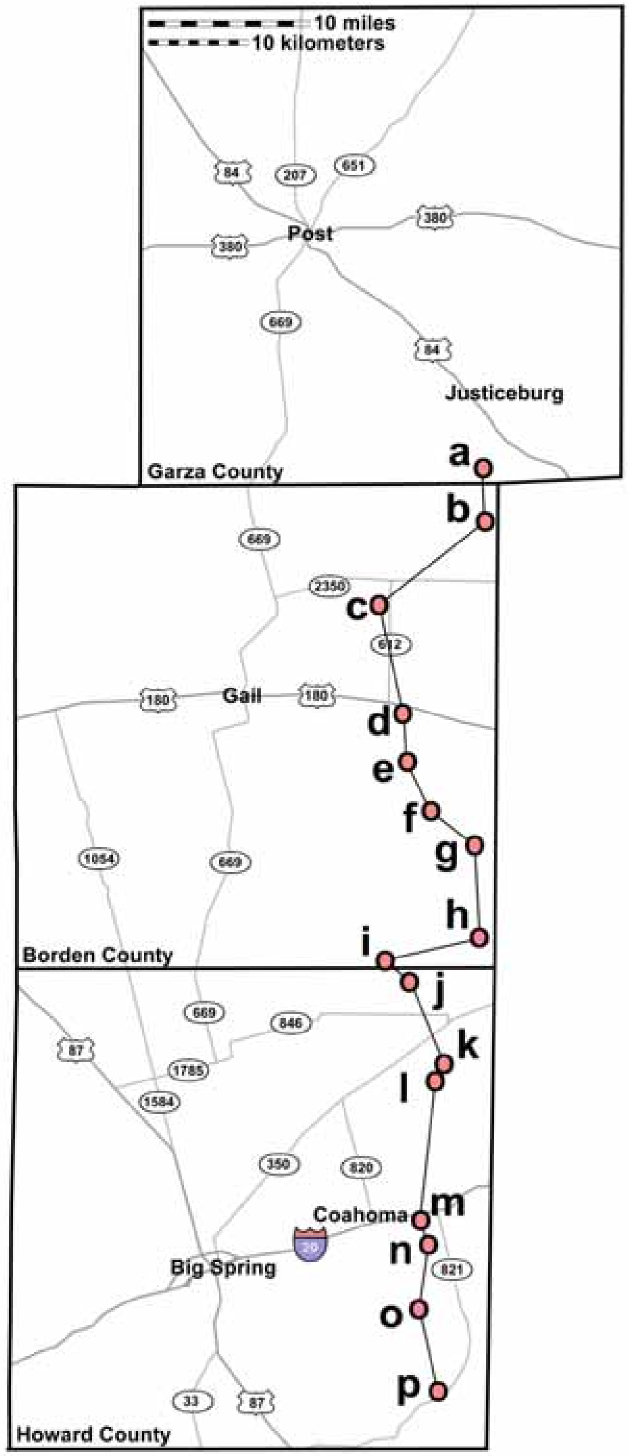


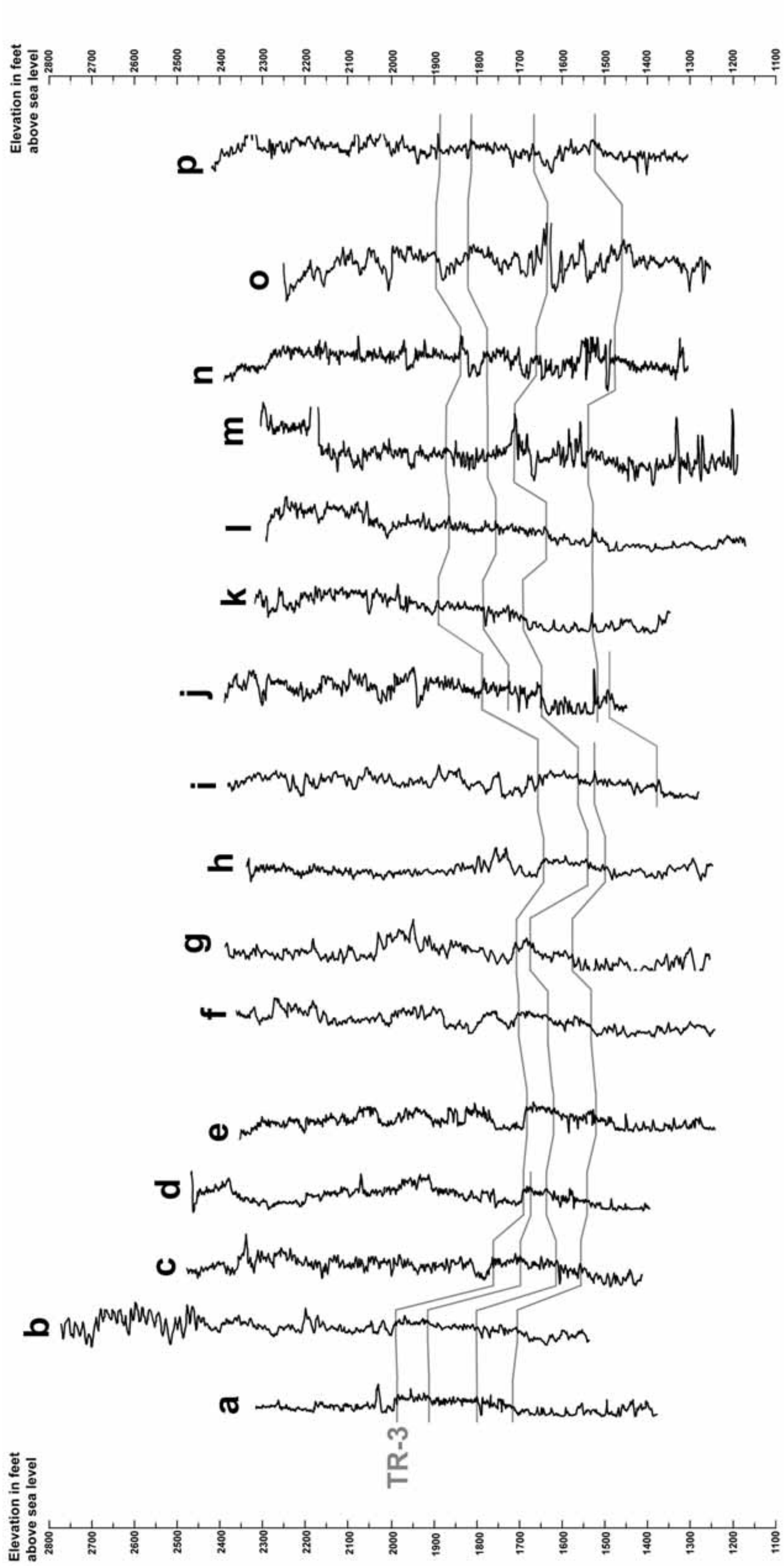
Fig. 2.41. Map showing position of well logs used to correlate the base of the Dockum Group through Garza, Borden, and Howard Counties. Well logs listed in caption for Fig. 2.44.

and Anderson, 1995, fig. 5) is a vertical distance for eastern Howard County not far from the Otis Chalk localities. Based on my own tentative well-log correlations, Lehman's (1994a, fig. 5) relatively modest vertical thickness of about 130 meters for the Otis Chalk area is probably more reasonable.

However, this nonetheless places the Otis Chalk localities above a considerable thickness of Upper Triassic strata. For example, in the log for well T.M. Evans Production Company No. 1 Slaughter (Fig. 2.36d) in the southwestern Garza County (Fig. 1.6), 130 meters (400') above the TR-3 unconformity, is probably well within the lower unit of the Cooper Canyon Formation, and it seems remarkable that 130 meters of mudstone-dominated strata is correlative with the Tecololito Member ("middle sandstone") of the Santa Rosa Sandstone in New Mexico and "Camp Springs Member" in New Mexico, as these other strata considered to be "Otischalkian" on the basis of their vertebrate faunas (Lucas, 1998), are sandstone and conglomerate-dominated units that are no more than a third that thickness (e.g. Lucas et al., 1985, p. 173; Lucas and Anderson, 1994, p. 7).

Lehman's (1994a) correlation of the "Colorado City Member" and Otis Chalk localities with the Cooper Canyon Formation, based on sandstone lithology and the fact that both units are dominated by mudstone, is more compelling. This correlation has been thought by both Lucas et al. (1994) and Lehman and Chatterjee (2005) to be in serious conflict with the four-part biochronological subdivision of the Late Triassic

Fig. 2.42. Well logs used to correlate the base of the Dockum Group through Garza, Borden, and Howard Counties: *a*, Permian Resources Inc. No. 1 Griffis "A"; *b*, Stanolind Oil and Gas Company A-3 Jordan; *c*, ADA Oil Company No. 1 Davenport; *d*, Brazos Petroleum Company, No. 1 Williams; *e*, Shell Western E & P Company No. 2 Gray; *f*, L.S. McDowell No. 1 (Wildcat); *g*, Amerada Petroleum Company No. 1 "NC" Von Roeder; *h*, Magnolia Petroleum Company No. 1 Conrad; *i*, Standard Oil Company of Texas No. 1 Griffin 6; *j*, Tom Brown Drilling Company No. 1 Kreber; *k*, Barnwell Industries Inc. No. 1 Meador; *l*, Shenandoah Oil Corporation No. 2 Helen Fleeman; *m*, Elmer J. Boeseke Jr. No. 33 Texas Land and Mortgage; *n*, Sun Oil Company D-X Division No. 8 L.C. Denman "B"; *o*, American Petrofina Company of Texas No. 1 Snyder Water Flood WIW; *p*, Wood, McShane, and Thams No. 12 G.O. Chalk. The Tr-3 unconformity and traceable gamma-ray responses in the Quartermaster Formation are correlated with gray lines.


Elevation in feet above sea level
2800
2700
2600
2500
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
a
b
c
d
e
f
g
h
i
j
k
l
m
n
o
p
TR-3
Elevation in feet above sea level

proposed by Lucas and his colleagues (e.g. Lucas and Hunt, 1993; Lucas, 1998; Lucas et al., 2007b), as the Cooper Canyon Formation was generally accepted by all to correlate with the Bull Canyon Formation, which contains a “Revueltian” fauna. However, given that the lower part of the type section of the Cooper Canyon Formation is now recognized to probably be correlative with the Tecovas Formation, which contains an “Adamanian” fauna supposedly intermediate in age between the “Otischalkian” and “Revueltian” faunas (as will be discussed in Chapter 6, the lower Cooper Canyon Formation fauna in southern Garza County is also “Adamanian” in character) this conflict is less severe. It’s possible resolution will be discussed in Chapter 6.

A Slightly Revised Depositional Model for the Dockum Group

Lehman and Chatterjee (2005) and Lehman et al. (unpublished) presented a depositional model for the Dockum Group (Fig. 2.43a), for which I propose slight modifications (Fig. 2.45b) based on the revised correlations discussed above. This model must be considered extremely tentative until it can be tested by more extensive mapping and studies of sedimentary petrology and provenance throughout the Dockum Group.

The base of the Dockum Group is marked by a broad regional unconformity found at the base of Upper Triassic strata throughout the western United States, the Tr-3 unconformity of Pipiringos and O’Sullivan (1978). This unconformity is at least post-Anisian in age due to its truncation of the Anton Chico Formation in New Mexico (Lucas, 1993b). Conflicting lines of evidence regarding the age of the oldest Upper Triassic strata above the unconformity, discussed in Chapter 6, make it difficult to provide an upper bracket for the age of the unconformity, but it is at least pre-Norian, and possibly pre-late Carnian (e.g. Lucas, 1993b). The Tr-3 unconformity, and other major lithostratigraphic transitions above it (such as the “Tr-4” unconformity), have been interpreted as being driven by eustatic sea level change (e.g. Lucas, 1991, 1993b). However, Lehman and Chatterjee (2005) suggested tectonic controls on deposition were more likely given the drastic changes in paleocurrents and lithology within the Dockum Group, suggesting reorientation of the depositional basin.

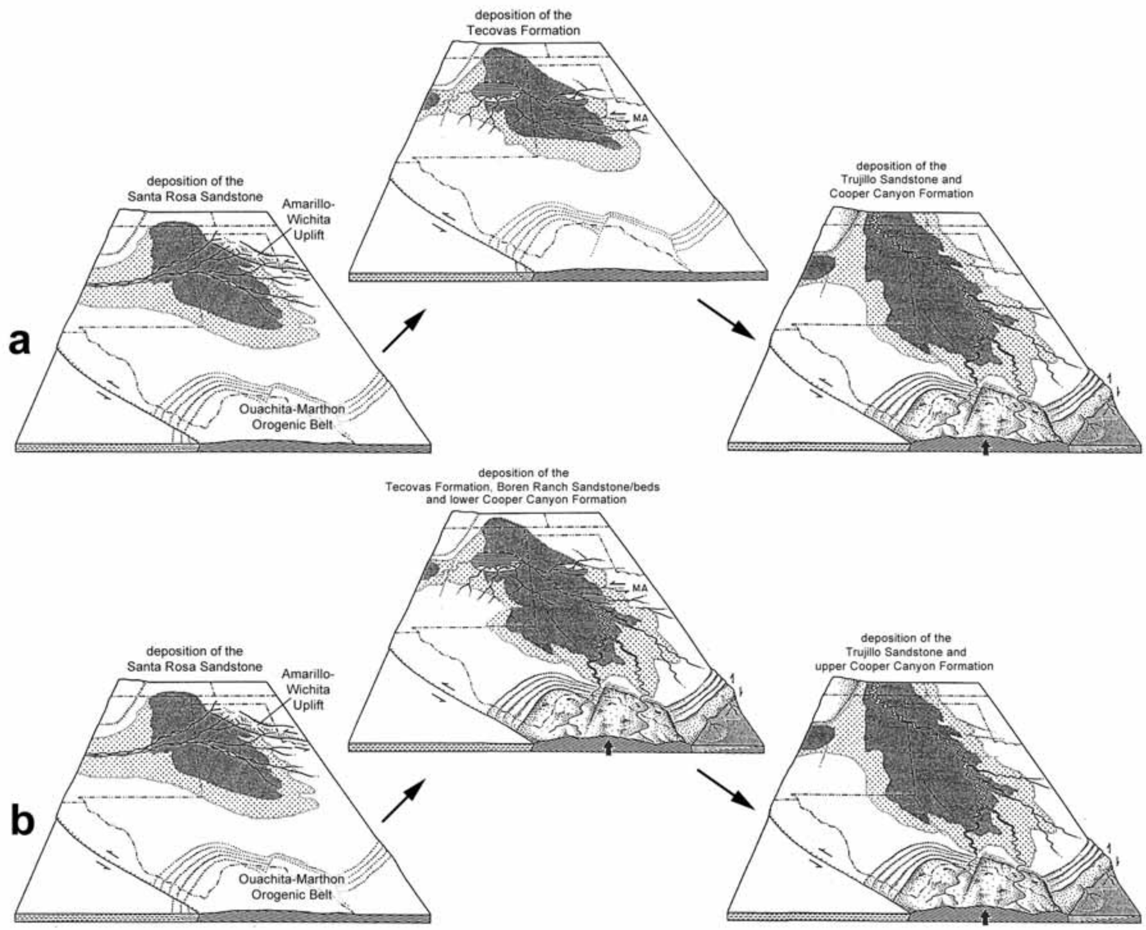


Fig. 2.43. Depositional model for the Dockum Group: *a*, model of Lehman and Chatterjee (2005) and Lehman et al. (unpublished); *b*, slightly revised model presented here. Figure modified from Lehman et al. (unpublished).

The Tecololito Member of the Santa Rosa Sandstone in New Mexico, and the entire Santa Rosa Sandstone (in part the “Camp Springs Conglomerate” *sensu* Lucas and Anderson, 1994) of West Texas was deposited by a braided river system that flowed through incised paleovalleys marking the Tr-3 unconformity (e.g. Lucas et al., 1985; Lupe, 1988; Fritz, 1991; Lucas and Hunt, 1987; Lehman and Chatterjee, 2005). Southwesterly paleocurrents and detrietal zircon studies suggest the source area for these braided rivers was the Amarillo-Wichita uplift, and that they flowed westward through the Chinle Formation (Riggs et al., 1996), with erosion of the "Palo Duro Geosol" of Kanhalangsy (1997) producing much of the siliceous content of the sediments (Lehman and Chatterjee, 2005). At least in southern Garza County, the mottled strata and unconformable upper surface of the Santa Rosa Sandstone suggests a brief depositional hiatus followed this braided river system.

However, in the northern part of the Dockum Group depocenter, the basal siliceous conglomeritic sandstones of the Tecololito Member the Santa Rosa Sandstone grade conformably into the mudstone dominated Los Esteros Member of the Santa Rosa Sandstone and lower "variegated shales" of the Tecovas Formation, which probably represent predominantly lacustrine deposits (McGowan et al., 1979; Murry, 1989; Fritz, 1991; Lehman and Chatterjee, 2005). Fluvial and deltaic sandstones deposited by rivers feeding this lake system are interbedded with these lacustrine deposits. These include notably the Tres Laguna Member of the Santa Rosa Sandstone and "sugar sands" in the Tecovas Formation in Texas, both of which are also siliceous (e.g. Lucas et al., 1985; May, 1988; Fritz, 1991). Paleocurrent data suggests highly varied source areas for the Tres Laguna Member (Fritz, 1991). Lehman et al.'s (unpublished) model (Fig. 2.45a, middle), suggests that during this lacustrine phase of later Santa Rosa Sandstone and Tecovas Formation deposition in the northern Texas Panhandle and East-Central New Mexico, sediments were not yet being derived from the Ouachita-Marathon belt to the south.

However, the Boren Ranch sandstone/beds (possibly including the "Camp Springs Member" of Lucas and Anderson, 1994), the lower unit of the Cooper Canyon Formation in southern Garza County, and possibly the "Colorado City Member" in Howard County, are probably syndepositional with the upper part of the Santa Rosa Sandstone and the "Garita Creek Formation" in New Mexico, and the Tecovas Formation in Texas. More precisely, the Los Esteros Member and Tres Lagunas Member of the Santa Rosa Sandstone, and the lower "variegated shales" of the Tecovas Formation, are suggested to the syndepositional with the Boren Ranch sandstone/beds and the base of the lower unit of the Cooper Canyon Formation. This may be corroborated by the apparently lacustrine character of some of these strata at the OS Ranch and Boren (Neyland) Quarry (Lehman and Chatterjee, 2005) in southern Garza County. These micaceous and feldspathic litharenites with schistose metamorphic rock fragments making up the Boren Ranch Sandstone are lithologically indistinguishable from those making up the Trujillo Sandstone and Cooper Canyon Formation (Frehlier, 1987; Lehman et al., 1992; Lehman et al., unpublished), and paleocurrents for this unit indicate a west-northwest paleoslope (Frehlier, 1987, p. 115), suggesting that the derivation of sediments from the Ouachita-Marathon orogenic belt began much earlier in Dockum history than previously suggested (Fig. 2.43b, middle). This is the only major departure from the model presented by Lehman and Chatterjee (2005) and Lehman et al. (unpublished).

The transition between the drab colored lower part of the Boren Ranch beds and the more reddish upper beds may represent the same transition from predominantly lacustrine deposits to predominantly overbank deposits seen in the transition from the "variegated shales" to "magenta shales" in the Tecovas Formation of Texas, and from the Los Esteros Member-Tres Lagunas Member to the "Garita Creek Formation" in New Mexico (e.g. Lehman and Chatterjee, 2005). The final stages of this transition may be recorded in the shift from the more orangeish beds seen in the lower part of the lower unit of the Cooper Canyon Formation along the North Fork of the Double Mountain Fork of the Brazos River, to the deeper red mudstones seen in the upper part.

These Tecovas Formation and lower unit of the Cooper Canyon Formation are followed across the Dockum Group by the massive and laterally extensive (though discontinuous) micaceous and feldspathic litharenite blanket sandstones making up the Trujillo Sandstone, Dalby Ranch sandstone and Route 669 Roadcut sandstone. Paleocurrents for these sandstones are more distinctly northerly in Lehman and Chatterjee's (2005) model than seen in the Santa Rosa Sandstone and Tecovas Formation. These units represent the spread of meandering rivers deriving from the Ouachita-Marathon orogenic belt across the Dockum depocenter (Fig. 2.43a, b, right). As already discussed, there is not a single regional "Tr-4" unconformity marking the regional spread of these sandstones. However, the shift from predominantly overbank deposits in the upper part of the Tecovas Formation and the lower unit of the Cooper Canyon Formation to these massive amalgamated meanderbelt sandstones spreading across West Texas and East-Central New Mexico, suggests some sort of dramatic regional event. As with the Tr-3 unconformity, both eustatic sea level changes (Lucas, 1991, 1993b) and tectonic reorientation of the region (Lehman and Chatterjee, 2005), have been suggested.

Higher in the section, these amalgamated meanderbelt sandstones become increasingly separated by the thickening overbank mudstones of the upper unit of the Cooper Canyon Formation in southern Garza County, and Bull Canyon Formation in East-Central New Mexico and the Texas Panhandle (Frehlier, 1987; Newell, 1993; Lucas et al., 2001; Lehman and Chatterjee, 2005). In East-Central New Mexico, deposition of the Bull Canyon Formation was followed by the formation of a massive freshwater lake depositing the Redonda Formation (Hester and Lucas, 2001). As will be discussed in Chapter 6, the Macy Ranch sandstone and uppermost Cooper Canyon Formation in southern Garza County may be approximately syndepositional with the Redonda Formation, indicating that the meandering river system depositing the Cooper Canyon Formation persisted in West Texas while it was replaced by lacustrine deposition in New Mexico.

CHAPTER 3

CHEMOSTRATIGRAPHY OF THE DOCKUM GROUP (UPPER TRIASSIC) OF SOUTHERN GARZA COUNTY, WEST TEXAS

Introduction

Although lithostratigraphic and biostratigraphic correlation have been employed for over 200 years, alternative methods of stratigraphic subdivision and correlation using heavy minerals in sandstones, clay minerals, and major and trace elements, are much more recent developments which have been useful in dating biostratigraphically barren sequences (e.g. Dunay and Hailwood, 1995). These methods have generally been adapted from tectonic environment and provenance studies (e.g. Roser and Korsch, 1986, 1988; Humphreys et al., 1991), with which they are often intimately associated. In such studies using major and trace elements, sedimentary units with different provenances are recognized by differences in major and trace element abundances, interpreted to represent lithological differences reflected the original source rocks. Changes in source rocks may therefore produce stratigraphic variation in major and trace elements composition which may be used for stratigraphic subdivision and regional correlation.

This method of stratigraphic subdivision and correlation has been practiced almost exclusively using well cores for Paleozoic, Mesozoic, and Cenozoic strata, especially beneath the Atlantic Ocean and North Sea (Pearce and Jarvis, 1995; Ehrenberg and Siring, 1992; Racey et al., 1995), although onshore sites have also been investigated (Pearce et al., 1999). These studies fortuitously include some involving continental red beds, and demonstrate that stratigraphic discrimination and subdivision of such strata using major and trace elements is feasible (Ehrenberg and Siring, 1992; Racey et al., 1995). However, few chemostratigraphic studies have been performed on terrestrial strata represented by well-exposed outcrops.

For this study, I chose to supplement lithostratigraphic correlations within the Dockum Group of southern Garza Count with major and trace element chemostratigraphy. The intention was to chemostratigraphically divide the primarily mudstone-dominated units of the Dockum Group at the same or finer scale than possible using lithostratigraphy. Even though petrological and paleocurrent data indicate that sediments in the Dockum Group in southern Garza County were probably supplied primarily by the Ouachita-Marathon orogenic belt throughout the deposition of the Boren Ranch sandstone/beds and Cooper Canyon Formation (e.g. McGowan et al., 1979; Long and Lehman, 1993, 1994; Lehman and Chatterjee, 2005; Lehman et al., unpublished), erosion of these source rocks through time might have gradually exposed different lithologies in the orogenic belt, producing shifts in major and trace element concentrations in the sediments.

The data from southern Garza County was also compared with unpublished data from the Tecovas Formation of Palo Duro Canyon in Randall County collected and analyzed by Ted Maloch in an unpublished TTU term paper, to determine if mudstones in the Tecovas Formation and Cooper Canyon Formation (particularly the lower unit, which is probably lithostratigraphically correlative with the Tecovas Formation) show distinct chemical signatures. The Tecovas Formation samples were collected from both the lower "variegated shales" and upper "magenta shales" of Gould (1907). Samples B1 and B2 were collected from the lower reddish beds of the variegated shales directly above the purplish-gray paleosol at the base of the Dockum Group (May, 1988). Samples M1 and M2 were collected from the yellow beds of the variegated shales above the lower reddish beds, and samples T1 and T2 were collected from the reddish "magenta shales" forming the upper part of the Tecovas Formation.

Methodology

Sample Collection

Since major and trace element abundances in sediment are direct reflections of sediment provenance, lithology, and diagenetic history, workers using chemostratigraphic subdivision and correlation must be mindful that all these factors may influence major and trace element values, and record sedimentological information associated with their samples. As noted by Ehrenberg and Siring (1992, p. 318) "care must be taken to exclude compositional variables that are obviously controlled by factors unrelated to stratigraphy." Grain size in particular is an important source of geochemical variation, even for stratigraphically equivalent sediments with the same provenance, as sediments with different grain sizes tend to contain different mineral fractions. For example, both De Lange (1987) and Pearce and Jarvis (1992) noted that in turbidites, grain size segregation has an important impact on chemical signatures. Consequently, even though it is possible in at least some cases for bulk geochemical data including both sand and mud-sized fractions to fall in a restricted enough range to allow provenance discrimination (e.g. Humphreys et al., 1991, p. 258; Roser and Korsch, 1986, 1988), effort was made to restrict sample collection in the Dockum Group to mudstones, although a few samples are muddy sandstones.

Fine grained samples, the relative stratigraphic positions of which were previously established through lithostratigraphic correlation and mapping (Figs. 2.3, 3.1, Appendix 1), were collected from surface outcrops. Samples were also collected from mudstone interbedded in sandstone and conglomerate-dominated sequences, such as mudstone pockets probably reworked from pre-existing overbank deposits (sample OS Gully-2) and mudstones probably representing oxbow lake deposits in the Macy Ranch sandstone (sample Patty-4). Samples were collected primarily from reddish brown (oxidized) mudstones often containing zones of reduction mottling, and samples were also collected from drab colored (reduced) mudstones, particularly in zones directly beneath major channel sandstones.

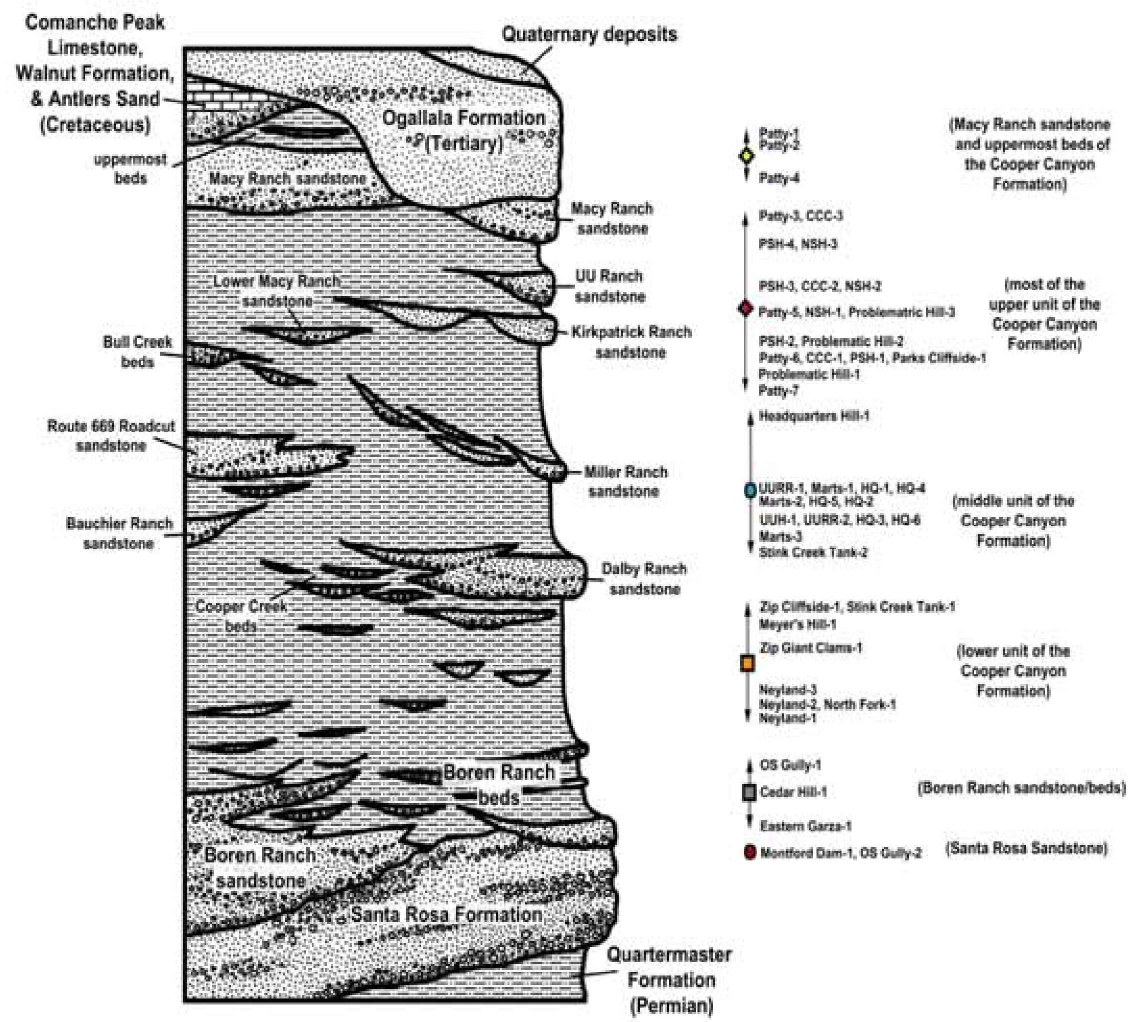


Fig. 3.1. Stratigraphic column of the Dockum Group of southern Garza County showing the stratigraphic distribution of geochemical samples, and the symbols used to represent stratigraphic intervals of samples in the text.

There are two particularly unfortunate limitations of this study compared to previous work. One is the degree of uncertainty in regard to the precise superpositional order of samples (Fig. 3.1). While most previous chemostratigraphic studies have relied on well cores, in which determining the superpositional order of samples is fairly straightforward, the current study used samples from disparate outcrops spread throughout the study area. It was therefore necessary to rely on lithostratigraphic correlation and mapping to place the samples in a superpositional sequence. Although I am broadly confident of the lithostratigraphic scheme established in Chapter 2, the Dockum Group nonetheless represents a complex fluvial depositional system. Fig. 3.1, which attempts to combine all mudstone samples into a composite lithostratigraphic section, probably has some margin of error with regard to their exact superpositional order. In particular, it may be that samples from the middle unit of the Cooper Canyon Formation are slightly out of order due to the complex and discontinuous nature of the Miller Ranch sandstone. Only more detailed mapping and correlation will make the superpositional placement of mudstone samples (and vertebrate localities) across the study area more robust and precise.

Another limitation of the current study mandated by time and economy is the relatively sparse stratigraphic sample density compared to that of previous workers. Ehrenberg and Siring (1992, fig. 3), for example, collected about 3-10 samples per 10 m, and Pearce and Jarvis (1992) used intervals of only 1-80 cm. However, such sample density would have been uneconomical for the current study. Only 47 samples were analyzed, and even in the composite section (Fig. 3.1) samples are usually spaced out vertically by at least several meters. As a result, stratigraphic resolution may be expected to be somewhat coarser than would be possible with more densely-spaced samples.

Sample Preparation and ICP-ES analysis

After collection, the samples were first reduced to a fine powder in a shatterbox. Then 0.20000 +/- 0.0002 g of each sample was mixed in a clean graphite crucible with 1.2000 +/- 0.0012 g of $LiBO_2$ (lithium metaborate), which served as a flux in order to lower the melting point of the sample. The samples were placed in a muffle furnace set to 1000° C and left for 20 minutes, during which time the powdered sample and flux melted. The melted samples were removed from the muffle furnace and poured into a 250 ml glass beaker containing 80 ml of a 5% HCl solution and stirred for 15-20 minutes in order to completely dissolve the sample. Each sample was transferred to a labeled 125 ml polypropylene wide-mouth bottle. These solutions were used for trace element analysis (Ni, Cu, Zn, Sc, V, Cr, Nb, Sr, Ba, Zr, Y). Major element analysis (Si, Ti, Al, Fe, Mg, Mn, Ca, Na, K, P, and also reruns of Sr, Ba, Zr, Y) requires a more dilute solution. The major element solution consists of 20 ml from the trace element solution added to 40 ml of 5% HCl in a 125 ml polypropylene wide-mouth bottle resulting in a solution that it 1/3 the concentration of the original trace element solution.

The dissolved samples were then analyzed by Inductively Coupled Plasma Emission Spectrometry (ICP –ES, also ICP-AES or ICP-OES; see Rollinson, 1993 for a discussion of this procedure). The Dockum Group B) samples were analyzed with standards (Appendix B) which were used to detect drift in the instrument. The in-house standards used were previously characterized by external laboratories using USGS standards, and several (RGMT, TMS, GSPT, MHA) are also recollections of USGS standards. BCM is a standard developed at the TTU Department of Geosciences. Data reduction used the analyzed values for these standards to calculate the degree of drift in the instrument in order to determine accurate concentrations for trace elements (in ppm) and major elements (in wt%) for the Dockum Group samples.

Data Analysis

Data were obtained for twenty-two major and trace elements (Appendix 2). Particular attention was paid, especially in the bivariate analyses, to the major oxides Al_2O_3 and TiO_2, and to the trace elements Zr and Y. These elements are relatively immobile, so their distribution is more likely to reflect their original stratigraphic distribution than that of the mobile elements, whose distributions may be largely a function of post-depositional diagenesis. This is especially true for Fe_2O_3 and CaO, both of which are clearly subject to strong pedogenic alteration in the Dockum Group red beds, due to redox processes (in the case of Fe_2O_3) and being remobilized to form calcium carbonate nodules and cement (in the case of CaO) (e.g. Turner, 1980; Frehlier, 1987). For some elements, particularly Ni and Be, and (for the Santa Rosa Sandstone samples) P_2O_5, many samples did not yield reliable values. Values for Sr, Ba, Zr, and Y are unavailable for the samples from the Tecovas Formation of Palo Duro Canyon.

For both multivariate and bivariate analyses, the samples were divided according to stratigraphic unit (Fig. 3.1): the Santa Rosa Sandstone (n = 2), Boren Ranch sandstone/beds (n = 3), lower unit (n = 8), middle unit (n = 14), and upper unit of the Cooper Canyon Formation. Samples for the latter divided into samples below the Macy Ranch sandstone (n = 18), and from the Macy Ranch sandstone and uppermost Cooper Canyon Formation (n = 3); these last three samples all came from the Patricia Site.

Bivariate Plots

For twenty-two major and trace elements, there are 261 possible pairwise combinations that might be graphed for bivariate plots. In order to reduce this to a more manageable number, it was decided to focus on bivariate plots using the immobile major oxides and trace elements Al_2O_3, TiO_2, Zr and Y. Individual pairs of major and trace elements were plotted against each other after converting the values to moles, in order to look for clusters of stratigraphically associated samples. Plots were also created for which the values in moles were divided by the values in moles for Al_2O_3, in order to normalize the data relative to the clay fraction.

Although, as already discussed, attempts were made to only collect mudstone samples in order to remove the impact of grain-size variability on mineralogy, these samples vary compositionally between claystone and siltstone, some contain a fair amount of sand, and a few are even muddy sandstones. It is therefore conceivable that bivariate plots which seem to show good *stratigraphic* separation of samples may be biased by grain size if the grain size of samples shows stratigraphic variation. A few additional bivariate plots were performed for the immobile elements listed above in order to determine if these differences in grain size influences major and trace element distributions, particularly in a way which parallels stratigraphic separation.

The bivariate plots are being used to look for *clusters* of data representing stratigraphically associated samples. Therefore correlation matrixes and regressions, which look specifically for *linear* relationships between variables, were not utilized. The fact that linear relationships between variables are not particularly relevant also means that the possibility of spurious correlations in bivariate plots when both elements are normalized to Al_2O_3 is not a concern.

Multivariate Plots

Multivariate analyses, specifically principal component analysis (PCA) and discriminant analysis, were conducted using Matlab with the assistance of Dr. Richard Strauss of the Department of Biological Sciences at TTU. As with the bivariate plots, PCA can be used as an exploratory analysis to determine if the major and trace element concentrations of mudstone samples cluster in a stratigraphically meaningful way. However, unlike bivariate analyses, which only consider two variables at a time (in this case, elements), PCA condenses all variables into a series of linear principal components which re-express total variation. The first two principal components (which account for the two largest percentages of the total variation) may be plotted like the bivariate graphs, but encompass all variables instead of only two. However, missing values for variables are a more serious problem for PCA than for bivariate plots, and requires that samples with a large number of missing values, and/or that the variables lacking values for a large number of samples, be removed.

Before conducting a PCA, the data are converted to a covariance matrix or a correlation matrix, which differ in how they treat variation within the sample set. A covariance matrix considers *absolute* variation within a sample set, while a correlation matrix considers *relative* variation. If values for some variables in a sample set are significantly smaller than for other variables, converting the data to a covariance matrix will emphasize those differences, allowing the variables with the higher values to "swamp out" the variables with smaller values. Consequently, the first two principal components will primarily represent variation for variables with higher values. However, converting the same data to a correlation matrix will "equalize" the variables by emphasizing how high and low values vary relative to *each other*, and the first two principal components therefore give more equal representation to all variables.

In the current study, where major and trace element values are all converted to moles, the trace elements generally have much lower values than the major elements. Consequently, the first two principal components for the data converted to a *covariance* matrix will tend to emphasize the major elements, while a *correlation* matrix will give more equal representation to all variables. It was decided to convert the sample set to a covariance matrix when possible, but I chose to use alternative methods of equalizing variation, specifically log transformation and normalization to an outside standard, to prevent any useful stratigraphic signals in the trace element values from being swamped out by the major elements.

As PCA uses all values for all variables, it is extremely sensitive to missing data, and it was necessary to remove samples which lack values. In the first analysis, in which the data were log-transformed, samples Montford Dam-1, OSG-2 (both from the Santa Rosa Sandstone), and the Palo Duro Canyon samples (all samples from the Tecovas Formation) were removed. Although this removes all samples for two lithostratigraphic units, it allowed the PCA to focus on variation within the Cooper Canyon Formation, which is where chemostratigraphic resolution was found to be most problematic (at least for the middle and upper units of the Cooper Canyon Formation) in the bivariate plots (see below). The trace elements Ni and Be were also eliminated, as they lack values for many of the remaining samples.

A second PCA, also using data log-transformed and converted to a covariance matrix, included samples from the Santa Rosa Sandstone and Tecovas Formation, so that they could be compared with the Boren Ranch sandstone/beds and Cooper Canyon Formation. As all samples were included, even those missing data for particular variables, it was necessary instead to remove all *variables* for which data was missing: P_2O_5, Sr, Ba, Zr, Y, Ni, and Be.

Instead of log-transformation, the third PCA used normalization to the North American Shale Composite (NASC) using the values obtained from Condie et al. (1993) (Appendix 2). Condie et al. (1993) unfortunately did not provide values for MnO, Cu, Zn, and Be, requiring that these variables not be used, and Ni was also removed due to lack of usable values for several samples. This PCA used the same sample set as the first, removing samples from the Santa Rosa Sandstone and Tecovas Formation, as well as samples Patty-3 and Problematic Hill-1 from the Cooper Canyon Formation. As normalization removes scale information, which is required for using a covariance matrix, this analysis was converted to a correlation matrix.

Discriminant Analysis is a slightly different multivariate technique that starts with *pre-identified* groups (in this case, different stratigraphic units), and then determines which variables are best at discriminating them. Similar to PCA, which condenses values for all variables onto principal components, discriminant analysis condenses variables onto discriminant functions, which can also be plotted on two-dimensional graphs. As the primary goal of this study is to *determine* whether or not major and trace elements cluster in stratigraphically meaningful ways, discriminant analysis is less useful, as it *assumes* the groups identified can be distinguished to begin with, and simply establishes the best way of doing so. However, the discriminant analyses may help determine which elements are most useful for distinguishing established lithostratigraphic units. Discriminant analyses were conducted for each of same data sets used for the four PCAs.

Each PCA and discriminant analysis is accompanied by vector plots made using a function designed for Matlab by Dr. Strauss. These vector plots are intended to be directly compared to the accompanying PCA and discriminant analysis graphs, and show how particular variables contribute to the separation of different samples. The plots show each variable as an arrow pointing in the direction of samples for which values for that element were particularly high, and the length of the arrow corresponds to how important that element is for separating samples in that direction. The vector plots are what allow the importance of particular elements in separating samples based on stratigraphy to be evaluated.

Provenance Discriminant Function Plots

As the bulk geochemical content of clastic sediments is primarily a function of source rocks, sorting during transport, and the diagenetic effects of particular tectonic environment of deposition (Siever, 1979; Roser and Korsch, 1986), it can be used to determine the provenance and tectonic environments of deposition of clastic sedimentary rocks. I decided to apply the bulk geochemical composition of the Dockum Group mudstones to previously established discriminant plots for determining tectonic environments and provenance, in order to compare the results with previous provenance studies for Dockum Group sandstones based on petrology and paleocurrent data (e.g. Riggs et al., 1993; Long and Lehman, 1993, 1994; Lehman et al., unpublished). I chose the discriminant plots of Roser and Korsch (1986, 1988) to plot the Dockum Group samples for the following reasons:

1. The samples collected from the Dockum Group were mostly mudstones, but studies using bulk geochemical data to determine provenance and tectonic environment often rely on sandstones (e.g. Valloni and Maynard, 1981; Bhatia, 1983; Bhatia and Crook, 1986), and those of Roser and Korsch (1986, 1988) are some of the few to incorporate mudstone data. Although geochemical content in sediments varies strongly as a function of grain size (Ingersoll et al., 1984; Roser and Korsch, 1985), Maynard et al. (1982) and Roser and Korsch (1986, 1988) demonstrated that mudstones show as much systematic variation with regard to provenance and tectonic environment as sandstones, and they were therefore able to combine bulk geochemical data from both sandstones and mudstones in their discrimination plots.
2. Although effort was made to only collect the finest-grained mudstones from each section sampled, some samples consist largely of sand. This makes the discriminant plot of Roser and Korsch (1986, 1988) which encompass a variety of grain sizes, especially valuable, as it eliminates the need to do separate plots for samples based on grain size.

Roser and Korsch (1986) used plots of SiO_2 wt% vs. K_2O/Na_2O in order to discriminate marine sandstone-mudstone suites deposited in different tectonic environments. The data for these plots were taken from bulk geochemical analyses of ancient depositional systems from around the world, but tested using data from modern sediments and ancient sedimentary terranes in New Zealand. Roser and Korsch (1986, pp. 637-638) were able to distinguish samples from three different tectonic environments of deposition, although the composition of the samples is of course also strongly dependant on provenance. These tectonic environments exhibit a general trend of decreasing SiO_2 wt%, and also a decreasing K_2O/Na_2O ratio:

1. Passive continental margins (PM): “Mineralogically mature (quartz-rich) sediments deposited in plate interiors at stable continental margins or intracratonic basins.” These sediments are deposited away from active plate boundaries, and include sediments recycled from older quartz-rich sedimentary deposits.
2. Active continental margins (ACM): “Quartz-intermediate sediments derived from tectonically active continental margins on or adjacent to active plate boundaries.” These sediments include those derived from continental magmatic arcs and uplifted areas associated with strike-slip faults, and deposited into trenches and other basins associated with continental arcs (forearc, intraarc, and backarc basins), and strike-slip pull-apart basins.
3. Oceanic Island Arc (ARC): “Quartz-poor volcanogenic sediments derived from oceanic island arcs.” These are sediments derived from primarily andesitic arcs, and deposited in similar types of associated basins as with the ACM sediments.

Roser and Korsch (1988) extended their previous work by examining sandstone-mudstone suites derived from four different provenance groups (pp. 120-122), based largely on the same ancient New Zealand terranes used by Roser and Korsch (1986), and tested using a variety of ancient igneous source rocks and sedimentary suites with established provenance (mostly based on sandstone petrology). Note that the provenance groups are ordered roughly in the opposite order in terms of associated tectonic environments of deposition as the categories of Roser and Korsch (1986) just listed:

1. “Primarily mafic and lesser intermediate igneous provenance” (P1). Sediments were probably derived ultimately from a tholeiitic to calc-alkaline oceanic island arc. The sandstones are composed of mafic to intermediate volcanic lithic fragments, plagioclase and mafic minerals.
2. “Primarily intermediate igneous provenance” (P2). The sediments were probably derived from an intermediate volcanic arc. The sandstone clasts are mostly andesitic, though some are dacite, rhyolite, and trachyte.
3. “Felsic igneous provenance (volcanic and plutonic)” (P3). Sediments were probably derived from silicic plutonic and metamorphic rocks, and to a lesser extent intermediate volcanic rocks, of a continental volcanic arc. The sandstones are greywackes (quartzofeldspathic).
4. “Quartzose sediments of mature continental provenance” (P4). Sediments probably derived from re-working of older sediments in the continental interior. The sandstones are extremely quartz-rich with relatively little feldspar or lithic fragments.

Roser and Korsch (1988) ran two different discrimination plots for their sample sets. The first set of discriminant plots used the following formulas for the two discriminant functions, with the SiO_2 and CaO content of the samples incorporated into the formulas:

$$DF1 = -1.773TiO_2 + 0.607Al_2O_3 + 0.76Fe_2O_3 + -1.5MgO + 0.616CaO + 0.509Na_2O – 1.224K_2O – 9.09$$

$$DF2 = 0.445TiO_2 + 0.07Al_2O_3 – 0.25Fe_2O_3 - 1.142MgO + 0.438 CaO + 1.475Na_2O + 1.426K_2O - 6.861$$

The second pair of discriminant functions were intended to remove the influence of biogenic sediments by removing SiO_2 and CaO from the formulas. TiO_2, Fe_2O_3, MgO, Na_2O, and K_2O, were also normalized in the discriminant functions to Al_2O_3:

$DF1 = 30.638TiO_2/Al_2O_3 – 12.541Fe_2O_3/Al_2O_3 + 7.329MgO/Al_2O_3 + 12.031Na_2O/Al_2O_3 + 35.402K_2O/Al_2O_3 – 6.382$

$DF2 = 56.500TiO_2/Al_2O_3 – 10.879Fe_2O_3/Al_2O_3 + 30.875MgO/Al_2O_3 - 5.404Na_2O/Al_2O_3 + 11.112K_2O/ Al_2O_3 – 3.89$

$CaCO_3$ is an extremely common diagenetic cement in sandstones of the Dockum Group, and is also subject to diagenetic remobilization in overbank mudstones (e.g. Frehlier, 1987; May, 1988; Fritz, 1992), so its distribution in the Cooper Canyon Formation, Boren Ranch Sandstone/beds, Santa Rosa Sandstone, and Tecovas Formation is likely to represent diagenesis rather than original detrietal mineralogy.

Results

Bivariate Plots

Only a handful of the bivariate plots using the immobile oxides and trace elements Al_2O_3 (Figs. 3.2-3.4), TiO_2 (Figs. 3.5-3.8), Zr (Figs. 3.3, 3.9-3.11), Y (Figs. 3.7, 3.11-3.12), and K (Figs. 3.2, 3.5), in which samples were grouped together according to stratigraphic position, are shown. The summarize, there is a strong indication of stratigraphic variation for many of the major and trace elements, although it seems doubtful that chemostratigraphy can yield a degree of stratigraphic resolution as high, or higher, than possible through lithostratigraphy. There are usually broad overlaps between samples from different stratigraphic units. In most cases the middle and upper units of the Cooper Canyon Formation have overlaps so broad that distinguishing or subdividing them chemically seems unlikely (e.g. Figs. 3.3-3.4, 3.7, 3.9, 3.11), at least with the current data set. However, the lower unit of the Cooper Canyon Formation and Boren

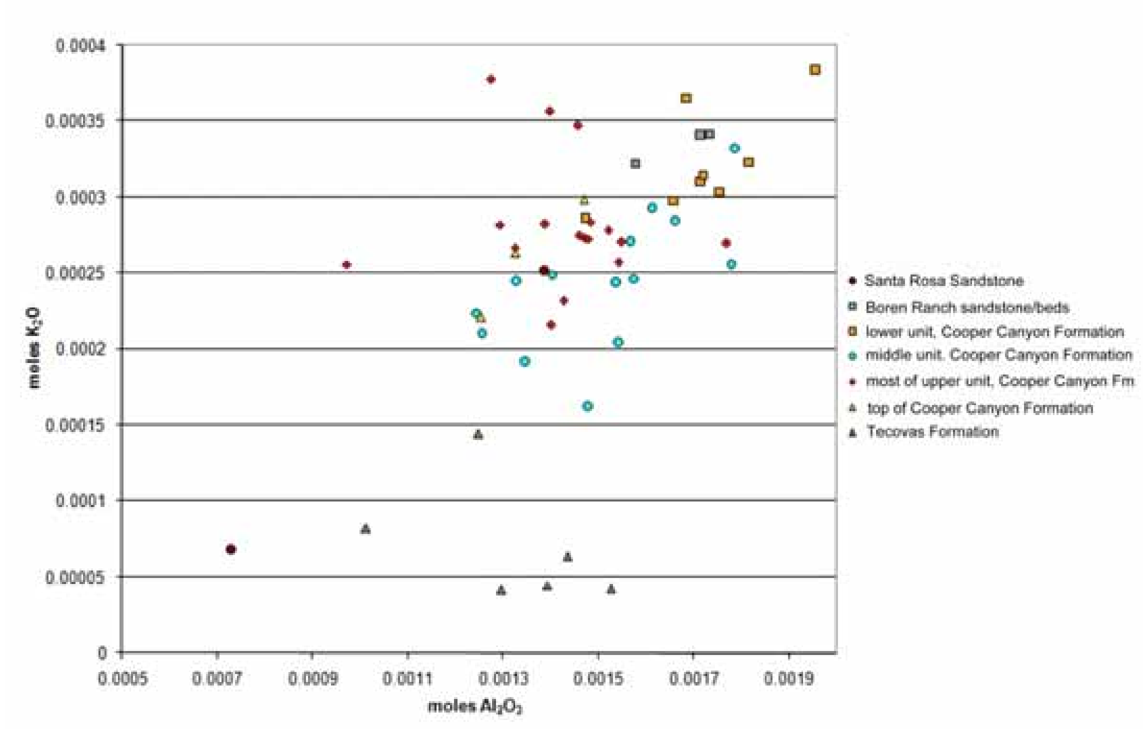


Fig. 3.2. Bivariate plot of moles K_2O vs. moles Al_2O_3, without normalization.

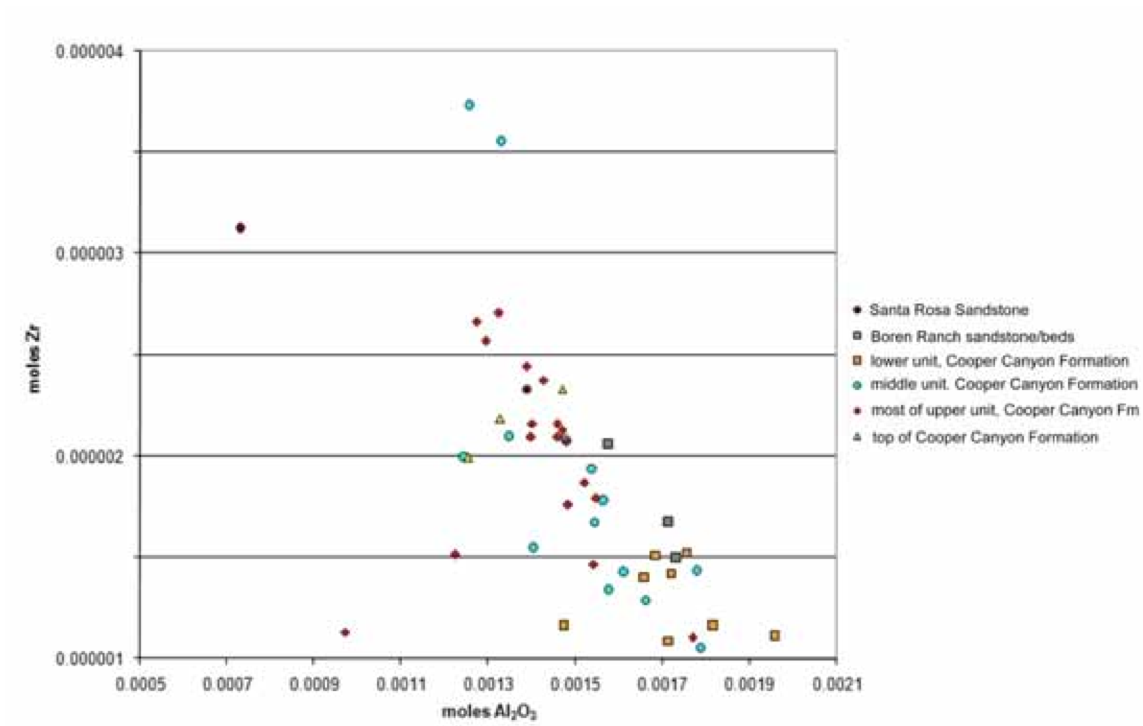


Fig. 3.3. Bivariate plot of moles Zr vs. moles Al_2O_3, without normalization.

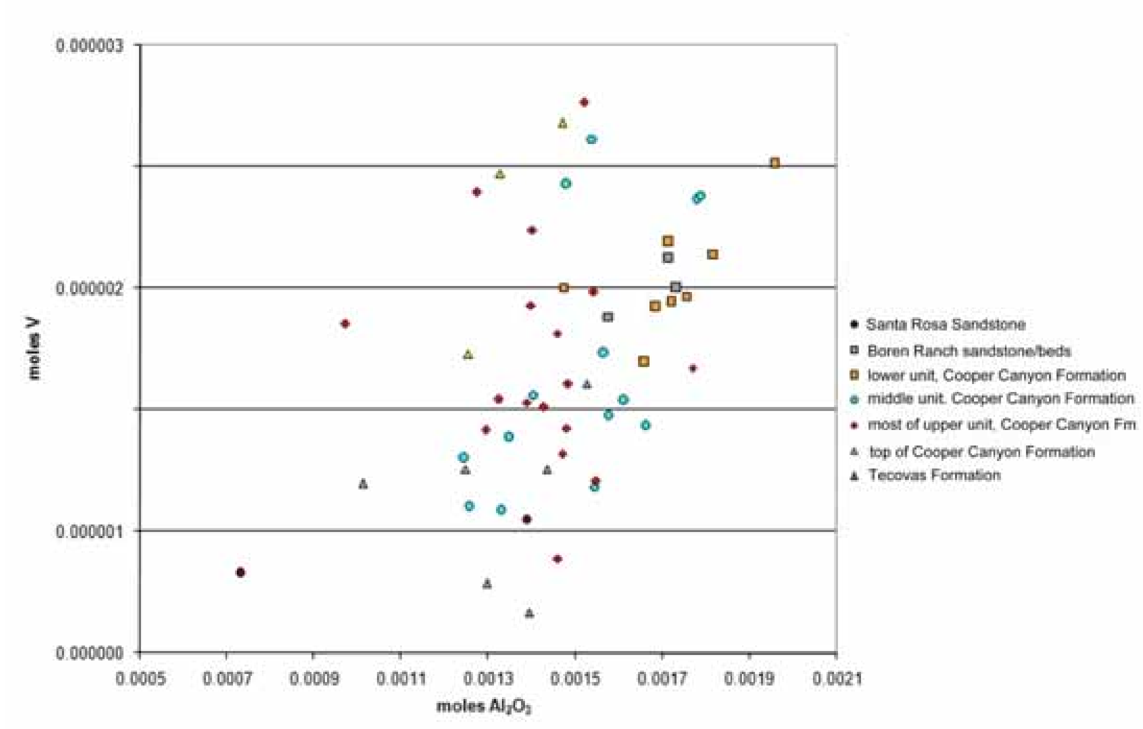


Fig. 3.4. Bivariate plot of moles V vs. moles Al_2O_3, without normalization.

Ranch sandstone/beds samples often cluster tightly together (albeit within the range of variation of the other samples; Figs. 3.2-3.12), and some element plots (particularly ones normalized to Al_2O_3) *do* provide some degree of separation between different parts of the Cooper Canyon Formation (e.g. Figs. 3.5b, 3.6b, 3.8b, 3.10, 3.12). The Palo Duro Canyon Tecovas Formation samples show a very interesting and consistent pattern of clustering which separates them from the Garza County samples, especially the lithostratigraphically equivalent lower unit of the Cooper Canyon Formation (Figs. 3.2, 3.4-3.5, 3.8).

The Santa Rosa Sandstone

The number of samples from the Santa Rosa Sandstone is extremely small (only two samples were collected), and moreover these samples are almost always widely

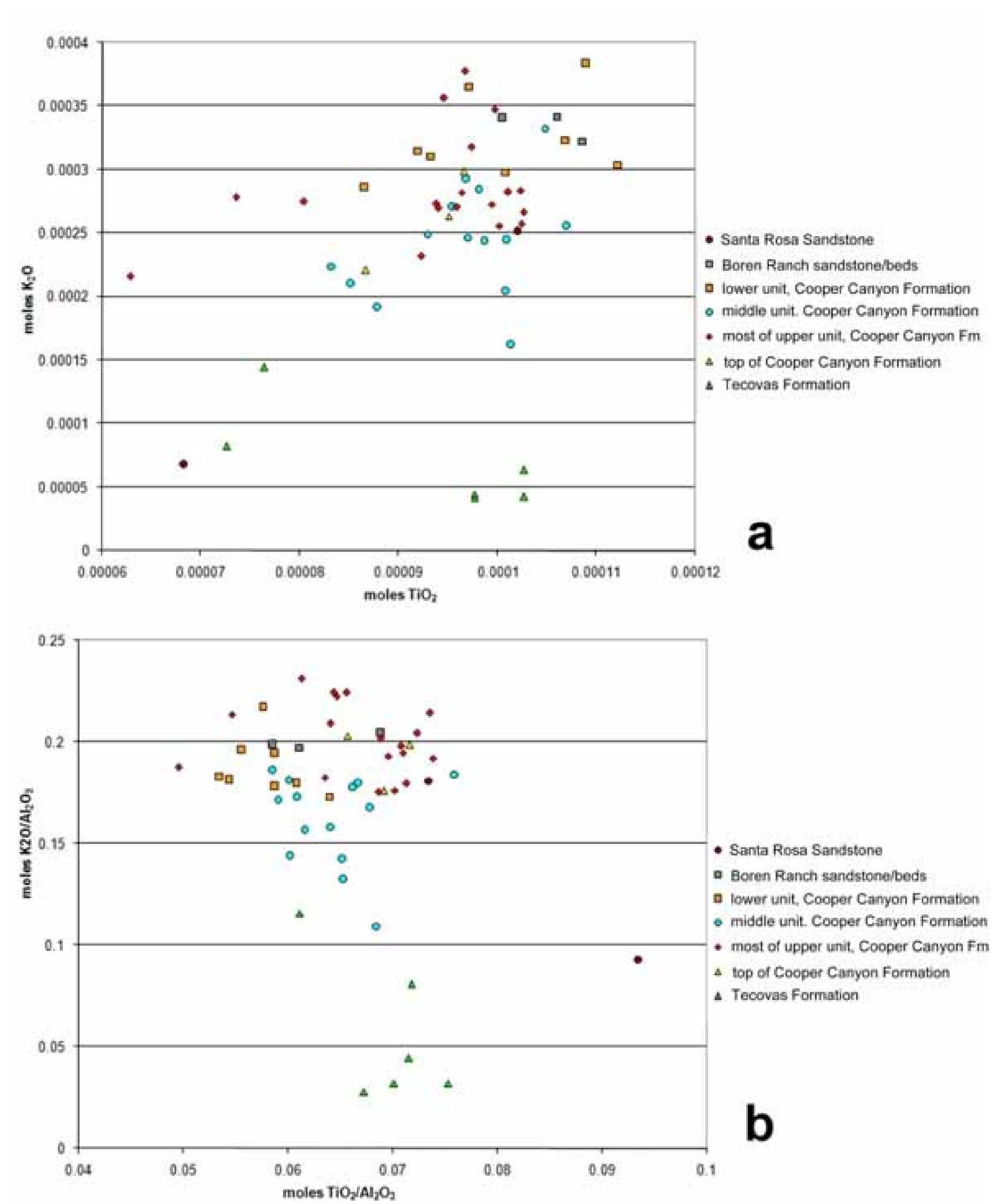


Fig. 3.5. Bivariate plot of moless K_2O vs. moles TiO_2: *a*, without normalization; *b*, normalized to moles Al_2O_3.

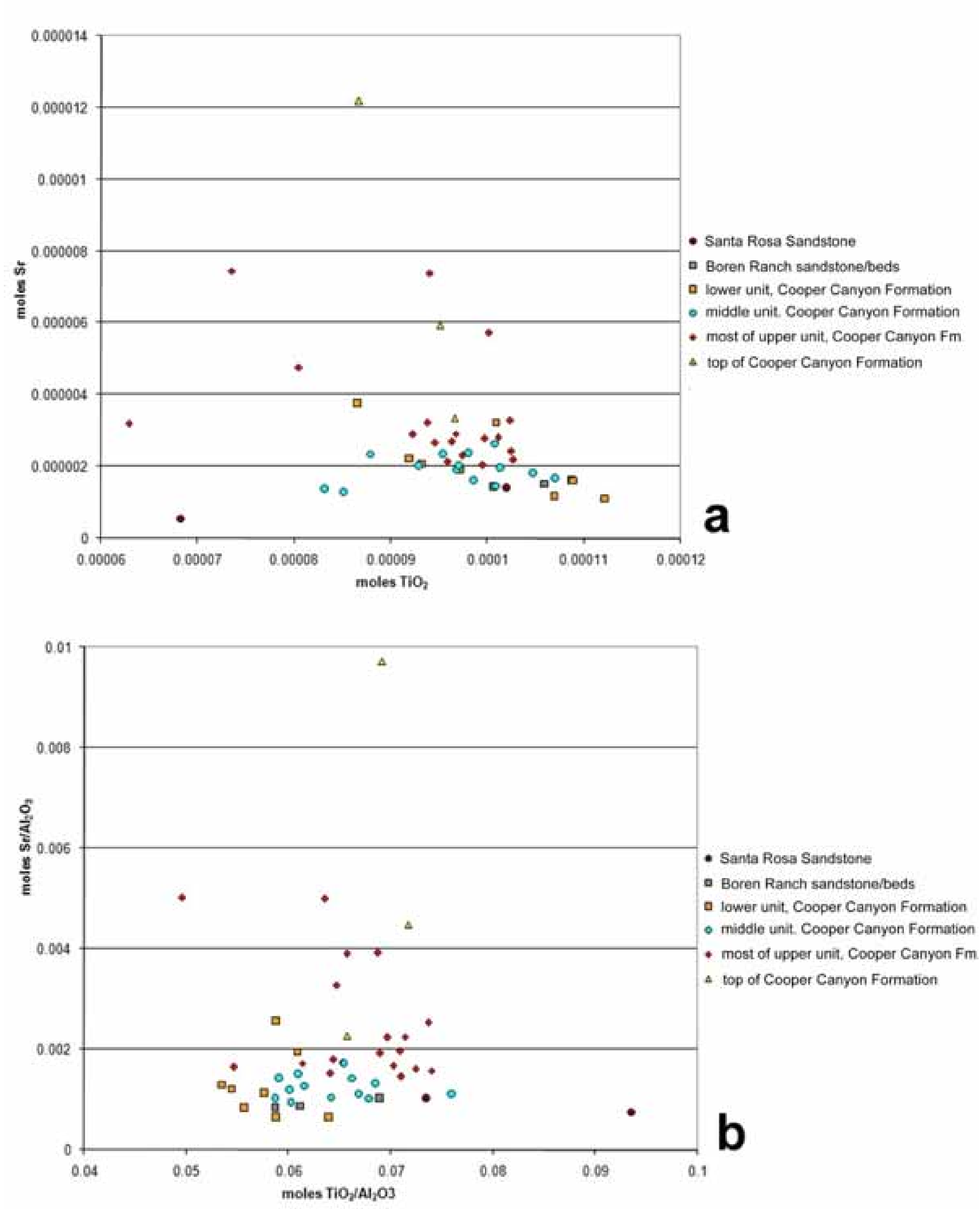


Fig. 3.6. Bivariate plots of moles Sr vs. moles TiO_2: *a*, without normalization; *b*, normalized to moles Al_2O_3.

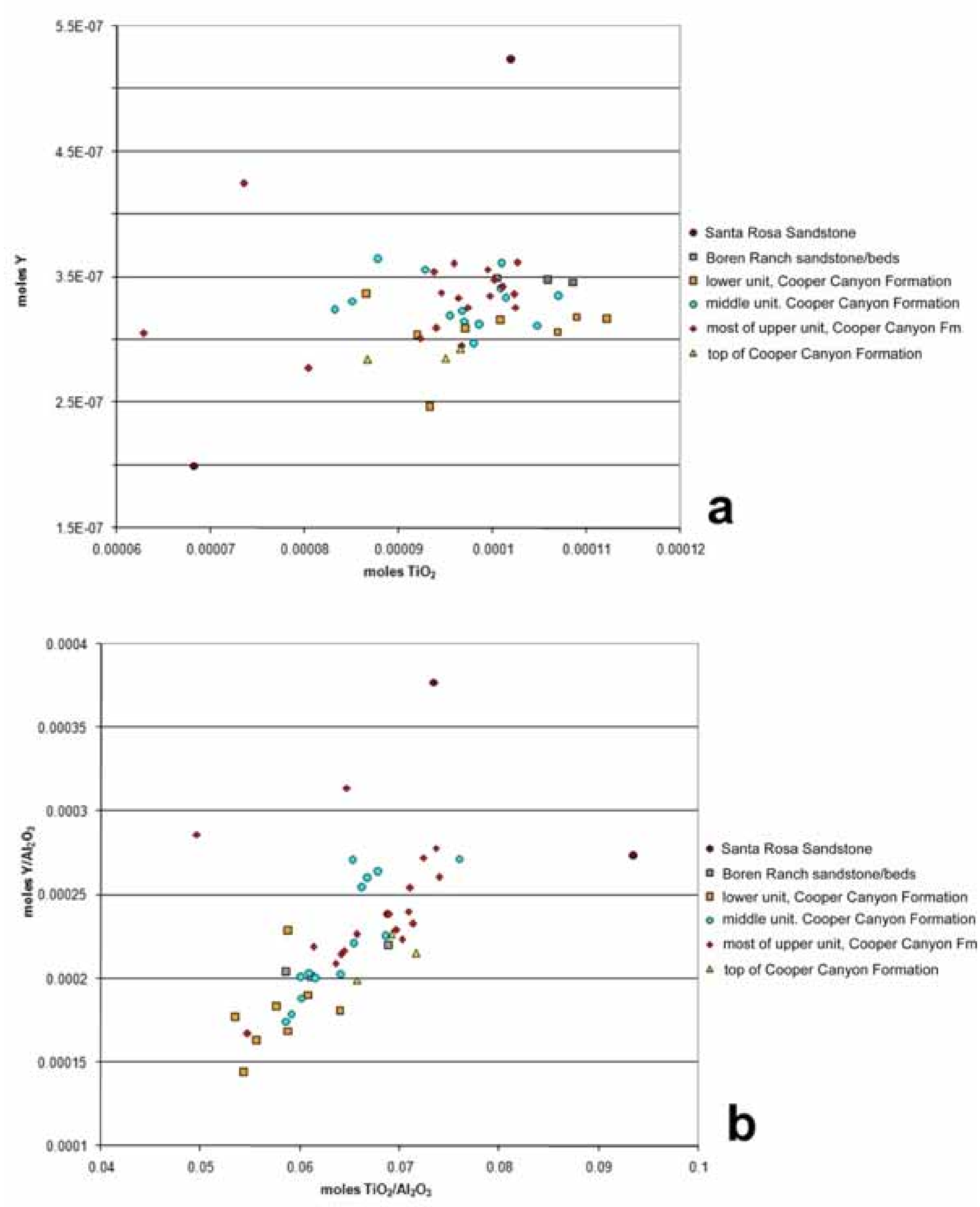


Fig. 3.7. Bivariate plots of moles Y vs. moles TiO_2: *a*, without normalization; *b*, normalized to moles Al_2O_3.

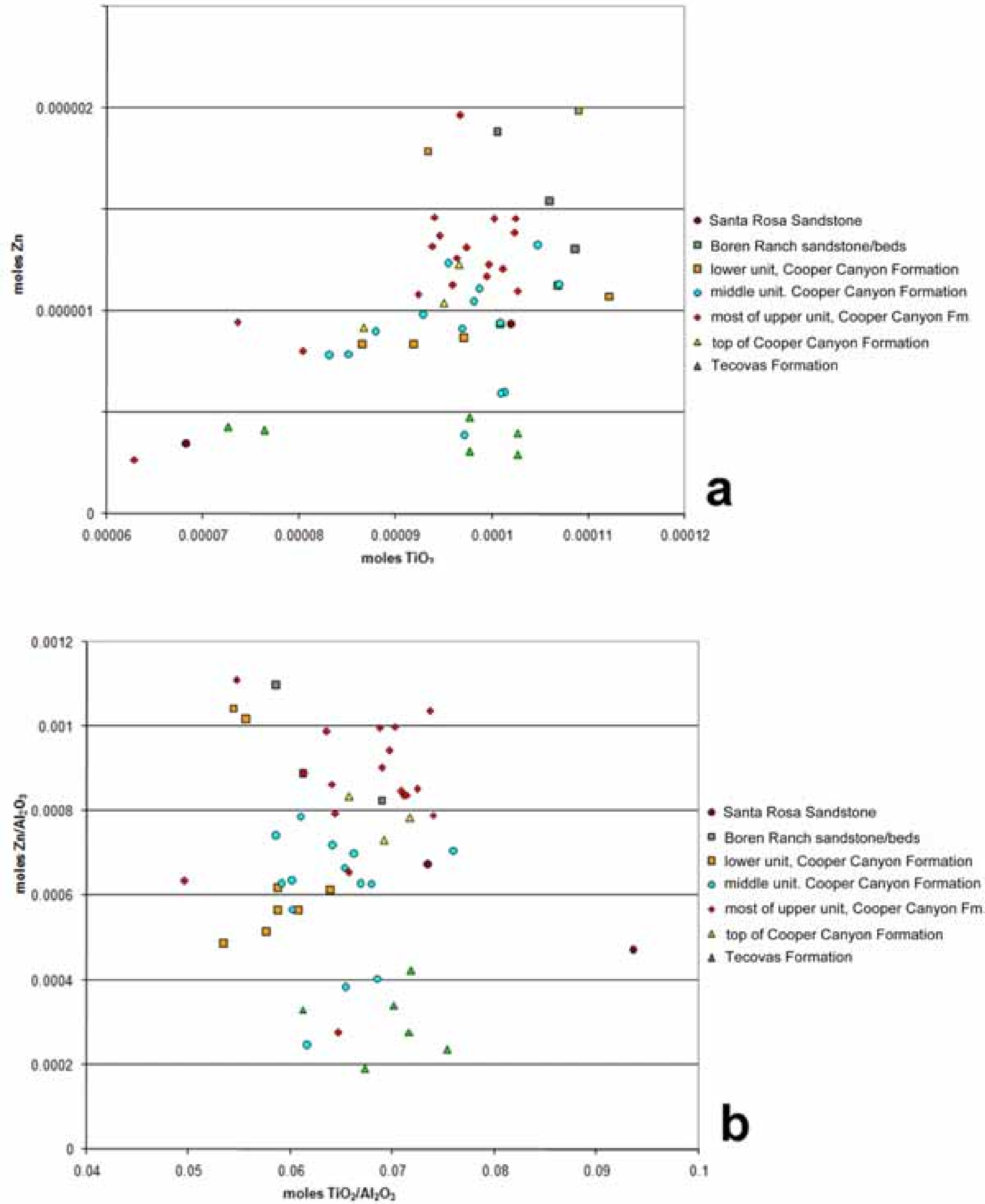


Fig. 3.8. Bivariate plots of moles Zn vs. moles TiO_2: *a*, without normalization; *b*, normalized to moles Al_2O_3.

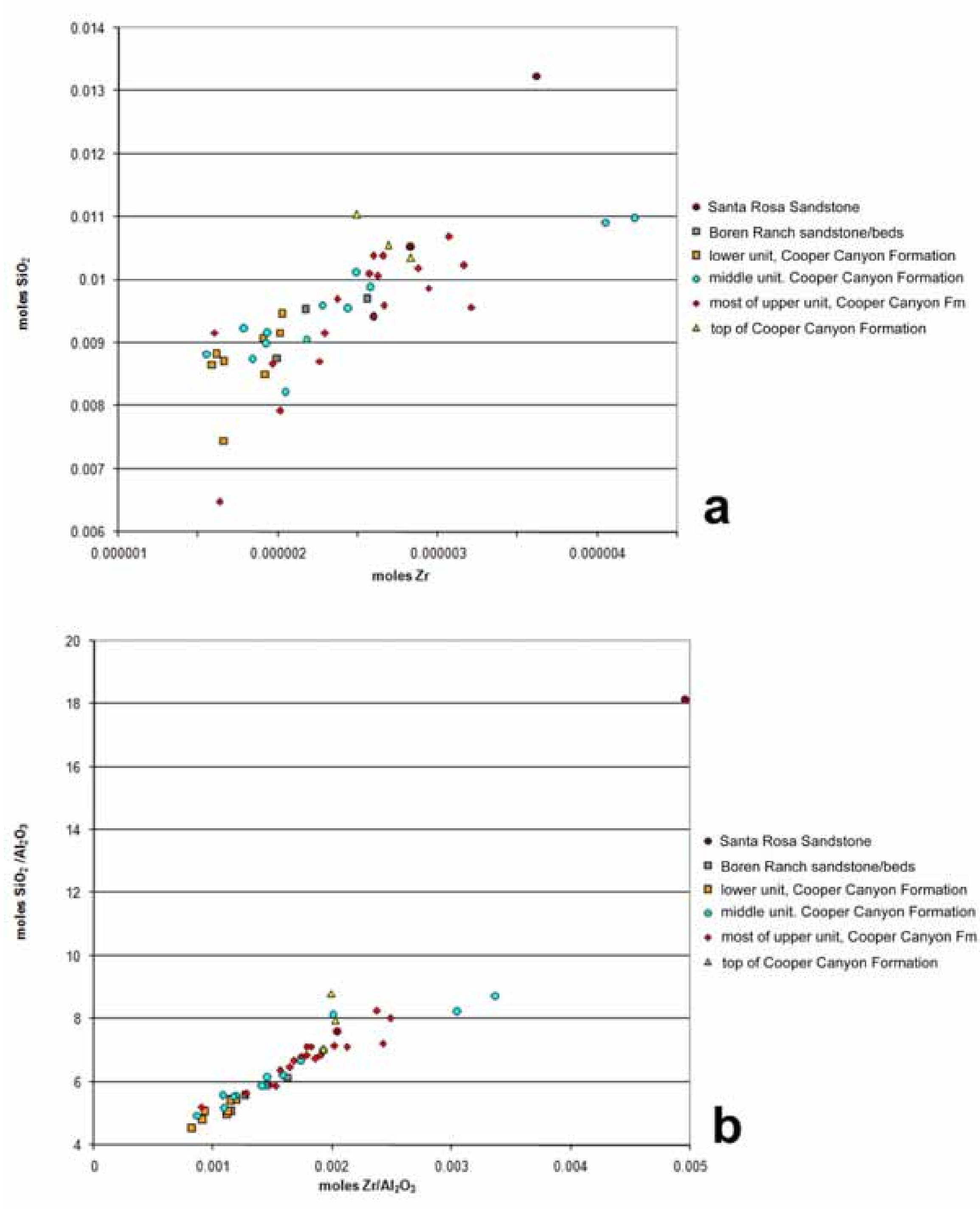


Fig. 3.9. Bivariate plots of moles SiO_2 vs. moles Zr: *a*, without normalization; *b*, normalized to moles Al_2O_3.

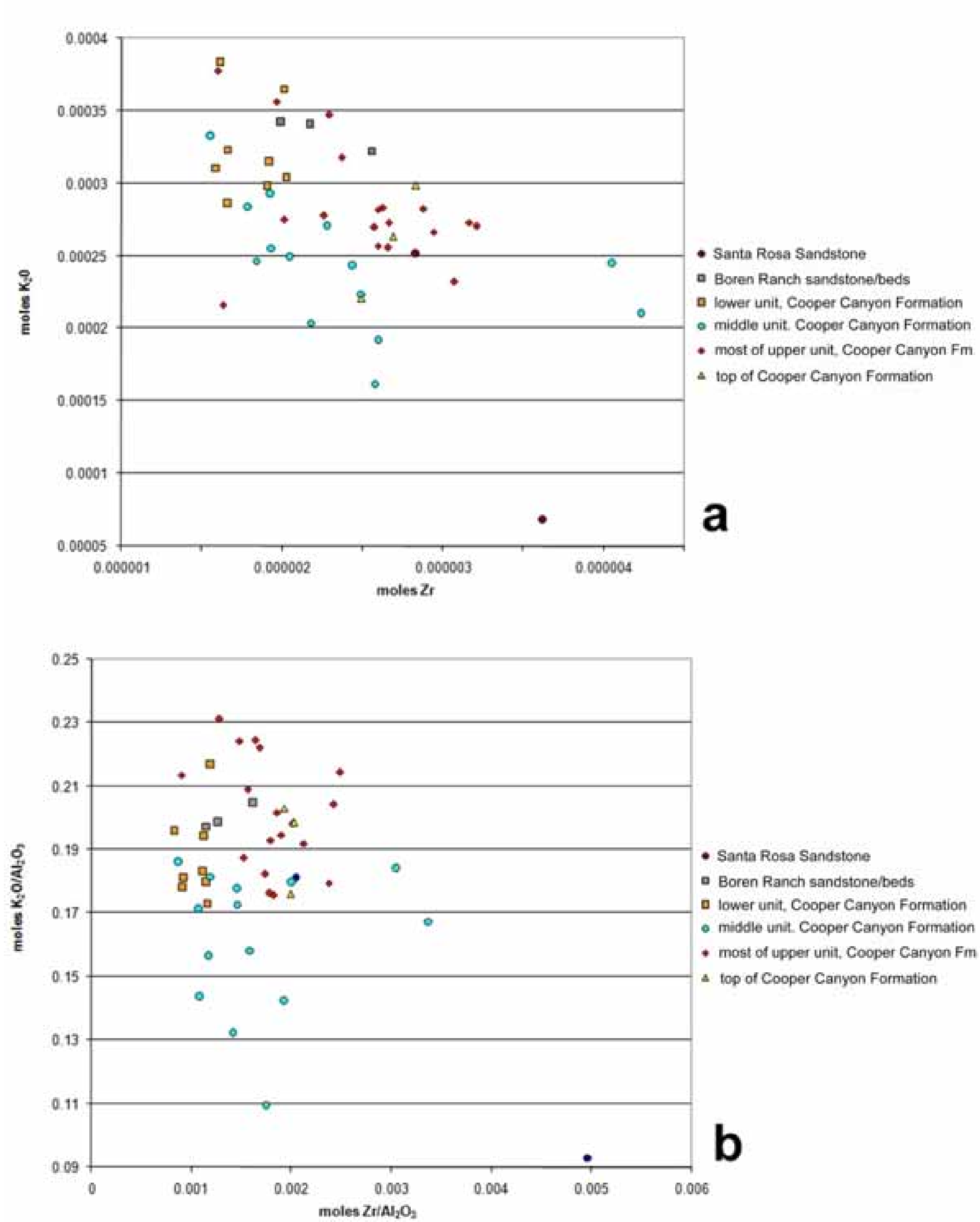


Fig. 3.10. Bivariate plots of moles K_2O vs. moles Zr: *a,* without normalization; *b,* normalized to moles Al_2O_3.

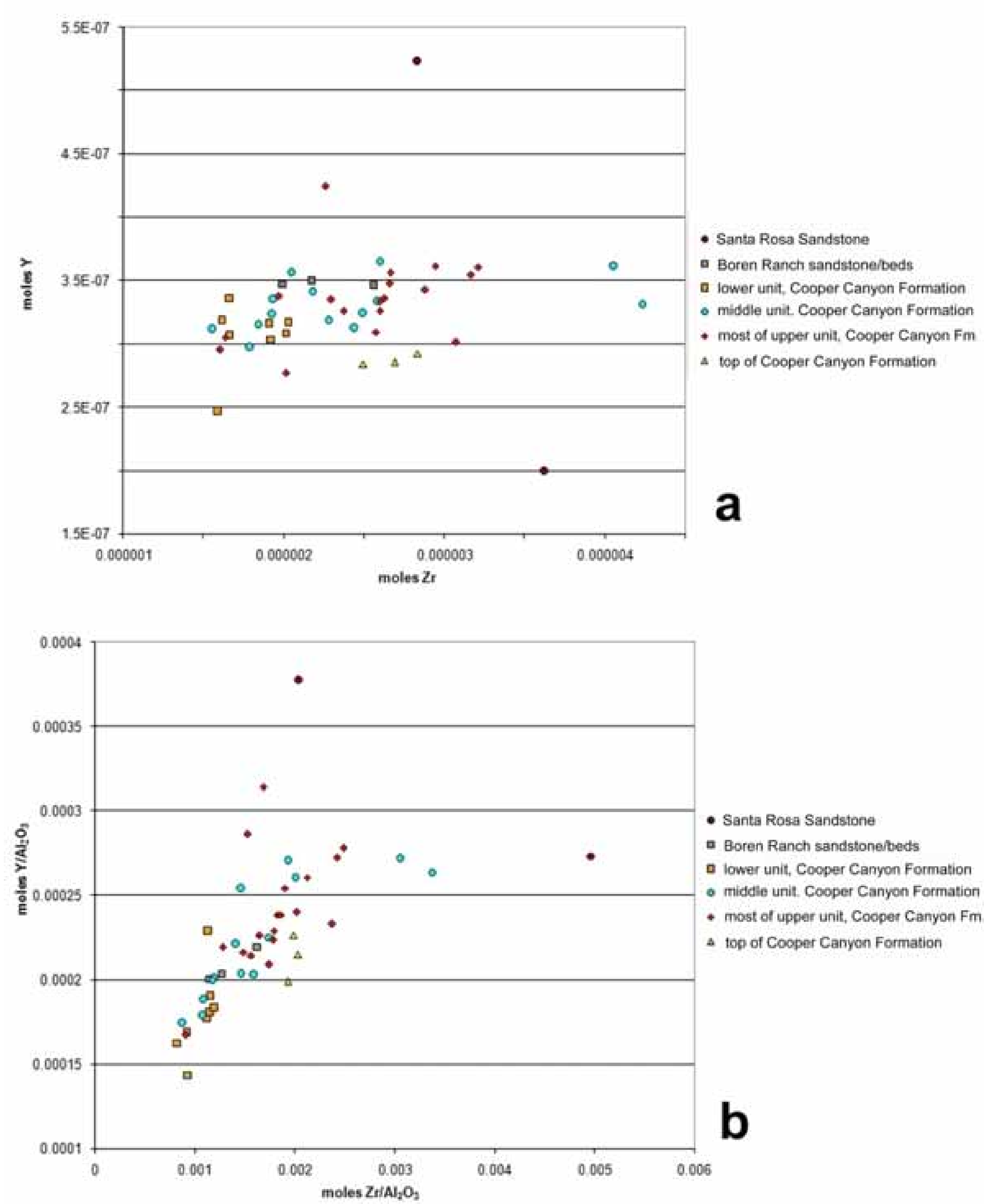


Fig. 3.11. Bivariate plots of moles Y vs. moles Zr: *a*, without normalization; *b*, normalized to moles Al_2O_3.

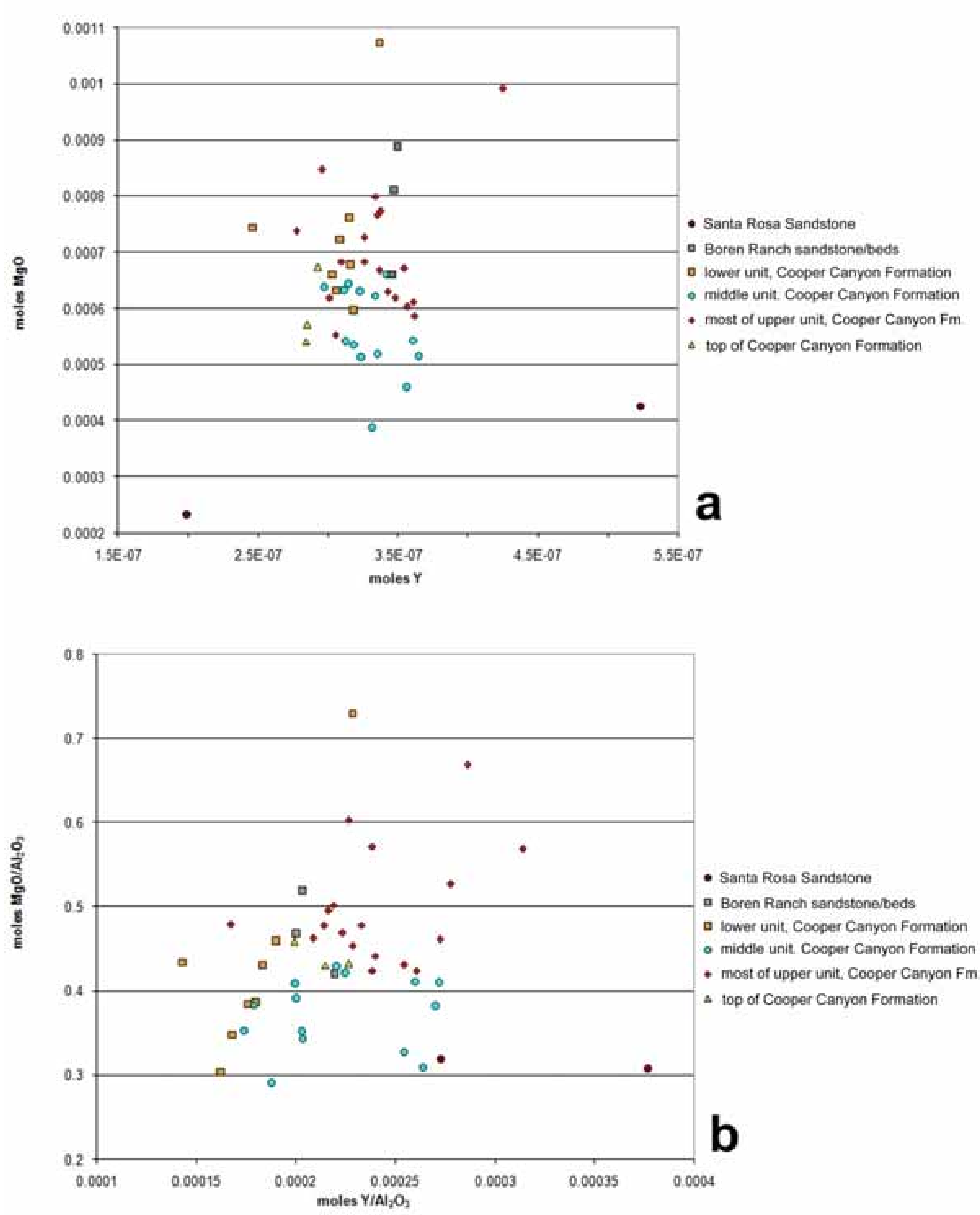


Fig. 3.12. Bivariate plots of moles MgO vs. moles Y: *a,* without normalization; *b,* normalized to moles Al_2O_3.

separated in bivariate plots rather than clustering together. It should also be considered that mudstones in the Santa Rosa Sandstone, which has a strongly unconformable lower contact with the underlying Quartermaster Formation, may represent reworking of Permian mudstones. This is particularly true in the case of the OS Ranch Gully sample, which was recovered from a mudstone pocket encased in sandstone probably representing a chunk of reworked overbank deposits.

Nonetheless, both the Santa Rosa mudstone samples share extremely low values for several elements, namely MgO (Fig. 3.12), MnO, CaO, Sr (Fig. 3.6), Nb, and V (Fig. 3.4), and in fact have the lowest values for these elements, or close to it, among all the samples. SiO_2 and Zr values are somewhat high compared to other samples (Figs. 3.2, 3.9-3.11). This is as might be expected given that the Santa Rosa Sandstone is highly siliceous, contains abundant detrietal zircons, and is derived largely from plutonic igneous source rocks in the Amarillo-Wichita belt (Fritz, 1991; Riggs et al., 1993; Lehman et al., unpublished). However, these SiO_2 and Zr values, although having high values compared to most other samples, are not the highest, and fall well within the range of variation for all samples. This may be due to grain-size fractionation concentrating most SiO_2 and Zr in the sand-sized fraction, a possibility difficult to explore given that both Santa Rosa Sandstone samples are mudstones. The bivariate plot of TiO_2 vs. Y, normalized to Al_2O_3 (Fig. 3.7b), also separates the Santa Rosa Sandstone samples somewhat from the others.

The Boren Ranch Beds

The number of samples for the Boren Ranch sandstone/beds is also quite small (only three), so as with the Santa Rosa Sandstone, generalizations need to be approached with caution. Nonetheless, although they usually lie well within the range of variation for samples from the Cooper Canyon Formation, the Boren Ranch sandstone/beds samples cluster together in several of the bivariate plots, suggesting the values for some elements may occur across a more restricted range. The Boren Ranch sandstone/beds have fairly high values for TiO_2, Al_2O_3, K_2O, Sc, and Zn, and somewhat low values for Sr (Figs. 3.2-

3.11). The samples from the Boren Ranch sandstone/beds also all have a narrow range of values for Na_2O, Y, Cr, Ni, and V (Figs. 3.4, 3.11-3.12).

The Lower Unit of the Cooper Canyon Formation

Like the Boren Ranch sandstone/beds, the samples for the lower unit of the Cooper Canyon Formation usually cluster tightly together within the range of samples from the middle and upper units, and the lower unit and Boren Ranch sandstone/beds also have other similarities in their major and trace element concentrations. The lower unit has relatively high values for Al_2O_3, K_2O, and Sc, and low values for Sr and Zn (Figs. 3.2-3.6, 3.8, 3.10). However, it also has a fairly broad range of values for TiO_2 (Figs. 3.5-3.7) which are therefore useful for discriminating the lower unit from the Boren Ranch sandstone/beds. Al_2O_3 in particular is useful for discriminating the lower unit from other stratigraphic units, both as a variable in bivariate plots, or used for normalizing both variables (Figs. 3.2-3.4, 3.5b-3.12b).

The Middle and Upper Units of the Cooper Canyon Formation

As already noted, the lower and middle units of the Cooper Canyon Formation tend to broadly overlap in terms of their major and trace element concentrations (e.g. Figs. 3.3-3.4, 3.7, 3.9, 3.11), and are usually difficult to discriminate. They also tend to have a broader range of variation for these variables, and more extreme outliers than seen in the lower unit and Boren Ranch sandstone/beds. This is especially true for the upper unit, particularly sample Patty-3, which lies at the upper and lower extremes for many elements.

However, the concentrations of some elements vary slightly between the middle and upper units of the Cooper Canyon Formation. Specifically, some samples in the middle unit have slightly higher Al_2O_3, Fe_2O_3, and Ni, and lower K_2O, MnO, MgO, Zr, Zn, and Ba, than samples from the upper unit. These create a very slight separation between samples from the middle and upper units, although is not clear how statistically significant this slight separation is. However, it is suggestive that some of the plots cluster samples from the lower and middle units of the Cooper Canyon Formation. Specifically, the lower and middle units generally share low Al_2O_3, Zr, Zn, and Sr (Figs. 3.3, 3.8) compared to the upper unit.

However, although some of these plots separate different lithostratigraphic units, finer resolution is apparently not possible. In plots showing slight separation of samples from the middle and upper units of the Cooper Canyon Formation, samples from both units that overlap on the plot are not stratigraphically adjacent. For example, in the plots of MgO vs. Y (Fig. 3.12b), the samples from the lower and middle units of the Cooper Canyon Formation show good separation from each other, but the samples from the two clusters which are closest to each other are not consistently adjacent stratigraphically. This suggests that although there are broad chemostratigraphy differences between the middle and upper units, there is not a distinct chemostratigraphic transition zone.

The samples from the Macy Ranch sandstone and uppermost Cooper Canyon Formation can be slightly separated from other upper unit samples by both normalized and non-normalized plots for Zr vs. Y (Fig. 3.11), though this may actually be a reflection of sample grain size (see below). Other bivariate plots, particularly those using TiO_2, K_2O, MgO, Zn, Y, and Sr, plot these samples from high in the upper unit closely together, although usually within the range of variation of samples from the rest of the upper unit and the middle unit (e.g. Figs. 3.5b, 3.6b, 3.8b, 3.10, 3.12).

Tecovas Formation

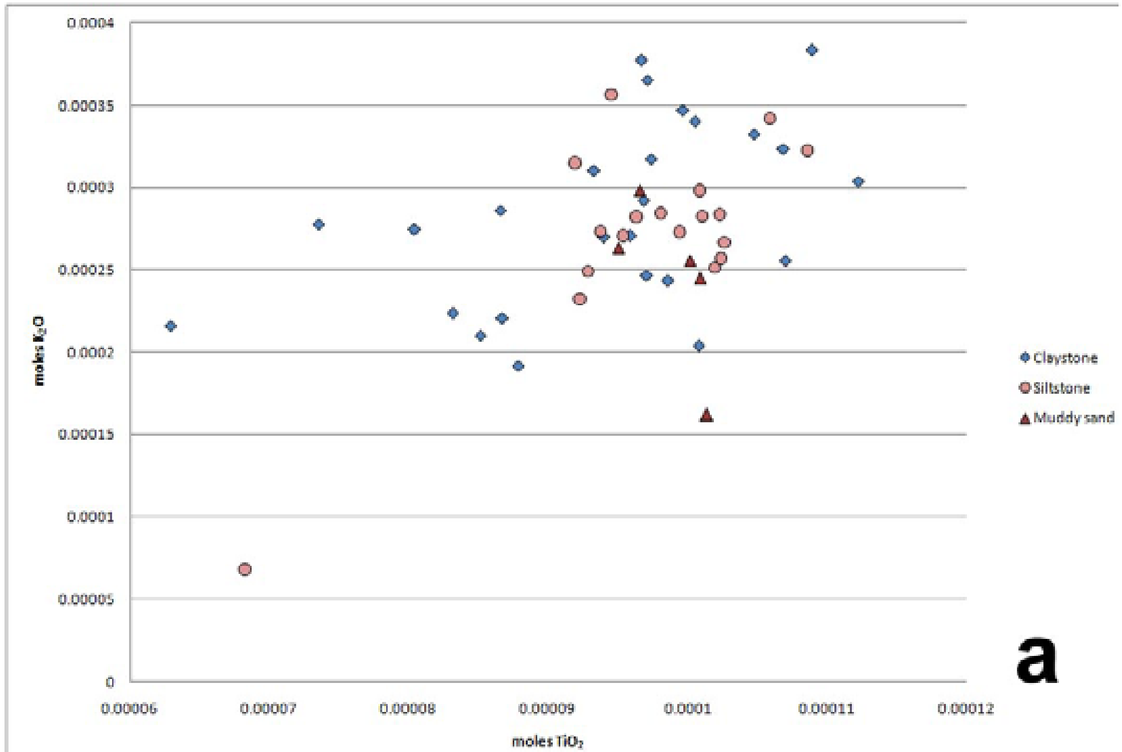
The results for the Palo Duro Canyon samples plotted with the southern Garza County samples were especially interesting. They almost invariably separate from the samples from the lower unit of the Cooper Canyon Formation, even though (as discussed in Chapter 2) they are probably stratigraphically equivalent, supporting my previous suggestion that the Tecovas Formation of the northern Panhandle region and the lower unit of southern Garza County are distinct in mudstone as well as sandstone composition. Compared to the lower unit samples, the Palo Duro samples all tend to have somewhat high values Nb, Ni and (when normalized to Al_2O_3) TiO_2, and low values for K_2O and Zn.

An additional point of interest is that the four samples from the lower "variegated shales" almost always separate from the upper "magenta shales", just as all these samples separate from the lower unit of the Cooper Canyon Formation. The magenta shales are distinct from the variegated shales particularly in having lower SiO_2 and TiO_2, and by higher Sc. Bivariate plots using these elements tend to provide better separation between these samples without normalization (e.g. TiO_2 vs. Nb, Ni, and Zn), although some (e.g. TiO_2 vs. K_2O and TiO_2 vs. MgO) provide better separation with normalization.

Influence of Sand Content on Major and Trace Element Concentrations

In order to help assess the influence of grain size on plots which seem to separate samples stratigraphically, four bivariate plots, plotting moles TiO_2 against moles K_2O, moles TiO_2 against moles Zn, and the same plots normalized to moles Al_2O_3 (Figs. 3.13-3.14) were done for direct comparison with Figs. 3.5 and 3.8. These plots were selected as they are two of the best for showing separation between the middle and upper units of the Cooper Canyon Formation.

Most samples are mudstone. Claystones and siltstone samples have fairly broad overlap with each other, and both include samples from all parts of the Cooper Canyon Formation, suggesting that there is no significant difference between clay and silt in terms of bulk geochemical composition. Only five samples (Marts-1, UURR-1, Patty-1, Patty-2, Patty-5) are dominated by sand-sized clasts, all of which are from the middle and upper units of the Cooper Canyon Formation. These samples seem to show a degree of cohesion on the bivariate plots. This indicates that grain size may be a factor in the clustering of samples from the uppermost Cooper Canyon Formation, as two of the three samples (Patty-1 and Patty-2) from that part of the section are muddy sand. None of these patterns seem to be influenced by normalization to Al_2O_3.



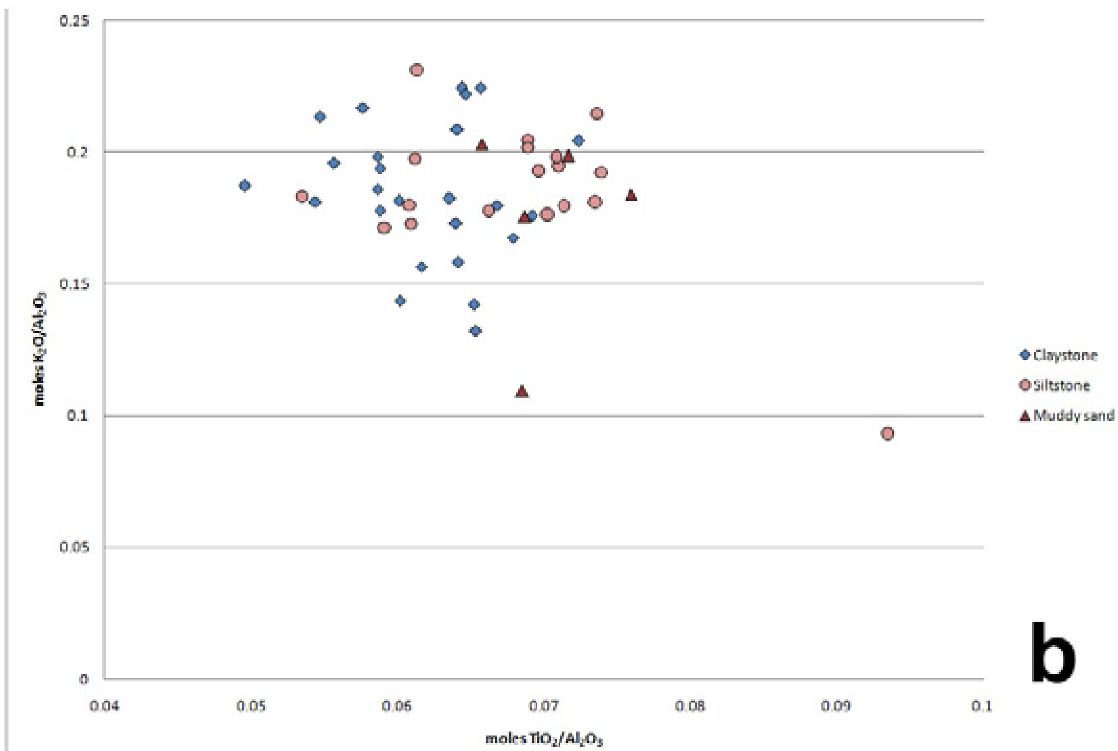


Fig. 3.13. Bivariate plots of moles K_2O vs. moles TiO_2, showing effect of grain size: *a,* without normalization; *b,* normalized to Al_2O_3.

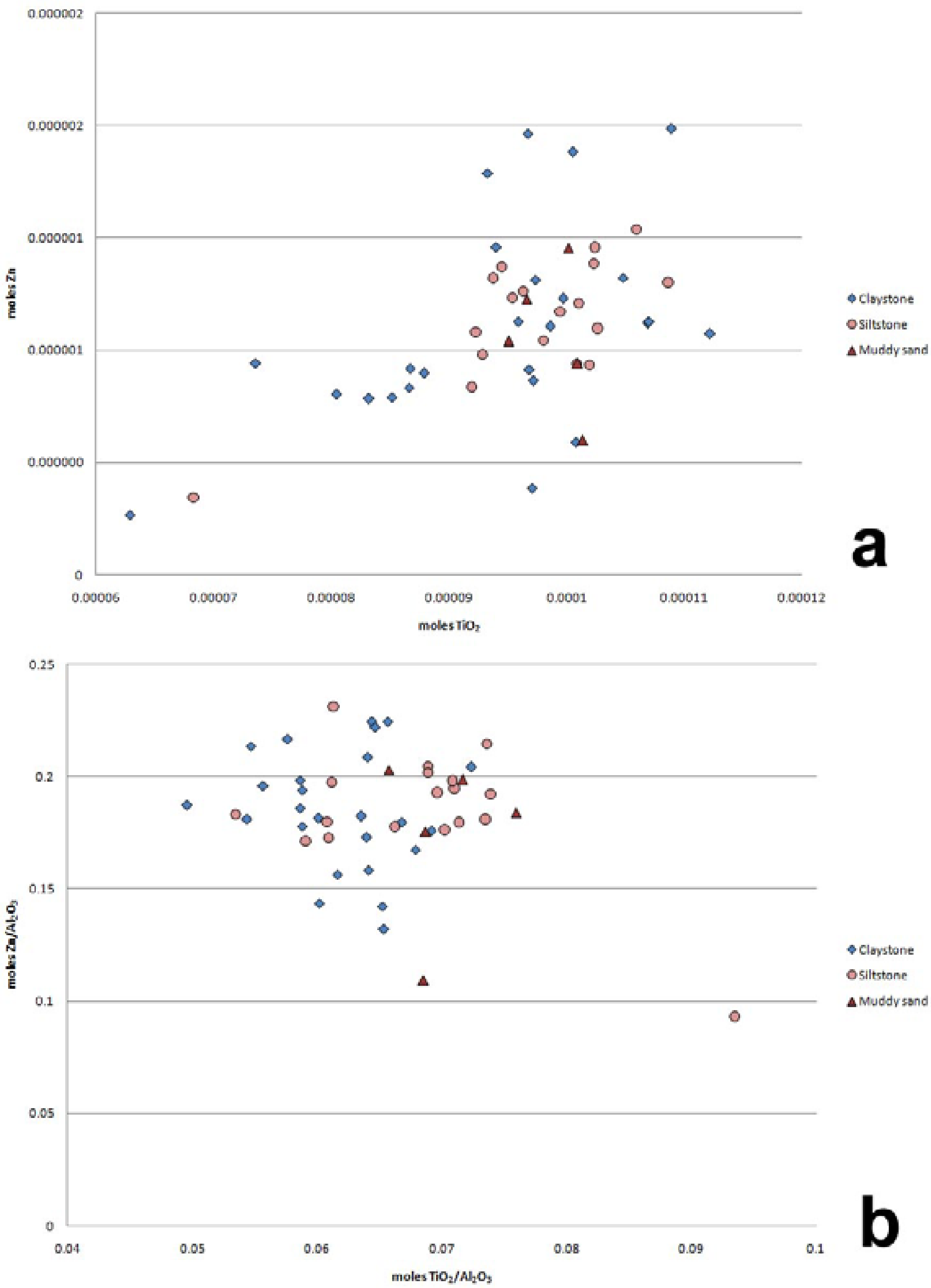


Fig. 3.14. Bivariate plots of moles Zn vs. moles TiO_2, showing effect of grain size: *a*, without normalization; *b*, normalized to Al_2O_3.

Multivariate Plots

Principal component analyses and discriminant analyses are presented together for each sample set. For each analysis, the first graph shows the sample points numbered according to the numbering system for samples given in Appendix B. The second graph is the same with the samples for each stratigraphic unit outlined and labeled. The third graph shows the vector plots for major and trace element concentrations for the first two graphs.

First Data Set: Log Transformed Values Converted to a Covariance Matrix (Boren Ranch sandstone/beds and Cooper Canyon Formation only)

The first PCA (Fig. 3.15) used log-transformed data on a covariance matrix, and included only samples from the Boren Ranch sandstone/beds and Cooper Canyon Formation. The first two principal components together account for only 51.9% of the total variation in the sample set (PC1 = 37.1%, PC2 = 14.8%). This PCA did not provide much stratigraphic separation for units in the Dockum Group in southern Garza County, with samples for different units showing a broad overlap (Fig. 3.15b). However, there is a hint of a stratigraphic trend down the PC2 axis. The accompanying vector plot (Fig. 3.15c) indicates that this trend roughly accompanies a decrease in Al_2O_3, TiO_2, Fe_2O_3, K_2O, and Sc, and a general increase in Zr and Sr.

In the discriminant analysis using the same data set (Fig. 3.16b), the first two discriminant functions account for 84.6% of the total variation (DF1 = 60.5, DF2 = 24.1). This discriminant analysis allows fairly good separation between the Boren Ranch sandstone/beds and most of the Cooper Canyon Formation. It is, interestingly, harder to separate the lower unit of the Cooper Canyon Formation from the middle unit than it is to distinguish the latter from the upper unit. The vector plot (Fig. 3.16c) indicates that the lower and middle units have generally high Al_2O_3, Fe_2O_3, and Sc, and low SiO_2, Zr, and Sr, as do the Boren Ranch sandstone/beds. The Boren Ranch sandstone/beds and middle and upper units of the Cooper Canyon Formation have high K_2O, MgO, MnO, Zn, and

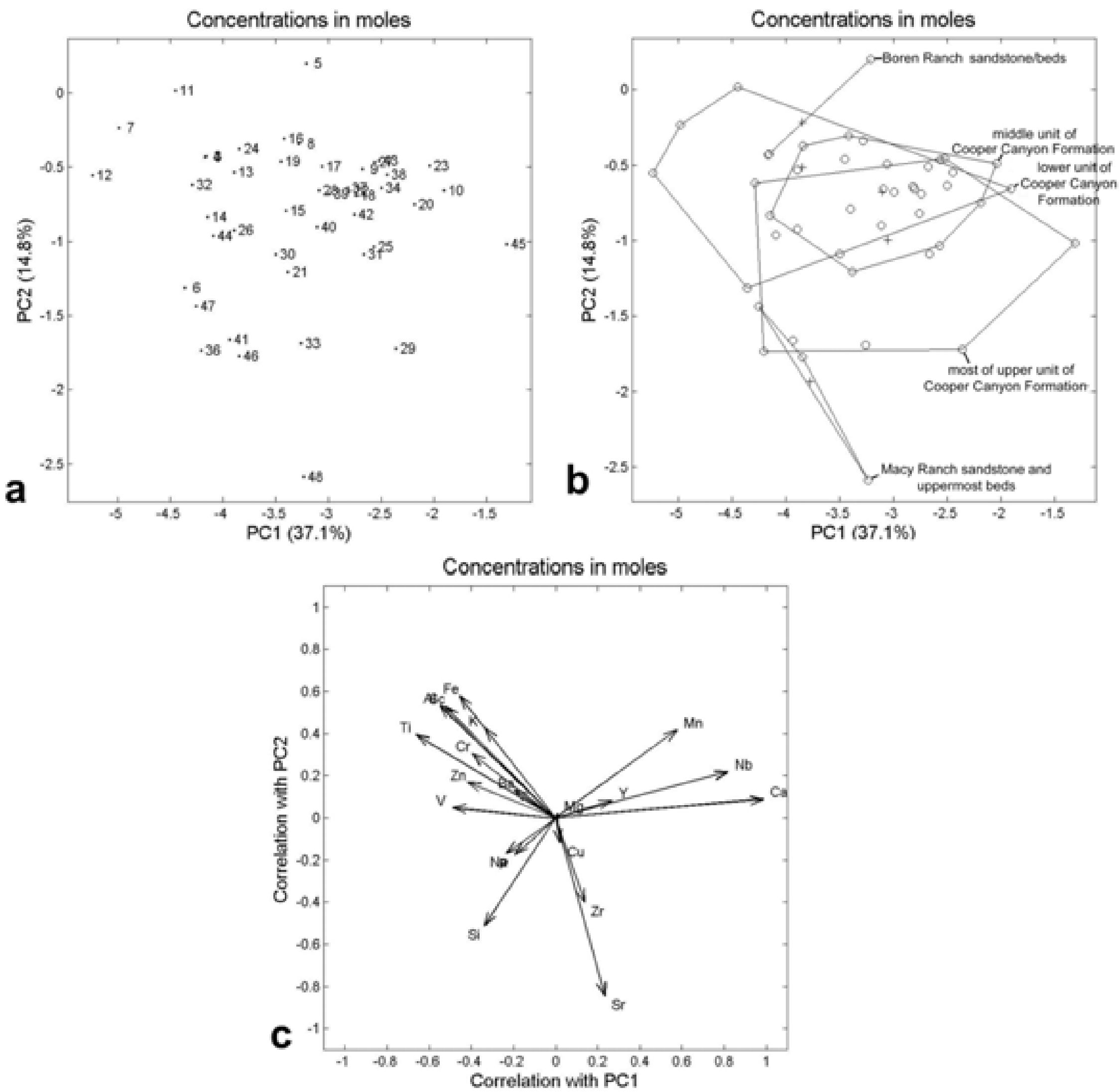


Fig. 3.15. Principal component analysis for log-transformed data converted to a covariance matrix, Boren Ranch sandstone/beds and Cooper Canyon Formation only: *a*, samples only; *b,* samples delineated by lithostratigraphic unit; *c,* vector plot.

these same elements have low values for the middle unit of the Cooper Canyon Formation.

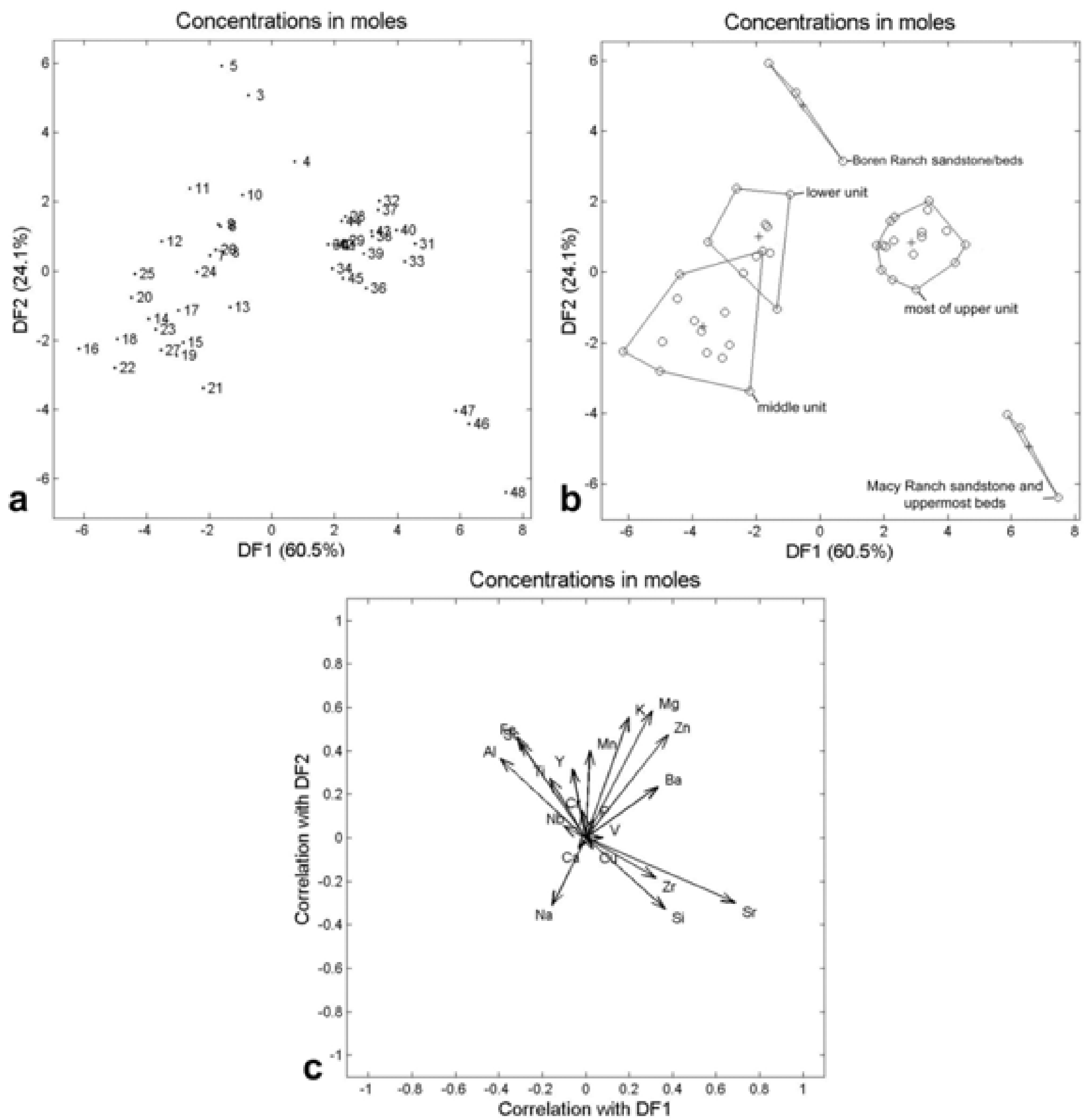


Fig. 3.16. Discriminant analysis for log-transformed data converted to a covariance matrix, Boren Ranch sandstone/beds and Cooper Canyon Formation only: *a*, samples only; *b*, samples delineated by lithostratigraphic unit; *c*, vector plot.

Second Data Set: Log Transformed Values Converted to a Covariance Matrix (All Stratigraphic Units)

The second PCA added samples from two additional units, the Santa Rosa Sandstone and Tecovas Formation. The first two principal components account for

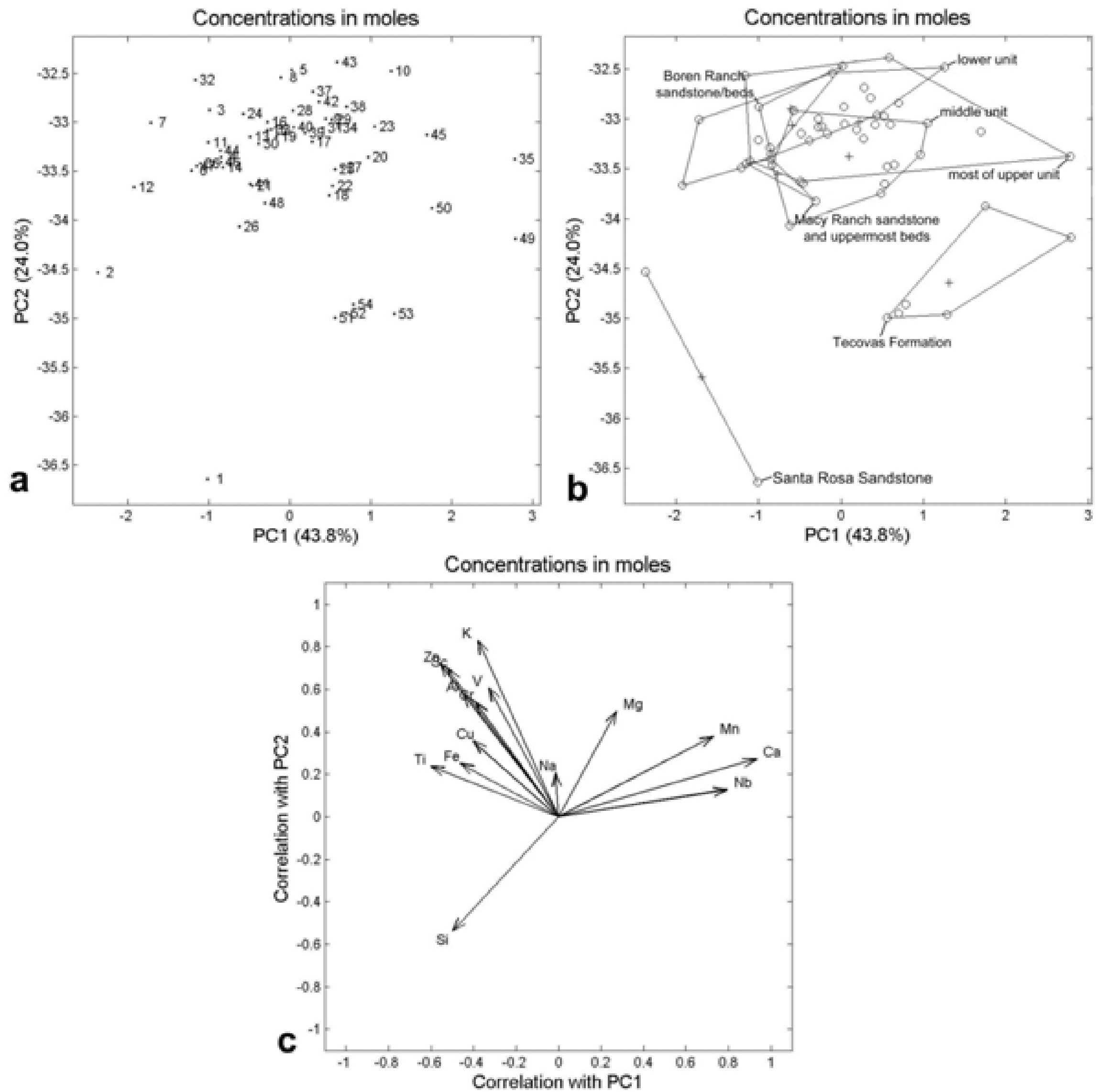


Fig. 3.17. Principal component analysis for log-transformed data converted to a covariance matrix, all stratigraphic units: *a*, samples only; *b*, samples delineated by lithostratigraphic unit; *c*, vector plot.

67.8% of the total variation (PC1 = 43.8, PC2 = 24%). The additional samples produce a striking pattern (Fig. 3.17a-b) in which there is broad overlap between samples from the Boren Ranch sandstone/beds and all parts of the Cooper Canyon Formation, as seen in the first PCA (Fig. 3.15b), but where the Santa Rosa Sandstone and Tecovas Formation samples are quite distinct; moreover, as with the bivariate plots, the lower "variegated shales" and upper "magenta shales" of the Tecovas Formation separate from each other. In the vector plots (Fig. 3.17c), the Santa Rosa Sandstone is distinguished from the other units by high SiO_2 and low MgO and MnO, while the Tecovas Formation samples are somewhat high in MnO, CaO, and Nb, and all other elements tend to be relatively high in the Boren Ranch sandstone/beds and Cooper Canyon Formation.

The discriminant analysis for the same data set (Fig. 3.18a-b) has the first two discriminant functions which account for 88.8% of the total variation (DF1 = 79.1, DF2 = 9.7). As in the PCA, this is slightly higher than in the first analysis. The discriminant analysis shows the same pattern as the PCA. The vector plot (Fig. 3.18c) indicates that the same elements are important in both the PCA and discriminant analysis in separating the Santa Rosa Sandstone and Tecovas Formation from the Boren Ranch sandstone/beds and Cooper Canyon Formation.

Third Data Set: Normalized Values Converted to a Correlation Matrix (Boren Ranch sandstone/beds and Cooper Canyon Formation only)

In the third and final PCA (Fig. 3.19), in which the Santa Rosa Sandstone and Tecovas Formation samples were excluded and the values were normalized to the North American Shale Composite and converted to a correlation matrix, the first two principal components account 67.8% of the variation (PC1 = 43.8, PC2 = 24). This PCA gives even poorer separation for the different stratigraphic units than with the first PCA (Fig. 3.15b). The distribution of samples from different units is similar to that seen in many of the bivariate plots (Figs. 3.2-3.12), in which there is a very wide and broadly overlapping distribution for samples from the middle and upper units of the Cooper Canyon Formation, with the samples from the lower unit and Boren Ranch sandstone/beds clustering together at one end of that distribution. As with the first PCA, there is the barest hint of a stratigraphic trend, this time right to left along PC1 (Fig. 3.19b), though it is weak. The vector plot (Fig. 3.19c) shows this trend involves a decrease particularly in Al_2O_3, K_2O, and Sc, with a general increase in SiO_2, Zr, Y, and Sr.

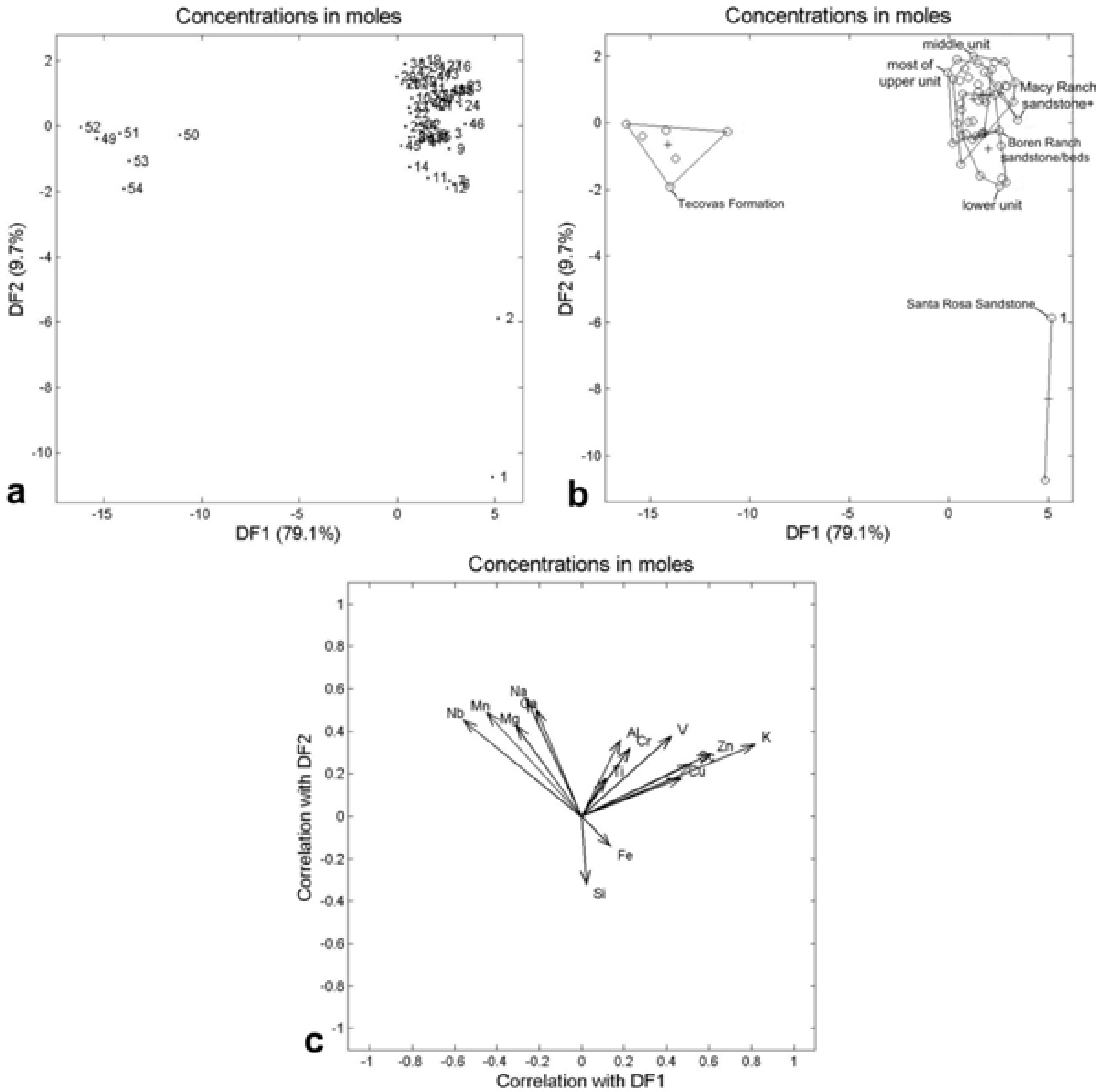


Fig. 3.18. Discriminant analysis for log-transformed data converted to a covariance matrix, all stratigraphic units: *a*, samples only; *b*, samples delineated by lithostratigraphic unit; *c*, vector plot.

The first two discriminant functions for this sample set account for 80.5% of the variation (DF1 = 53.9, DF2 = 26.6). The discriminant analysis (Fig. 3.20b) shows similar separation of the samples as seen in the discriminant analysis for the first sample set (Fig. 3.16b), with fairly good separation of all units except for the lower and middle units of

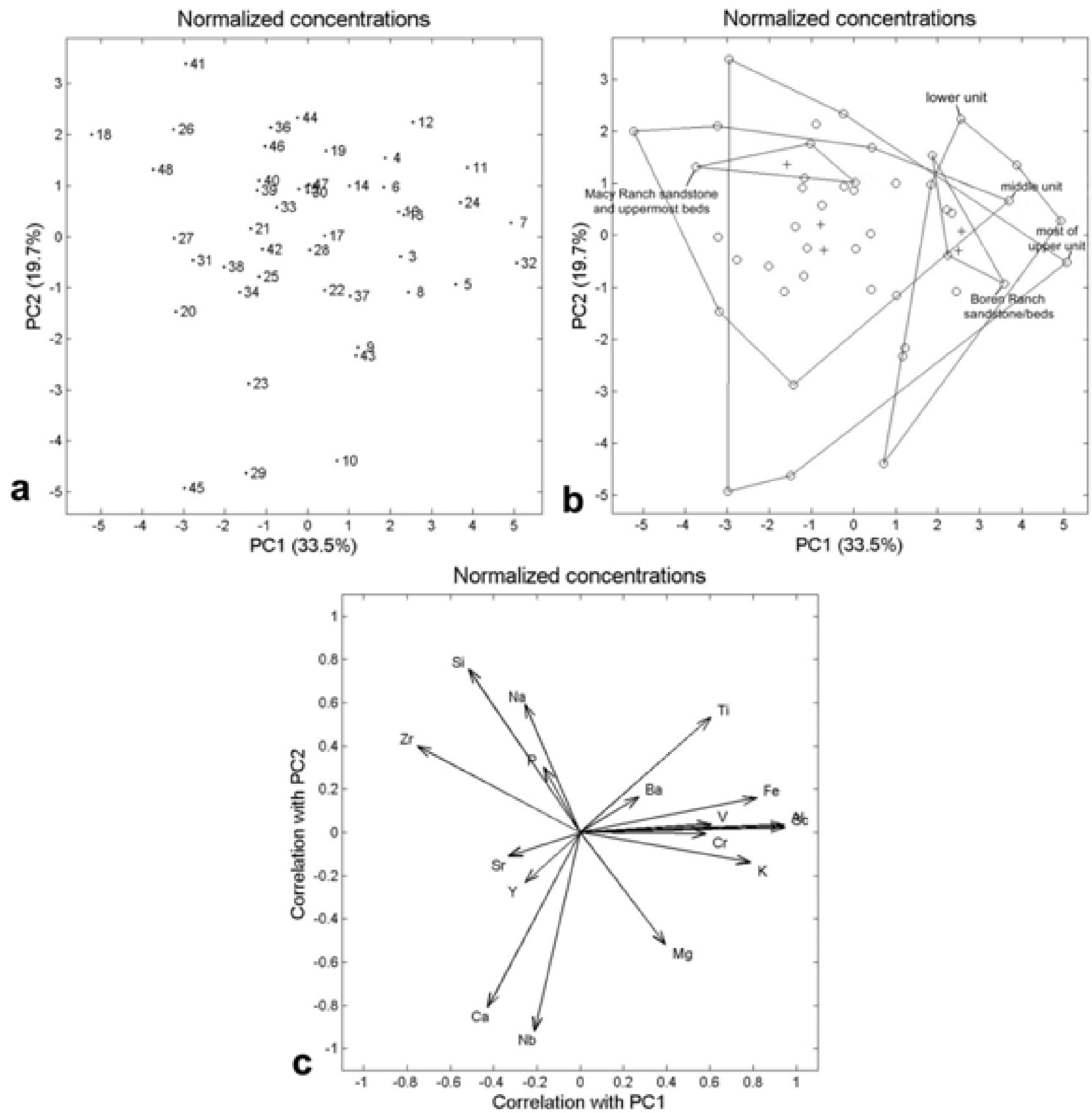


Fig. 3.19. Principal component analysis for normalized data converted to a correlation matrix, Boren Ranch sandstone/beds and Cooper Canyon Formation only: *a*, samples only; *b*, samples delineated by lithostratigraphic unit; *c*, vector plot.

the Cooper Canyon Formation, and the vector plot (Fig. 3.20c) indicates that major and trace elements separate the samples in more or less the same ways as with the PCA.

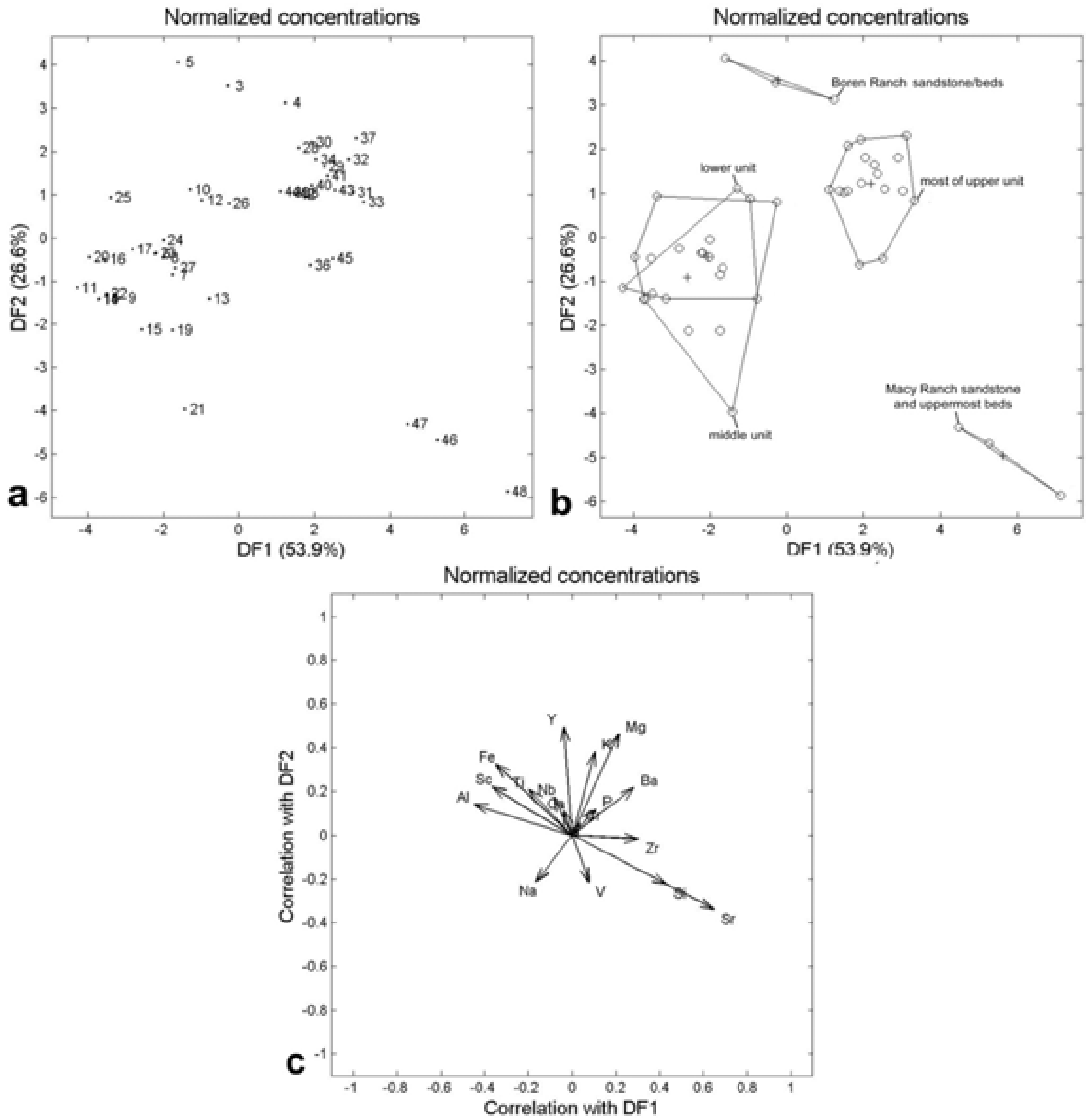


Fig. 3.20. Discriminant analysis for normalized data converted to a correlation matrix, Boren Ranch sandstone/beds and Cooper Canyon Formation only: *a*, samples only; *b*, samples delineated by lithostratigraphic unit; *c,* vector plot.

Provenance Discriminant Function Plots

Tectonic Setting Discriminant Plots (Roser and Korsch, 1986)

The discriminant plot of Roser and Korsch (1986) is intended to separate sandstone and mudstone samples according to tectonic environment of deposition, and to

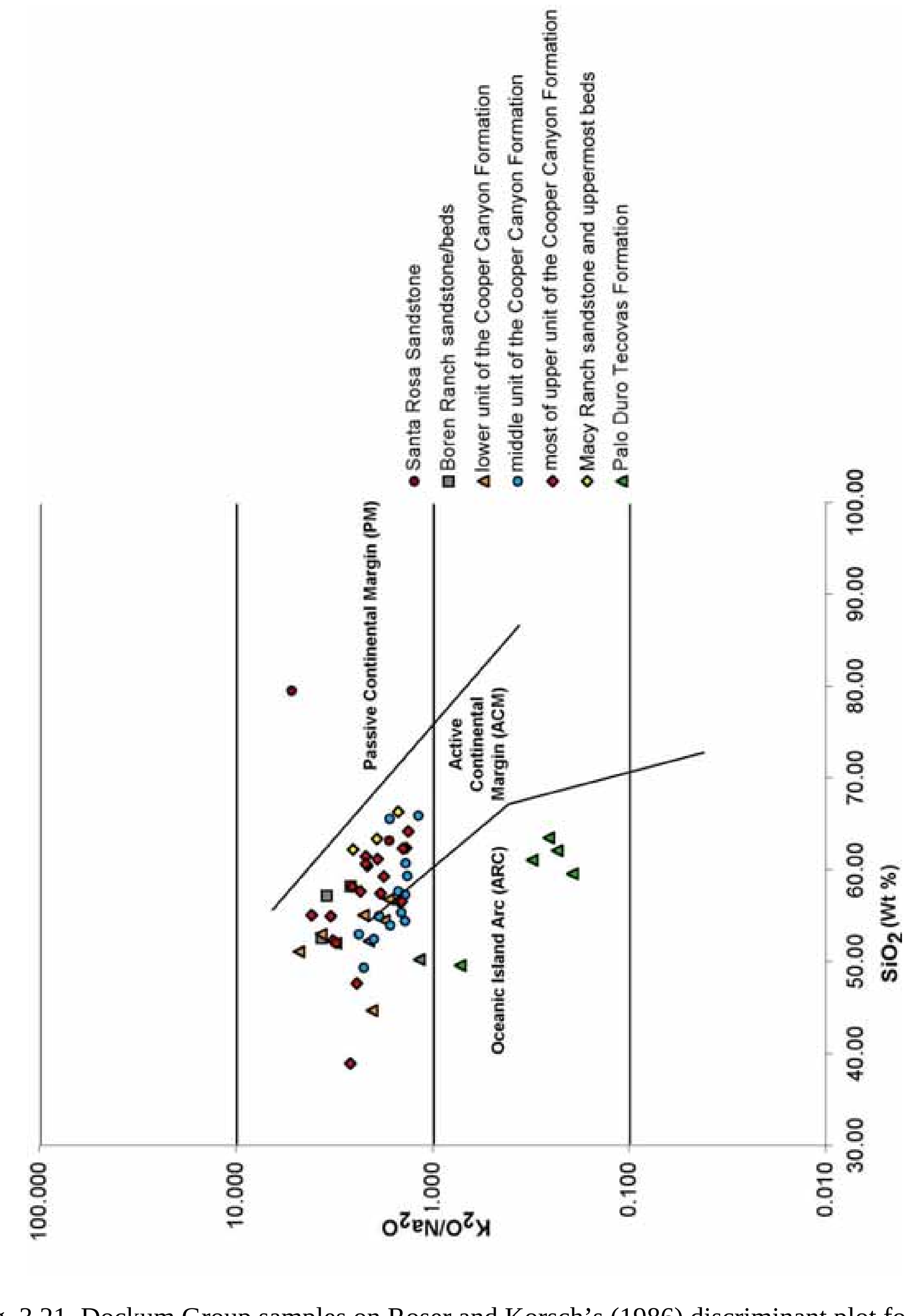


Fig. 3.21. Dockum Group samples on Roser and Korsch's (1986) discriminant plot for tectonic depositional environment.

some degree, the tectonic provenance of the sediments. The samples plotted using values for K_2O/Na_2O vs. SiO_2, with the dividing lines used by Roser and Korsch (1986) to distinguish different tectonic settings superimposed on the graph (Fig. 3.21), mostly plot together with the exception of samples from the Tecovas Formation of Palo Duro Canyon. The main cluster of samples mostly plot in the Active Continental Margins (ACM) region, with some spreading slightly into the Oceanic Island Arc (ARC) field. The samples are mostly restricted to the high K_2O/Na_2O, low SiO_2 region of these fields. Roser and Korsch (1986) also observed that mudstones tended to plot with relatively high K_2O/Na_2O and low SiO_2 compared to sandstones. Samples of the main cluster falling in the ACM field include one of the Santa Rosa Sandstone samples (OS Ranch Gully-2), the Boren Ranch sandstone/beds samples, most of the lower unit samples, and nearly all the samples from the middle and upper units from the Canyon Formation. A cluster of samples from the middle unit of the Cooper Canyon Formation, and a few samples from the lower and upper units, plot in the ARC field near the dividing line between it and the ACM field.

One of the Santa Rosa Sandstone samples (Montford Dam-1) lies well within the Passive Margin (PM) field, with SiO_2 values that are strikingly higher than for any of the other samples. The K_2O/Na_2O ratio for this sample is also fairly high, although values for both oxides are actually quite low among samples. The K_2O values are lower than for any of the samples except for the Tecovas Formation samples, and the Na_2O values are the lowest among all samples. The Tecovas Formation samples from Palo Duro Canyon all lie well within the ARC field. The Tecovas Formation samples show SiO_2 values in the same range as those of the Cooper Canyon Formation and Boren Ranch sandstone/beds, but with lower K_2O/Na_2O values. The "variegated shale" samples, which have higher Na_2O and lower K_2O, lie lower along this axis and higher along the SiO_2 axis, than the "magenta shale" samples.

Roser and Korsch (1986) tested their model with samples from ancient terranes for which the tectonic setting had been established by other methods. Mudstones derived from the Torlesse terrane of New Zealand, which has been interpreted as an accretionary wedge shed off a continental magmatic arc, and pelitic schists of the Haast Schist terrane of New Zealand, which may represent altered Torlesse sediments, plotted in roughly the same area of the discriminant plot as the main cluster of Dockum Group samples (Roser and Korsch, 1986, figs. 7-8). The Haast Schist metapelitic schists even partially extend into the ARC field, as with the main cluster of Dockum Group samples.

Provenance Discriminant Plot (Roser and Korsch, 1988)

The discriminant plots of Roser and Korsch (1988) were intended to separate sandstone and mudstone samples according to the tectonic provenance of the sediments, and present quite a startling contrast to the tectonic depositional setting discriminant plots of Roser and Korsch (1986). The samples for the first plot (Fig. 3.22), which incorporated the influence of SiO_2 and CaO into the discriminant functions, lie almost entirely in “quartzose sediments of mature continental provenance” (P4) field, and most of the samples spreading into adjacent fields still remained fairly close to this main cluster. Several samples from the middle unit of the Cooper Canyon Formation spread into all three of the other fields, although again, most stayed fairly close to the edge of the P4 field. Two samples from the upper unit of the Cooper Canyon Formation lie in the “primarily intermediate igneous provenance” (P2) field, further from the P4 field than most of the other samples. Three of the “variegated shales” samples from the Tecovas Formation lie in the “primarily mafic and lesser intermediate igneous provenance” (P1) field, and two samples from the lower unit of the Cooper Canyon Formation fell in the P1 and P2 fields.

For the various igneous and sedimentary samples which Roser and Korsch (1988) used to test their discrimination plots, the Dockum Group distribution most closely resembles Australian volcanogenic sandstones of andesitic provenance, which also plotted primarily in the P4 field with most of the remaining samples falling in P1 and P2, although the grain-size difference between this sample and the Dockum mudstones probably makes this comparison dubious.

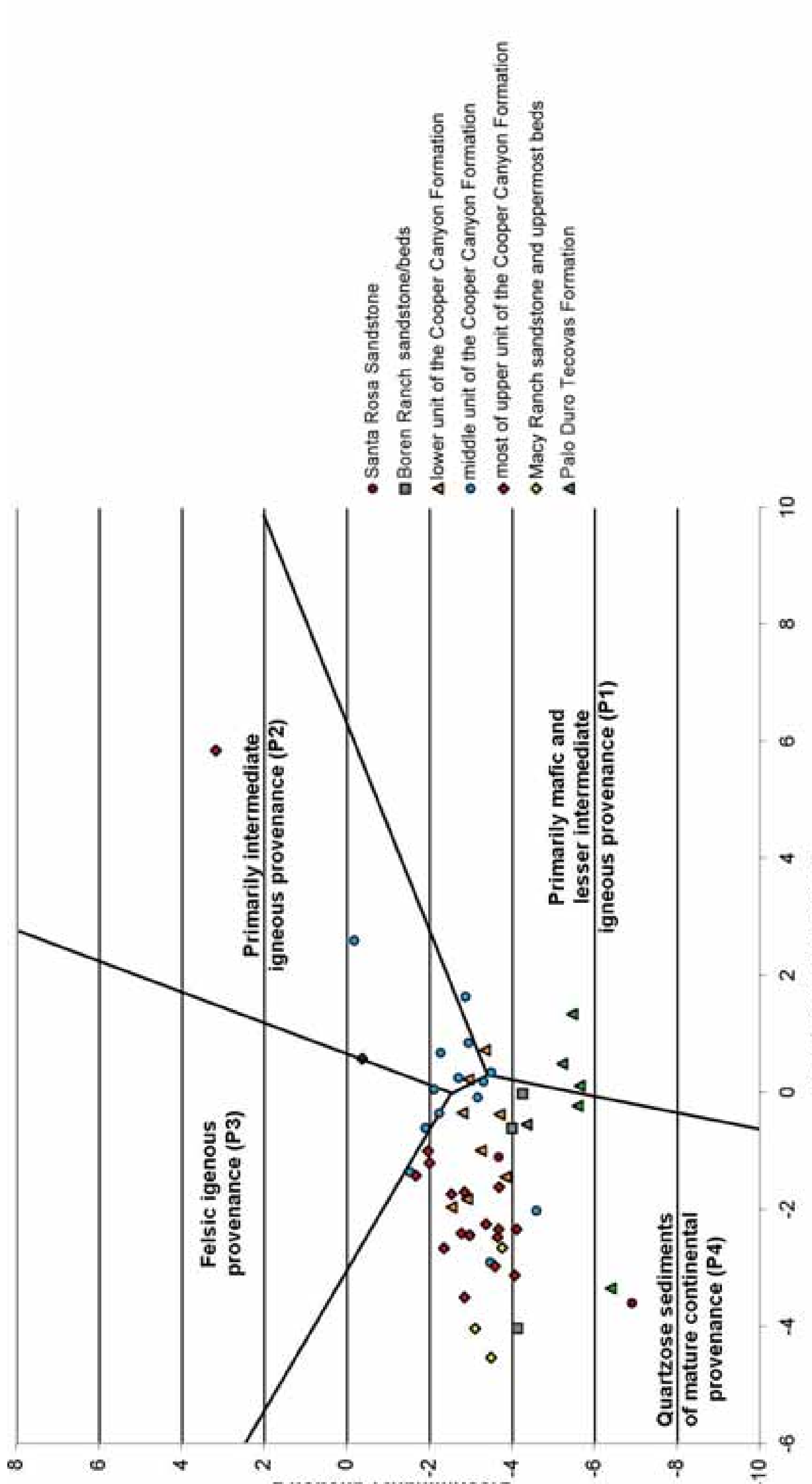


Fig. 3.22. Dockum Group samples on Roser and Korsch's (1988) discriminant plot for provenance, where the discriminant functions consider influence of SiO_2 and CaO.

However, Tertiary arkoses and shales from the Santa Ynez Mountains of California also showed interesting similarities to the Dockum Group samples. These sediments were derived from calc-alkaline plutonic and metamorphic terranes with some input from volcanic rocks. The sandstones mostly plot in the P3 field, as expected, but the mudstones mostly lie in the P2 and P4 fields. Roser and Korsch indicate this is an effect of grain size, citing Van de Camp et al.'s (1976) observation that all sediments were depleted in Na and Ca relative to the source, and also that the mudstones were enriched in Fe, Mg, and Ti due to the formation of clay minerals. Interestingly, the Torlesse terrane and pelitic schists of the Haast Schist terrane, which both had similarities to the Dockum samples in the tectonic depositional environments plots of Roser and Korsch (1986), do not plot in the same part of the field in the provenance plot.

The second discriminant plot, which removed the influence of SiO_2 and CaO from the discriminant functions (Fig. 3.23), displaced many of the Dockum Group samples into the "primarily intermediate igneous provenance" (P2) field, as Roser and Korsch (1988) noted also occurred with many of the samples in their study. Interestingly, samples from different lithostratigraphic units tend to be more strongly discriminated with respect to provenance than in the first plot. Most lie in an elongate cluster spread between the "quartzose sediments of mature continental provenance" (P4) field they occupied in the first discriminant plot, and the P2 field. Most of the samples from the middle unit of the Cooper Canyon Formation fall in the P2 field, and most of the upper unit samples fall in the P4 field, as do the "magenta shales" samples from the Tecovas Formation. The lower unit and Boren Ranch sandstone/beds samples occur in both the P2 and P4 fields. One of the Santa Rosa Sandstone samples and all of the "variegated shales" samples lie in the "primarily mafic and lesser intermediate igneous provenance" (P1) field. The Tecovas Formation samples are more distinctly separated from the Garza County samples, and the "variegated shales" and "magenta shales" samples are more distinct from each other, than seen in the first discriminant plot.

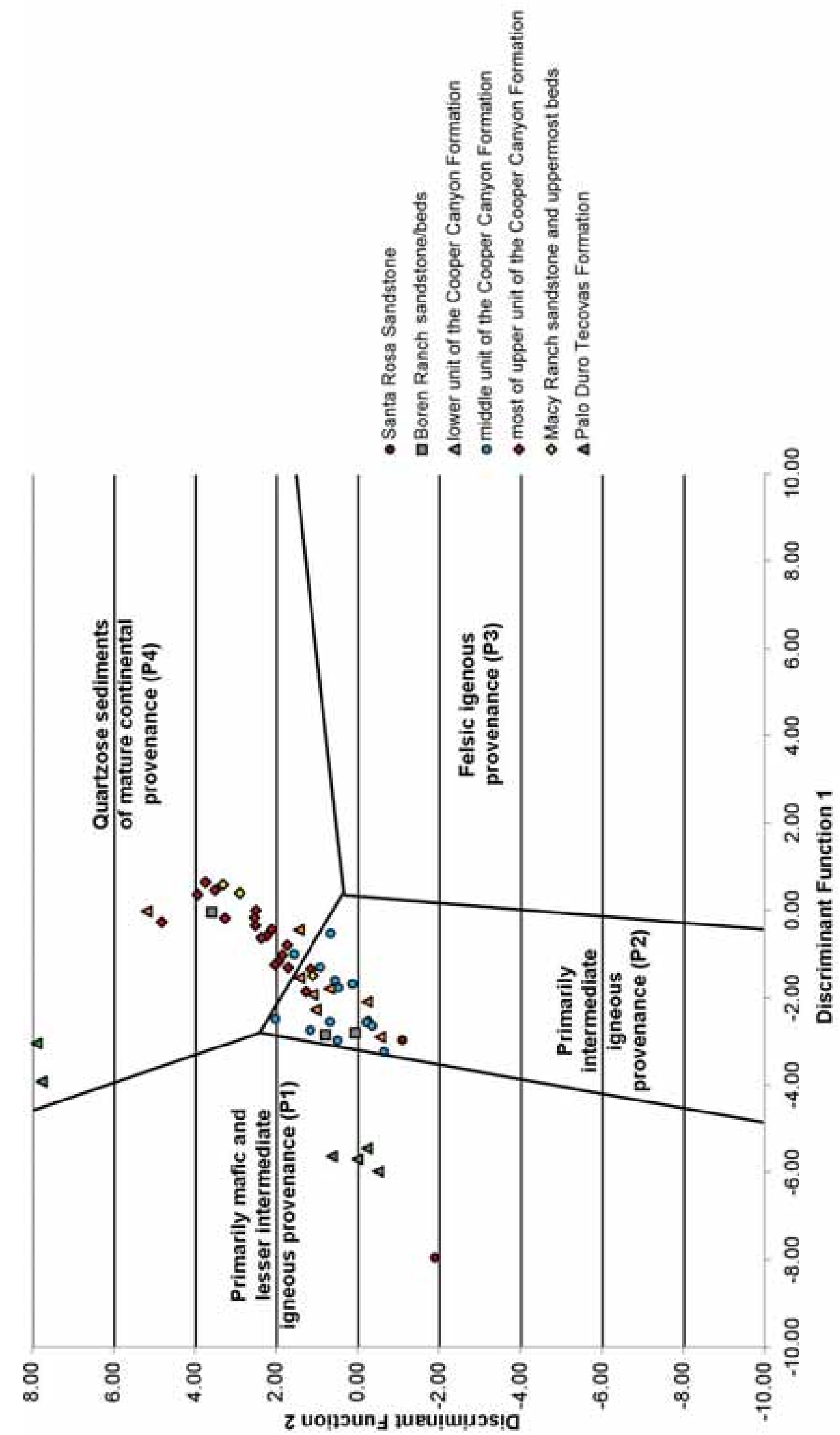


Fig. 3.23. Dockum Group samples on Roser and Korsch's (1988) discriminant plot for provenance, where the discriminant functions remove the influence of SiO_2 and CaO.

Summary and Discussion

Chemostratigraphic subdivision

The original intent of this study was to provide chemostratigraphic subdivision of the Dockum Group in southern Garza County. There was some limited measure of success in attempting to achieve this objective. The mudstones of the Santa Rosa Sandstone show values for several elements as low or lower than for any other samples, specifically for MgO, MnO, CaO, Sr, Nb, and V, and somewhat high values for SiO_2 and Zr. There is usually broad overlap for mudstone samples from the Boren Ranch sandstone/beds and all parts of the Cooper Canyon Formation, consistent with Frehlier (1987) Lehman's (1994; Lehman et al., 1992) observation that the sandstones of the Boren Ranch sandstone and Cooper Canyon Formation sandstones are lithologically identical. Within the Boren Ranch sandstone/beds and Cooper Canyon Formation, there is a general upward stratigraphic decrease in Al_2O_3, K_2O, and Sc, and increase in SiO_2, Zr, Y, and Sr. Mudstones from the lower unit and Boren Ranch sandstone/beds are very similar geochemically save that the latter have higher TiO_2, and at least some samples from the middle unit of the Cooper Canyon Formation seem to show greater geochemical similarity to the lower unit and Boren Ranch sandstone/beds samples than with the upper unit.

However, this study also makes the possibility of fine-scale chemostratigraphic subdivision of the Cooper Canyon Formation seem doubtful. Although the Boren Ranch sandstone/beds and lower unit samples often cluster together, they generally do so within the range of variation for the rest of the Cooper Canyon Formation, and there is usually fairly broad overlap for samples from the middle and upper units of the Cooper Canyon Formation. There is also no clear evidence that samples which are closely associated stratigraphically *within* these informal subdivisions of the Cooper Canyon Formation are more geochemically similar to each other than to other samples, so it does not seem possible to subdivide the Cooper Canyon Formation at a finer scale than possible through the tracing and mapping of sandstone and mudstone-dominated lithostratigraphic units.

In summary, chemostratigraphic subdivision of the Dockum Group is possible, using both bivariate techniques and multivariate techniques (although the former are better for subdividing the Boren Ranch sandstone/beds and parts of the Cooper Canyon Formation), but only broadly.

Geographic Variation and Provenance

Even though the geochemical data is of dubious value for fine-scale chemostratigraphic subdivision, it does suggest that geochemical variation may be an important tool in *provenance* studies for the Dockum Group, and for helping identify regional variation in lithostratigraphic units. The Tecovas Formation of Palo Duro Canyon is high in MnO, CaO, and Nb, and low in K_2O, TiO_2, Zn, and Sc compared to the Cooper Canyon Formation and Boren Ranch sandstone/beds of southern Garza County. The difference is striking, especially between the Tecovas Formation and the lower unit, which are probably lithostratigraphically correlative (discussed in Chapter 2).

It is not yet known what causes this sharp difference in overall geochemical composition. That local depositional and diagenetic conditions may play a part is suggested by the fact that the "variegated shales" and "magenta shales" within the Tecovas Formation tend to separate in nearly every graph, as these beds are thought to have been formed respectively as lacustrine and overbank deposits (e.g. May, 1988). This may also account for the slight separation between samples from the Boren Ranch sandstone/beds and lower unit, which are suspected of being roughly correlative to the "variegated shales" and "magenta shales" respectively (discussed in Chapter 2).

However, by the same token, the fact that the Boren Ranch sandstone/beds and "variegated shales" are geochemically distinct from each other, as are the lower unit and the "magenta shales," suggests that sedimentary provenance is also an important factor. The petrologic and paleocurrent data suggesting that the sediments of the Boren Ranch sandstone/beds and Cooper Canyon Formation were derived largely from the Ouachita Marathon Orogenic Belt, and that those of the Santa Rosa Sandstone and Tecovas Formation were derived in part from the Amarillo-Wichita Uplift (McGowan et al., 1979;

Frehlier, 1987; May, 1988; Fritz, 1991; Riggs et al., 1993; Long and Lehman, 1993, 1994) has already been discussed, and these differences in sedimentary provenance are probably reflected in the mudstone geochemistry.

Plotting the geochemical data for the Dockum Group on the tectonic depositional environment and provenance plots of Roser and Korsch (1986, 1988) provides equivocal support for a difference in provenance between southern Garza County and Palo Duro Canyon. However, there are peculiarities to these plots which may be due to the fact Roser and Korsch (1986, 1988) were using sediments deposited primarily in marine settings. Most samples plotted on the tectonic depositional environment plot of Roser and Korsch (1986) fell in the active continental margin (ACM) field (Fig. 3.21). The Ouachita-Marathon Orogenic Belt is composed largely of Paleozoic marine shelf sediments uplifted and metamorphosed by the continental collision between North America and Gondwana, and deposited (in the case of southern Garza County) over the Paleozoic Midland Basin, a foreland basin associated with the formation of the orogenic belt (McGowan et al., 1979; Viele and Thomas, 1989; Ewing, 1991). The ACM field, which was characterized by Roser and Korsch (1986) as representing quartz-intermediate sediments deposited in basins associated with active continental margins, comes closest of their three fields to describing the Midland Basin, although the Ouachita-Marathon Belt is unusual among orogenic belts in lacking associated magmatic activity (Viele and Thomas, 1989; Ewing, 1991). The Dockum Group samples plot in roughly the same part of the ACM field as mudstone samples from the Torlesse terrane and metapelites of the Haast Schist terranes (Roser and Korsch, 1986, figs. 7-8) both of which were probably ultimately derived from a continental magmatic arc. As the metapelites of the Haast Schist terrane partially extend into the ARC field, this may reflect slight imprecision in the ability of the discriminant plots to keep samples from different tectonic environments isolated.

More difficult to understand is why the Tecovas Formation samples plot well within the ARC field (Fig. 3.21). Of the various modern and ancient sediments plotted by Roser and Korsch (1986), the Tecovas Formation samples are similar to mudstones of the Maitai terrane (Roser and Korsch, fig. 10), which are mostly derived from high Al basalt and basaltic andesite of an arc, and deposited in a forearc basin. However, given that the Dockum Group consists of fluvial and lacustrine deposits laid down hundreds of miles inland from the active margin of western North America (Fig. 2.1) the derivation of Tecovas Formation sediments from an andesitic island arc is highly unlikely. The samples are all within the range of SiO_2 of the Cooper Canyon Formation samples, so the primary difference is in the K_2O/NaO ratio. Values for K_2O are extremely low for the Tecovas Formation samples, and NaO values for the "variegated shales" samples (Appendix B), which plot further in the ARC field than the magenta shales samples, are extremely high. It may be that terrestrial diagenetic processes influenced the Tecovas Formation mudstones in a way not accounted for by the plots of Roser and Korsch (1986), which were using sediments deposited primarily in marine settings.

The results for the graph using Roser and Korsch's (1988) discrimination plot for provenance (Figs. 3.22-3.23), are even harder to explain. The provenance indicated for the samples is inconsistent not only with petrologic and paleocurrent studies for the Dockum Group, with the tectonic depositional environment plots just discussed (Fig. 3.21). The bulk of the samples, which mostly plotted in the field for sediments deposited in basins associated with active continental margins (ACM) in the first plot, largely lie in the provenance plots in the field for quartzose sediments derived from reworking of older deposits in the continental interior (P4) (Fig. 3.22). This makes sense only for the "magenta shales" samples, as these beds are often interbedded in Palo Duro Canyon with extremely siliceous "sugar sands" (May, 1988). With the removal of CaO from the discriminant functions (Fig. 3.23), many samples move into the field for sediments of intermediate igneous provenance usually derived from andesitic island arcs (P2), and the "variegated shales" samples and one of the Santa Rosa Sandstone samples (Montford Dam-1), lies in the field for sediments derived mostly from mafic to intermediate island arcs (P1), which is even more puzzling.

However, Roser and Korsch (1988,) noted that for some localities, fine-grained samples were sometimes displaced into different fields than coarser grained samples.

Roser and Korsch (1988, p. 129) noted that for arkoses and mudstones of the Santa Ynez Mountains of California, which were derived from a "calc-alkaline plutonic and metamorphic terrane with a lesser volcanic component" (probably a continental arc), the sandstones tend to plot in the felsic igneous provenance (P3) field, as they should, but the mudstones were usually distributed between the intermediate igneous provenance (P2) field and the quartzose sediments of mature continental provenance (P4) field. Roser and Korsch (1988) suggested that for at least some sample sets, fine-grained samples alone were not enough to determine provenance, and were displaced into a different field from the sandstones. Samples from the Ouachita-Marathon Orogenic Belt should be expected to plot in the P3 field, which encompasses sediments derived from felsic plutonic and metamorphic continental arcs, and the distribution of the mudstone samples from the Santa Ynez Mountains is strikingly similar to that for the Dockum Group samples (Fig. 3.22). It may be therefore that unexpected distribution of the Dockum Group samples in the provenance plots reflects grain size segregation.

To summarize, geochemical variation in mudstone samples from the Dockum Group, at least based on this limited sample size, shows patterns of segregation in bivariate and multivariate graphs consistent with postulated differences in sediment provenance proposed by earlier workers, although they may also be influenced by local differences in depositional environment and diagenesis. The segregation of samples is also seen when the Dockum Group samples are applied to the tectonic depositional environment and provenance plots of Roser and Korsch (1986, 1988), although the plotting of some samples is highly unexpected given the tectonic setting and previous work on provenance (McGowan et al., 1979; Riggs et al., 1993; Long and Lehman, 1993, 1994; Lehman and Chatterjee, 2005). In the case of the Tecovas Formation samples in the tectonic depositional environment plot, the sample distribution may represent depositional and/or diagenetic conditions not predicted by the primarily marine sample set used by Roser and Korsch (1986) to construct the discrimination plot, while for the provenance plots (Figs. 3.22-3.23) the peculiar distribution may be a reflection of grain size segregation. In the case of both tectonic depositional environment and provenance plots, the mudstones from the Boren Ranch sandstone/beds and Cooper Canyon Formation plot in the same areas of Roser and Korsch's (1986, 1988) plots as mudstones or metapelites of probable plutonic-metamorphic composition derived from continental arcs (the Torlesse terrane and Haast Schist of New Zealand, the Santa Ynez Mountains of California), which is consistent with the previous work on the tectonic setting and provenance of these Upper Triassic deposits.

Prospectus

Although this study has made fine-scale subdivision of the Dockum Group using chemostratigraphy seem dubious, this possibility can be tested further through the development of finer-resolution lithostratigraphic correlation within the Dockum Group, and denser sample collection. One possible project might be to measure two sections as transects from the base of the Dockum Group to the top, collecting samples at high frequency along the way. The sample data could be ordered stratigraphically, and the chemostratigraphic profiles for these transects could be compared to determine if fine-scale similarities in the pattern of bulk geochemical variation exist which can be used to correlate the sections chemostratigraphically.

However, the possibility of using geochemistry to help resolve issues of large-scale lithostratigraphic correlation, provenance, and nomenclature seems far more promising. Assuming that major and trace element composition is largely a function of mudstone lithology and provenance, collecting lithostratigraphically constrained geochemical samples from the Dockum Group in Howard County and Borden County to the south of the study area, and Crosby County and other exposures of the Dockum Group to the north, could establish regional and stratigraphic patterns of variation in the bulk geochemical composition of the Dockum Group throughout Texas. Combined with petrological studies for sandstones, and continued mapping of sandstone and mudstone-dominated units, this could be used to infer regional and stratigraphic variation in sandstone and mudstone lithology, which could then be tied to regional and stratigraphic variation in sediment provenance. These patterns could be used to help resolve how sedimentation within the Dockum Group varied over time and space, and also how lithostratigraphic nomenclature should best be applied throughout the Dockum Group to reflect this lithologic variation. As Roser and Korsch's (1986, 1988) discrimination plots were based on both fine-grained and coarse-grained sediments, incorporating sandstone samples into the geochemical data set might resolve some of the peculiarities discussed above.

CHAPTER 4

FOSSIL VERTEBRATES AND VERTEBRATE LOCALITIES OF THE DOCKUM GROUP (UPPER TRIASSIC) OF SOUTHERN GARZA COUNTY, WEST TEXAS

Introduction

Vertebrate fossils have been collected from the Dockum Group of West Texas for over a century. The Dockum Group of Howard County contains the Otis Chalk Quarries (Gregory, 1945; Sawin, 1945, 1947; Elder, 1978, 1987) collected for the University of Texas at Austin, and the Tecovas Formation of the Canadian River Valley and southern Crosby County (Case, 1922; Murry, 1982, 1986, 1989; Lucas and Hunt, 1990; Long and Murry, 1995; Heckert, 2004; Martz and Small, 2006; Weinbaum and Hungerbühler, 2007), from which particularly significant collections have been made by the University of Michigan, New Mexico Museum of Natural History and Science, Southern Methodist University, and Texas Tech University. Other Dockum Group vertebrate localities in West Texas are widely scattered, with notable finds in Palo Duro Canyon in Randall County (Hunt and Lucas, 1991a), Kent County (Case, 1931, 1932; Houle and Mueller, 2004), Scurry County (Langston, 1949), and Borden County (Long and Murry, 1995; Spielmann et al., 2005, 2007a). However, with the exception of early excavations at the Post Quarry by the Dallas Museum of Natural History in 1977 (Long and Murry, 1995), and the recent recovery of an aetosaur skull from near the Borden County line by the Houston Museum of Natural History (Anne Proske, personal communication), Texas Tech is the only research institution to make significant collections in Garza County.

Green (1954) was the first to describe vertebrate material from the Dockum Group of Garza County. Most of Green's material was collected in the northern part of the county from a locality several miles east of Southland, probably in the Cooper Canyon Formation. This material consisted of fragmentary phytosaur material, a tiny procoelous vertebra, and a long, slender limb element. The latter was identified in the text as a fibula referable to *Trilophosaurus* (p. 79) or *Typothorax* (caption for pl. VIID), but it probably belongs to a shuvosaurid.

Nearly all subsequent collections in Garza County were made in the southern part of the county. The most productive and best known locality in this area is the Post (Miller) Quarry (MOTT 3624), which was excavated by workers at the Dallas Museum of Natural History and Texas Tech University during the late 1970s and early 1980s. The Dallas Museum collection contains important aetosaur material (Long and Murry, 1995), but the Texas Tech collection is larger and more diverse, consisting of numerous specimens (including several holotypes) of temnospondyls, therapsids, phytosaurs, aetosaurs, rauisuchians, and a variety of enigmatic diapsids (Chatterjee, 1986a; Small, 1989a; Long and Murry, 1995; Lehman and Chatterjee, 2005).

Other sites in southern Garza County have been collected during the last two decades, although little of this material has yet been published. The Boren Quarry (also called the Neyland Quarry, MOTT 3869), located near Justiceburg, has produced a rich microvertebrate fauna, as well as important metoposaur, phytosaur, and dicynodont material (Edler, 1999; Atanassov, 2002; Lehman and Chatterjee, 2005). A new taxon of procolophonid, *Libognathus sheddi*, was described from the UU Sand Creek (MOTT 3882) locality just southeast of Post, associated with a new aetosaur taxon (Small, 1997; Martz et al., 2003), and additional *Libognathus* material recovered from the Simpson Ranch (MOTT 3874) west of Post currently being described by Bill Mueller and Sankar Chatterjee (in review). Considerable vertebrate material, including cranial and postcranial material of the phytosaur *Pseudopalatus*, have been recovered from the Macy Ranch (MOTT 3631), Patricia Site (MOTT 3870), and associated localities along the caprock escarpment southwest of Post (McQuilkin, 1998; Cunningham et al., 2002; Hungerbühler et al., 2003; Lehman and Chatterjee, 2005). A new species of *Trilophosaurus*, *T. dornorum*, was recently described from the Lott Hill (MOTT 3878), Post Quarry, and Boren Quarry localities (Mueller and Parker, 2006). These localities, as well as others scattered throughout the southern part of the county, sample multiple stratigraphic levels in the Dockum Group, and provide a broad (if probably incomplete) picture of faunal change.

Systematic Paleontology

As I will be discussing largely unpublished material, it is important to note that, with the exception of aetosaur material being investigated by myself, most identifications were made by other researchers who have been extremely generous in sharing their unpublished observations. Current research on Dockum Group vertebrates from southern Garza County is being undertaken by Bill Mueller (metoposaurs, dicynodonts, most microvertebrates), Axel Hungerbühler and Michelle Stocker (phytosaurs), Bill Parker and myself (aetosaurs), Jonathan Weinbaum, Sterling Nesbitt, Randy Irmis, and Jeremiah Kokes (rauisuchians and dinosauromorphs), Susan Evans, and Nick Fraser (assorted small diapsids). Although I have examined the material discussed below, nearly all identifications were originally made by these workers.

Not all material in the MOTT collections from southern Garza County is discussed below. There are numerous specimens consisting of isolated and often fragmentary elements, some of which may ultimately prove diagnostic, but for now can only be placed tentatively in higher taxa such as “Vertebrata *incertae sedis*,” “Reptilia *incertae sedis*,” or “Archosauriformes *incertae sedis*.” Such material cannot contribute anything to biostratigraphy, so there is little point in discussing it. There are also numerous isolated teeth in the MOTT collections from the Dockum Group in southern Garza County which are probably diagnostic, although these will not be discussed here.

OSTEICHTHYES Huxley, 1880

ACTINOPTERYGII Klein, 1885

PALAEONISCIDAE Vogt, 1852

***TURSEODUS* Leidy, 1857**

***Turseodus dolorensis* Schaeffer, 1967**

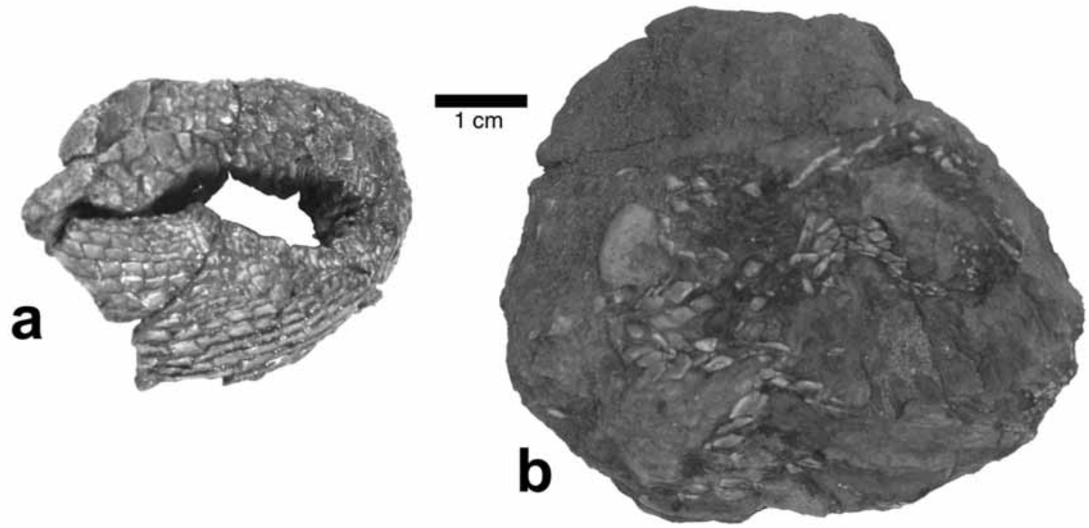


Fig. 4.1. Osteichthyans: *a, Turseodus dolorensis* (TTU P-10361) from the OS Ranch Fish locality; *b*, unidentified mass of bones and scales from the Patricia Site.

Occurrences in Southern Garza County: OS Ranch Fish (MOTT 3702), Boren Ranch beds.

Osteichthyes *incertae sedis*

Occurrences in Southern Garza County: OS Ranch (MOTT 3867), Boren Ranch beds; Boren Quarry (MOTT 3869), lower unit of the Cooper Canyon Formation; Headquarters South (MOTT 3898), middle unit of the Cooper Canyon Formation; Patricia Site (MOTT 3870), upper unit of the Cooper Canyon Formation.

Discussion: Remarkably, fish remains are rarely collected in the Dockum Group of southern Garza County, and the only specimen in the MOTT collections identified to an alpha taxon is a partial skull and series of scales (TTU P-10361, Fig. 4.1a) referable to *Turseodus dolorensis* (Schaeffer, 1967) (Bill Mueller and Sankar Chatterjee, personal communication). This specimen was collected by Father Malcom Neyland from the OS Fish locality (MOTT 3792) on the OS Ranch, which probably lies in the Boren Ranch beds or lowermost Cooper Canyon Formation. Most other fish remains are undiagnostic, although a well preserved mass of scales and associated bones (Fig. 4.1b) recovered from the Patricia Site (MOTT 3870) may be identifiable. The lacustrine deposits associated with the Boren Ranch beds and base of the lower unit of the Cooper Canyon Formation are probably the best place to look for fish material, especially when considering that correlative strata in the Tecovas Formation of Crosby County have produced abundant fish faunas (Warthin, 1928; Murry, 1982, 1986; Heckert, 2004).

TETRAPODA Goodrich, 1930

AMPHIBIA Linnaeus, 1758

LABYRINTHODONTIA H. von Meyer, 1842

TEMNOSPONDYLI Zittel, 1887-1890

STEREOSPONDYLI Zittel, 1887

METOPOSAURIDAE Watson, 1919

***METOPOSAURUS* Lydekker, 1890**

***Metoposaurus bakeri* Case, 1931**

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869), lower unit of the Cooper Canyon Formation.

***APACHESAURUS* Hunt, 1993**

***Apachesaurus gregorii* Hunt, 1993**

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

METOPOSAURIDAE *incertae sedis*

Occurrences in Southern Garza County: OS Ranch (MOTT 3867) and OS Ranch East (MOTT 3873), Boren Ranch beds; Boren Quarry (MOTT 3869), lower unit of the Cooper Canyon Formation; Green Tooth Arroyo (MOTT 3901), middle unit of the Cooper

Canyon Formation; Patricia Site (MOTT 3870), Patty East (MOTT 3880), and Audad Bluff (MOTT 3895), upper unit of the Cooper Canyon Formation.

Discussion: Metoposaur systematics was reviewed most recently by Hunt (1993), who also provided the first thorough revision of the group following the work of Colbert and Imbrie (1956) and Roy-Chowdury (1965). Hunt (1993) placed all the previously named North American taxa into three: *Metoposaurus bakeri* (Case, 1931), *Buettneria perfecta* (Case, 1922), and *Apachesaurus gregorii* (Hunt, 1993). *Apachesaurus* is distinguished from the other two taxa by its smaller adult size and several morphological characters, including a shallow otic notch and reduced tabular horn (Gregory, 1980; Davidow-Henry, 1987, 1989). Hunt (1993) suggested it might have had more terrestrial lifestyle than the larger forms due to its association with terrestrial vertebrates, its weakly developed lateral line system, and a well-developed acetabulum on the illium. The larger taxa with deep otic notches and enlarged tabular horns, *Buettneria* and *Metoposaurus*, were distinguished from each other by Hunt (1993) primarily on whether or not there was contact between the lacrimal and orbit. Hunt claimed that the lacrimal is excluded from the orbit in *Metoposaurus diagnosticus* (Lydekker, 1890; the European type species), and therefore assigned North American material sharing this feature to the genus *Metoposaurus* as the species *M. bakeri*, and used Case's (1922) genus *Buettneria* for specimens in which the lacrimal contacted the orbit. This alpha taxonomy has been generally followed by subsequent workers, although Mueller (2007) has noted that the genus name *Buettneria* (Case, 1932) is preoccupied, and the next available genus name for material referred to *Buettneria perfecta* is *Koskinonodon* (Branson and Mehl, 1929), which alters the species name to *K. perfectum*.

However, Sulej (2002) and Milner and Schoch (2004) reexamined the European material and determined that in *Metoposaurus diagnosticus*, the lacrimal does indeed enter the orbit. Lucas et al (2007c, fig. 2) continue to argue that the lacrimal is separated from the orbit in *Metoposaurus diagnosticus*, although their interpretive drawing of the elements shows a broad contact between the jugal and prefrontal pushing the lacrimal alongside the nasal almost to the external nares, a configuration which looks considerably different from "*Metoposaurus" bakeri* (Fig. 4.2a-c; Hunt, 1993, fig. 4B) and it may be that their "lacrimal" is actually part of the maxilla and their "jugal" is actually the lacrimal. If the lacrimal character is sufficient justification for generic distinction and the reinterpretations of Sulej (2002) and Milner and Schoch (2004) are correct, this would require *Koskinonodon perfectum* to be lumped into *Metoposaurus*, and a new genus being found for "*Metoposaurus" bakeri*. However, in *Metoposaurus diagnosticus*, the area of the interclavicle covered with rounded and hexagonal pits was smaller than in both of the North American species (Colbert and Imbrie, 1956; Sulej, 2002). Sulej (2002) lumped both North American species into "*Buettneria*," presumably based on either the shared interclavicle ornamentation or its geographic co-occurrence, so an alternative might be to assign both North American species to *Koskinonodon*.

In summary, during the past decade and a half, assignment of the two North American species to particular genera has been based only on single characters; either the contact of the lacrimal with the orbit (Hunt, 1993), or the patterning on the interclavicles (Sulej, 2002). Neither of these characters seem sufficient to warrant a genus level distinction, and the best solution may ultimately be to simply lump *both* North American species into *Metoposaurus*. However, pending a thorough re-evaluation of the North American material, for the time being I maintain the distinction advocated by Hunt (1993), though it is dubious as to whether it can be defended on the basis of either the lacrimal or interclavicles characters.

The only large metoposaur specimens from southern Garza County in which the alpha taxon is identifiable are two large, beautifully preserved skulls (TTU P-10530, TTU P-11046; Fig. 4.2a-c; Houle and Mueller, 2004) from the Boren Quarry (MOTT 3869), at the base of the lower unit of the Cooper Canyon Formation. The lacrimal is excluded from the orbit in these specimens, and they are therefore referable to "*Metoposaurus" bakeri* using Hunt's (1993) criterion, although they are considerably larger than other specimens referred to this taxon from the Elkins Place locality (Case, 1931, 1932), and

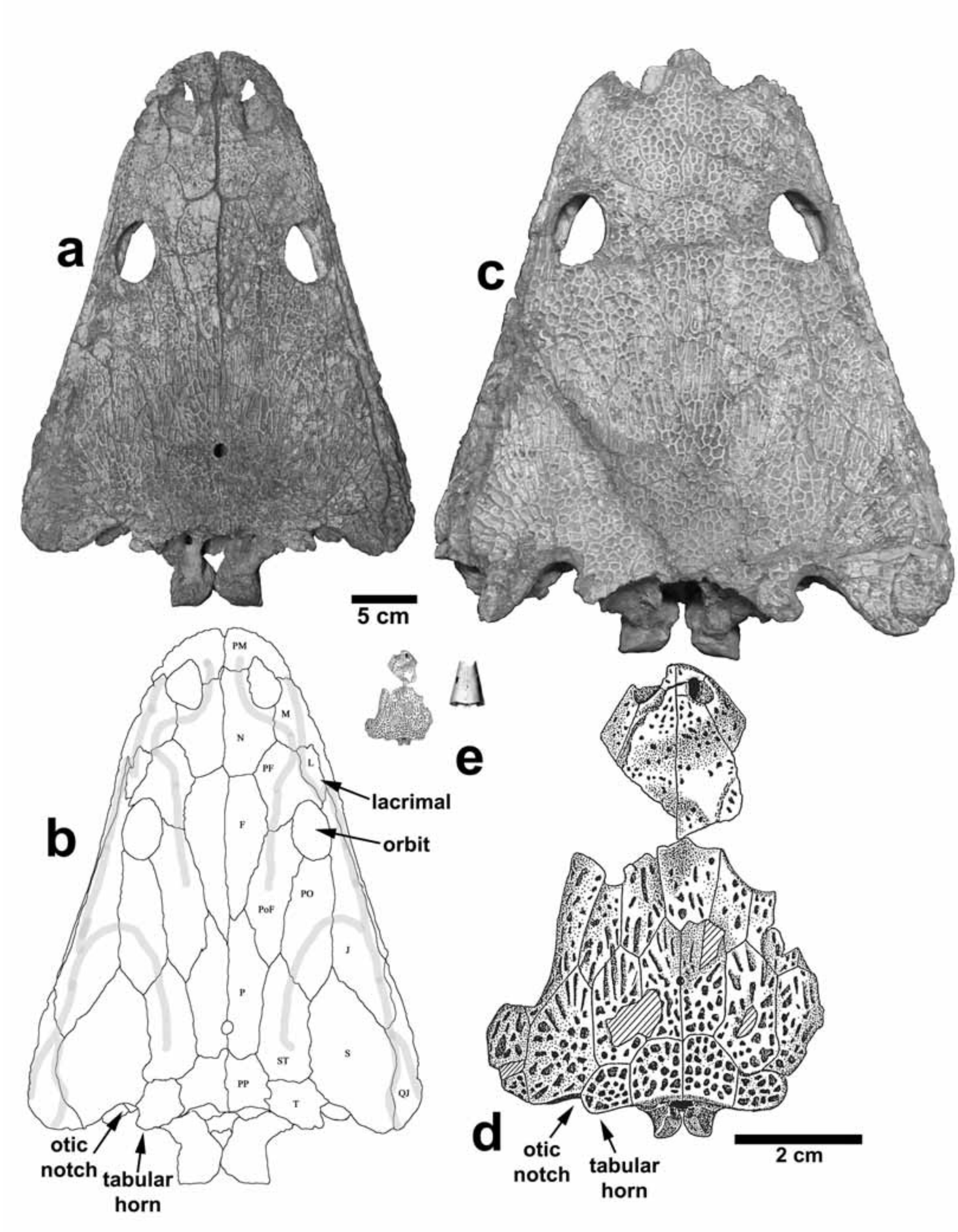


Fig. 4.2. Metoposaurs: a, skull of "Metoposaurus" bakeri (TTU P-10530) from the Boren Quarry in dorsal view; b, interpretive drawing of same specimen showing diagnostic features of taxon (photo and drawing both courtesy Bill Mueller); c, another skull of "Metoposaurus" bakeri (TTU P-11046) from the Boren Quarry in dorsal view; d, skull of Apachesaurus gregorii (TTU P-9216) from the Post Quarry in dorsal view (source: Davidow-Henry, 1989, fig. 1); e, Apachesaurus and Rilleymillerus skulls from the Post Quarry to same scale as Metoposaurus skulls.

may represent a new species (Houle and Mueller, 2004; Bill Mueller, personal communication).

The only material from southern Garza County definitely referable to *Apachesaurus gregorii* is a partial skull and mandible (TTU P-9216; Fig. 4.2c-d; Davidow-Henry 1987, 1989; Long and Murry, 1995) collected from the Post Quarry (MOTT 3624) near the top of the lower unit of the Cooper Canyon Formation. This specimen was misplaced while on loan, and its current whereabouts are unknown, although a natural mold remains in the MOTT collection.

The identification of other metoposaur material is more problematic. Isolated elements may be identifiable as metoposaur, particularly the distinctive highly sculptured cranial and pectoral elements, but referral to a particular alpha taxon presents problems. As *Apachesaurus* is a small metoposaur, even fragmentary material of a large specimen probably belongs to either "*Metoposaurus" bakeri* or *Koskinonodon perfectum* (sensu Hunt, 1993; Mueller, 2007), the only two metoposaur taxa known from the western United States. However, these cannot be assigned to one or the other unless enough of the skull is preserved to show the relationship between the lacrimal and the orbit. Moreover, the diagnostic features of *Apachesaurus* lie in the skull, vertebrae, and illium (Hunt, 1993a), so unless these elements are well preserved it is difficult to determine if a small specimen belongs to *Apachesaurus* or to a juvenile of "*Metoposaurus"* or *Koskinonodon*. All such undiagnostic material is referred here to Metoposauridae *incertae sedis*. I am also mindful of Hunt's (1993a) admonition that large non-metoposaur temnospondyls may yet turn up in North America, so caution should be taken in identifying all undiagnostic temnospondyl material to the Metoposauridae, but I will do so until definite large non-metoposaur temnospondyls emerge.

In southern Garza County, the fragmentary remains of indeterminate large metoposaurs (e.g. TTU P-9424, TTU P-11295), are most commonly found in at the OS Ranch and associated localities (MOTT 3867, MOTT 3873) in the Boren Ranch beds, and the Boren Quarry (MOTT 3869) at the bottom of the lower unit of the Cooper Canyon Formation, but large metoposaur remains (e.g. TTU P-10761, TTU P-11158,

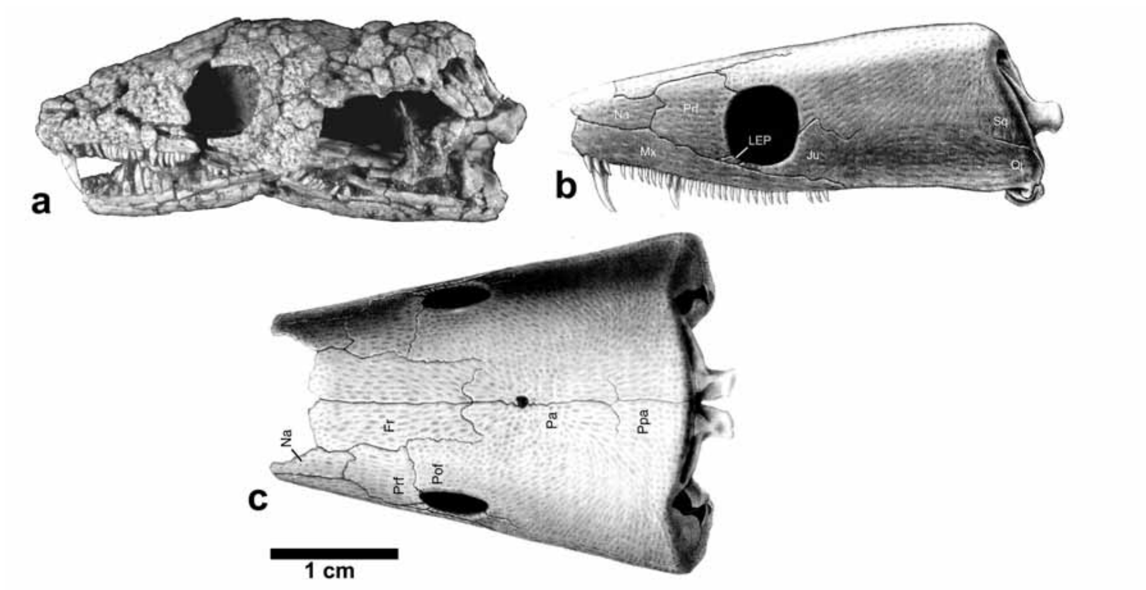


Fig. 4.3. *Rileymillerus cosgriffi* (TTU P-9168) from the Post Quarry: *a*, skull in left lateral view (photo courtesy Bill Mueller); skull reconstructions in *b*, left lateral view and *c*, dorsal view (source: Bolt and Chatterjee, 2000, text fig. 2).

TTU P-10775) are also known from the Patricia Site (MOTT 3870), Patty East (MOTT 3880), and Audad Bluff (MOTT 3895) localities near the top of the upper unit of the Cooper Canyon Formation, indicating that "*Metoposaurus"* or *Koskinonodon* persisted until the end of Cooper Canyon Formation deposition.

TEMNOSPONDYLI *incertae sedis*

***RILEYMILLERUS* Bolt and Chatterjee, 2000**

***Rileymillerus cosgriffi* Bolt and Chatterjee, 2000**

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

Discussion: Except for *Latiscopus disjunctus* from the Otis Chalk locality of Howard County (Wilson, 1948), *Rileymillerus cosgriffi* (Fig. 4.3) is the only known temnospondyl from western North America that is definitely not referable to the Metoposauridae.

The type and only specimen (TTU P-9168) from the Post Quarry (MOTT 3624) in the lower unit of the Cooper Canyon Formation is a tiny, nearly complete skull and mandible with an associated string of vertebrae. The skull shows several features distinguishing it from metoposaurs, including the lack of lateral line grooves, highly derived ascending lamina of the pterygoid, complete lack of tabular horns or squamosal embayments (Fig. 4.3c), and the relatively unflattened nature of the skull (Fig. 4.3b; Bolt and Chatterjee, 2000). The lack of lateral line canals, highly ossified nature of the skull, and presence in the overbank deposits of Post Quarry associated with primarily terrestrial vertebrates, all suggest that little *Rileymillerus* may have been more terrestrial than larger metoposaurs (Bolt and Chatterjee, 2000; Lehman and Chatterjee, 2005).

AMNIOTA Haeckel 1866

SYNAPSIDA Osborn, 1903

THERAPSIDA Broom, 1905

ANOMODONTIA Owen, 1859

DICYNODONTIA Owen, 1859

DICYNODONTIA nov. gen. et sp.

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869), lower unit of the Cooper Canyon Formation.

DICYNODONTIA *incertae sedis*

Occurrences in Southern Garza County: OS Ranch (MOTT 3867), Boren Ranch beds; Boren Quarry (MOTT 3869), Meyer’s Hill (MOTT 3881), and Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

Discussion: All dicynodont material in southern Garza County (Fig. 4.4) comes from the lower part of the Dockum Group, from the mudstone-dominated Boren Ranch beds, and from the lower unit of the Cooper Canyon Formation. The majority of this material is

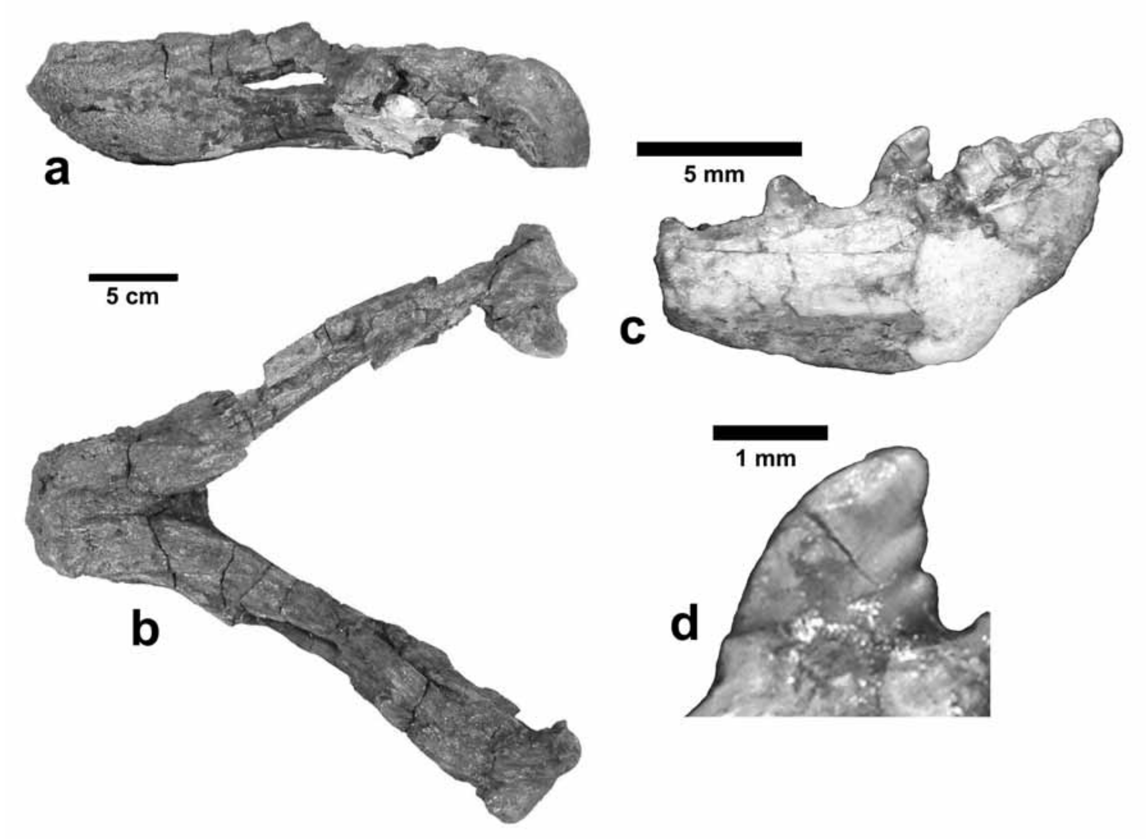


Fig. 4.4. Therapsids: *a*, mandible (TTU P-9421) possibly referable to a new dicynodont taxon from the Boren Quarry in left lateral view; *b*, same mandible in dorsal view; *c*, indeterminate trithelodontid dentary with teeth (TTU P- 9020) from the Post Quarry, holotype of *Pachygenelus milleri* (Chatterjee, 1983); *d*, close up of postcanine tooth of same specimen (photograph courtesy Bill Mueller).

taxonomically indeterminate beyond being dicynodont, but some is diagnostic. Interestingly, none of the material can be assigned with certainty to *Placerias*, the only dicynodont yet named from North America (Camp and Welles, 1956; Cox, 1965), and at least some is clearly not referable to that taxon (Mueller and Chatterjee, 2007). The stratigraphically lowest dicynodont material is a large right scapula (TTU P-10404) from the OS Ranch (MOTT 3867) in the Boren Ranch beds. The only taxonomically diagnostic dicynodont material in southern Garza County comes from the Boren Quarry (MOTT 3869) near the bottom of the lower unit of the Cooper Canyon Formation. Contra Edler (1999), the alleged partial "dicynodont" skull (TTU P-9427) from this site she referred to the South American genus *Ischigualastia* is not dicynodont (Axel Hungerbühler, personal communication), and although there is a fair amount of bona-fide dicynodont material, none is referable with certainty to *Placerias* (Mueller and Chatterjee, 2007, in prep). The best is a partial skull (TTU P-10402) referable to a new taxon which seems to have closer affinities to South American and Moroccan dicynodonts than to *Placerias* (Mueller and Chatterjee, in prep.). TTU P-9421, an excellent, nearly complete mandible (Fig. 4.4a-b; previously figured by Lehman and Chatterjee, 2005, fig. 12) and other fragmentary cranial and postcranial dicynodont material were recovered at the same locality and stratigraphic level, and may also be referable to this taxon (Mueller and Chatterjee, in prep).

From near the top of the lower unit of the Cooper Canyon Formation there is a large left humerus (TTU P-10421) from Meyer's Hill (MOTT 3881) which is probably not referable to *Placerias* (Mueller and Chatterjee, 2007), and a small left femur (TTU P-9417, Fig. 4.4f) from the Post Quarry (MOTT 3624). These are the stratigraphically highest dicynodont specimens in southern Garza County, both from not far below the base of the Dalby Ranch sandstone and Cooper Creek beds.

CYNODONTIA Owen, 1861

PROBAINOGNATHIA Hopson, 199

TRITHELODONTIDAE Broom, 1912

TRITHELODONTIDAE *incertae sedis*

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

Discussion: Chatterjee (1983) reported a new species of the genus *Pachygenelus*, a trithelodont taxon known from South Africa and Nova Scotia (Gow, 1980; Shubin et al., 1991), from the Post Quarry (MOTT 3624). The holotype of "*Pachygenelus milleri*" (TTU P-9020) is a dentary fragment containing a few emergent tooth crowns (Fig. 4.4c), the best of which Chatterjee (1983) identified as the second postcanine (Fig. 4.4d). The tooth is mediolaterally compressed and has a smoothly recurved main cusp with two posterior cusps. Chatterjee (1983) erroneously reported three posterior cusps, the main basis for identifying TTU P-9020 as a new species.

Shubin et al. (1991, p. 1063) claimed that the referral of TTU P-9020 to *Pachygenelus* was dubious as it "lacks any diagnostic cynodont characters because all the teeth are fused to the jaw and there are no cingula on the postcanine teeth." TTU P-9020 does indeed lack a cingulum on either the lingual or buccal surface of the good tooth. However, although cingula are present and well developed on the posterior lower postcanines of *Pachygenelus monus* (Gow, 1980), they are absent on the lower postcanines of other recently described trithelodont taxa (Bonaparte et al., 2001; Martinelli et al., 2005), which seem to be similar to the Post Quarry specimens. The claim by Shubin et al. (1991) that the tooth is fused into the socket is also questionable. The dentary is somewhat overprepared, including around the base of the teeth, and there is still matrix in place around the base of the crown that cannot be removed without damaging the tooth, obscuring the nature of the tooth implantation.

Hopson (personal communication to Sidor and Hancox, 2006) suggested that TTU P-9020 is a fish. This allegation is dubious, as the tooth does not resemble that of any known fish from the Upper Triassic of western North America. TTU P-9020, although probably not referable to *Pachygenelus* due to the lack of a cingulum, is probably still a trithelodont. It is tentatively referred here to Trithelodontidae *incertae sedis*. Two additional specimens from the Post Quarry, a tooth in another partial mandible (TTU P-9245) and an isolated crown (TTU P-10826), both have identical tooth morphology to TTU P-9020, and may be referable to the same taxon.

REPTILIA Linnaeus, 1758

PARAREPTILIA Olson, 1947

PROCOLOPHONIDAE Seeley, 1888

LEPTOPLEURONINAE Ivachnenko, 1979

***LIBOGNATHUS* Small, 1997**

***Libognathus sheddi* Small, 1997**

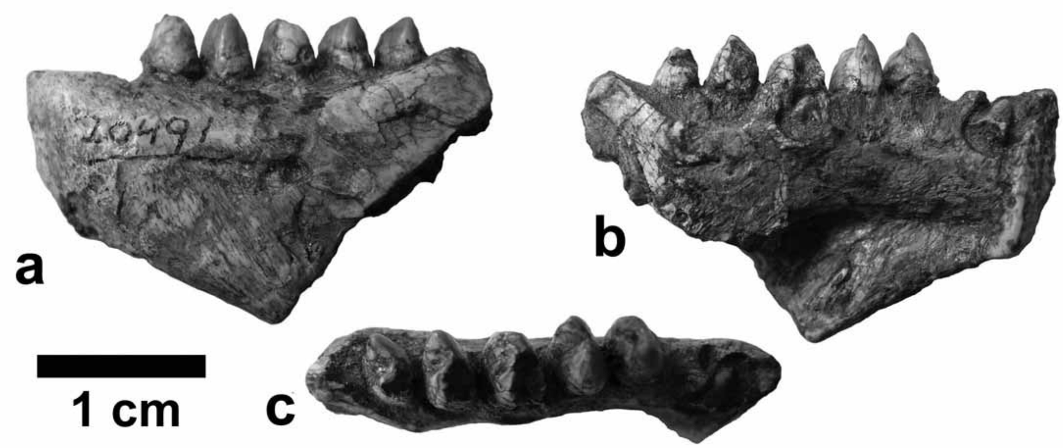


Fig. 4.5. Holotype left dentary with partial coronoid of *Libognathus sheddi* (DMNS 20491) in*: a*, lateral view; *b*, medial view; *c*, and dorsal view (photos courtesy Bill Mueller).

Occurrences in Southern Garza County: UU Sand Creek (MOTT 3882), middle unit of the Cooper Canyon Formation; Simpson Ranch (MOTT 3874), upper unit of the Cooper Canyon Formation.

Discussion: The procolophonids subfamily Leptopleuroninae (Ivachnenko, 1979; Modesto et al., 2002) includes the well known Upper Triassic taxa *Hypsognathus* (Colbert, 1946; Sues et al., 2000) and *Leptopleuron* (Benton and Walker, 1985; Spencer, 2000). Most if not all other Upper Triassic procolophonids, including those known from western North America, are probably leptopleurines, or at least have affinities with members of the group (Benton and Spencer, 1995; Sues and Baird, 1998; Sues et al., 2000; Fraser et al., 2005). *Libognathus sheddi* (Small, 1997), a taxon known only from the Dockum Group of southern Garza County, also falls within this group (Small, 1997; Sues et al., 2000; Mueller and Chatterjee, in review). The holotype (Fig. 4.5) is a partial mandible (DMNS 20491) Small (1997) described from the UU Sand Creek locality (MOTT 3882) just southeast of Post, associated with a new aetosaur taxon. This locality lies in a conglomerate closely associated with the Miller Ranch sandstone. More recently, additional specimens, including cranial and mandibular material (TTU P-10068, TTU P-10069, TTU P-10081; TTU P-10523) and associated postcrania (TTU P-10524, TTU P-10525, TTU P-11151) were recovered from the Simpson Ranch (MOTT 3874) west of Post (Mueller and Chatterjee, 2003, in review). This locality is located higher in the Cooper Canyon Formation than the type locality (contra Mueller and Chatterjee, 2003), not far below the Macy Ranch sandstone. The peculiar putative procolophonid *Colognathus* (Murry, 1986; Heckert, 2004) is not known from southern Garza County.

EUREPTILIA Olson, 1947

DIAPSIDA Osborn, 1903

SAURIA Gauthier, 1984

LEPIDOSAUROMORPHA Benton, 1983 *sensu* Gauthier et al., 1988

LEPIDOSAURIA Haeckel, 1866

RHYNCHOCEHALIA Günther, 1867

SPHENODONTIA Williston, 1925

cf. *Clevosaurus*

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

SPHENODONTIA *incertae sedis*

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869) and Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

Discussion: Nick Fraser (personal communication) has been reviewing some material from the Dockum Group of southern Garza County, and has confirmed the presence of a sphenodontian pterygoid (TTU P-9487) from the Boren Quarry (MOTT 3869) and of a sphenodontid mandible (TTU P-9473) and a premaxilla with similarities to *Clevosaurus* (TTU P-9472) from the Post (Miller) Quarry (MOTT 3624). No other sphenodontid material is yet known from southern Garza County.

ARCHOSAUROMORPHA Huene, 1946 *sensu* Gauthier et al., 1988

PROTOROSAURIA Huxley, 1871

***MALERISAURUS* Chatterjee, 1980**

***Malerisaurus* sp.**

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869) and Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation, and Headquarters North (MOTT 3900), middle unit of Cooper Canyon Formation.

Discussion: *Malerisaurus robinsonae* is a putative protorosaur Chatterjee (1980) described Upper Triassic material in India, and he later referred a second species, *M. langstoni*, based on material from Otis Chalk Quarry 2 (the "Small Reptile Quarry") in Howard County, western Texas (Chatterjee, 1986b). Both specimens are based on fairly good postcranial material representing most parts of the skeleton, and somewhat fragmentary skull material.

Both Evans (1988) and Rieppel et al. (2003) were hesitant about the assignment of *Malerisaurus* to "Protorosauria" (largely due to the incomplete nature of the cranial material) although they accepted that the taxon is probably some kind of archosauromorph, but Benton and Allen (1997) and Jalil (1997) considered it a protorosaur in their analyses. Recently, Spielmann et al. (2006a) claimed that the holotype of *Malerisaurus langstoni* is a chimera composed of trilophosaur, aetosaur, phytosaur, and rhynchosaur material. However, they based their referral of elements on non-diagnostic plesiomorphies found in a variety of archosauromorphs (e.g. un-used review of the paper by Sterling Nesbitt), and several subtle differences between the postcrania of *Trilophosaurus* and Chatterjee's (1986b) *Malerisaurus* material may distinguish them (Bill Mueller, personal communication).

Several elements have been recovered from the Boren Quarry (MOTT 3869) in southern Garza County, which appear generally consistent with Chatterjee's (1980, 1986b) descriptions and figures for *Malerisaurus*. However, few elements preserve the species diagnostic characters identified by Chatterjee (1986b), and others show subtle differences from previously described material, so the Boren Quarry specimens are referred only to *Malerisaurus* sp. Two cervical vertebrae (TTUP P-10346, TTU P-10347) and several femora (e.g. TTU P-10563, TTU P-10567, TTU P-11688) appear identical to those of *Malerisaurus* (Chatterjee, 1980, 1986b), but most of the other material from the Boren Quarry consists of limb elements which are slightly different from the previously described specimens. An unprepared skeleton, including some skull material (TTU P-10482) may shed more light on the morphology of this taxon. A cervical vertebra (TTU P-11338) is known from the Post Quarry at the top of the lower unit, and a proximal femur (TTU P-11334) has been collected from the Headquarters North site in the middle unit of the Cooper Canyon Formation.

DREPANOSAURIDAE Olson and Sues, 1986
cf. *DREPANOSAURUS*

Occurrences in Southern Garza County: Headquarters South (MOTT 3898), middle unit of the Cooper Canyon Formation.

***PROTOAVIS*? (in part) Chatterjee, 1991**
***Protoavis texensis*? (in part) Chatterjee, 1991**

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

DREPANOSAURIDAE *incertae sedis*

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869) and Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation; Headquarters (MOTT 3892) and Headquarters South (MOTT 3898), middle unit of the Cooper Canyon Formation.

Discussion: Identification of drepanosaur elements from southern Garza County has been somewhat problematic, consisting of isolated and often fragmentary material. This material is currently being described by Bill Mueller and Sankar Chatterjee, and includes material from the Boren Quarry (MOTT 3869) at the bottom of the lower unit of the Cooper Canyon Formation (TTU P-10843), and from the Post Quarry (MOTT 3624), near the top of the lower unit (TTU P-10843, TTU P-9604, TTU P-9606, TTU P-11237). The suggestion by Renesto (2000) and Paul (2002) that *Protoavis texensis* material from the Post Quarry (Chatterjee, 1991) may also be a drepanosaur will be discussed later.

All other putative drepanosaur material from southern Garza County comes from the Headquarters and Headquarters South localities (MOTT 3892 and 3898), lying just below the Miller Ranch sandstone. The material mostly consists of vertebrae (e.g. TTUP P-10814, P-10816, P-10823, P-10887, P-10907, P-10976, and P-11154) although there are a few other intriguing postcranial elements (TTU P-10894, TTU P-10890, P-10896, TTU P-10898, TTU P-10895).

TRILOPHOSAURIA Romer, 1956

TRILOPHOSAURIDAE Gregory, 1945

***TRILOPHOSAURUS* Case, 1928**

***Trilophosaurus buettneri* Case, 1928a**

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869), lower unit of the Cooper Canyon Formation.

***Trilophosaurus jacobsi* Murry, 1987**

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869), lower unit of the Cooper Canyon Formation.

***Trilophosaurus dornorum* Mueller and Parker, 2006**

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869) and Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation; Lott Hill (MOTT 3878), middle unit of the Cooper Canyon Formation.

Trilophosaurus sp.

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869), lower unit of the Cooper Canyon Formation.

Discussion: Three species of *Trilophosaurus* have been named. The type species, *Trilophosaurus buettneri* (Case, 1928) is best known from extensive cranial and postcranial material from the Otis Chalk localities in Howard Country. This material was described in detail by Gregory (1945), with later work by Parks (1969), Elder (1978), Demar and Bolt (1981), and Merck (1995) dealing primarily with cranial and dental morphology. *Trilophosaurus jacobsi* (Murry 1986, 1987; =*Chinleogomphius* Sues and Olsen, 1993; Long and Murry, 1995) is best known from extensive cranial and postcranial material from the Kahle Quarry in the Dockum Group of Borden County (Heckert et al. 2006; Spielmann et al., 2005, 2007a). Most recently, Mueller and Parker (2006) described a third species, *Trilophosaurus dornorum*, based on jaw and tooth material from the Chinle Formation of Arizona and the Dockum Group of southern Garza County. Mueller and Parker (2006, p. 123) also alluded to two as of yet undescribed trilophosaurs from southern Garza County being described by Bill Mueller.

The teeth of *Trilophosaurus* exhibit a degree of heterodonty, with the anteriormost and posteriormost teeth being relatively small and nearly conical, while the intervening teeth are large and transversely expanded, with three distinct cusps and a cingulum. The different species of *Trilophosaurus* are distinguished primarily on differences between the transversely expanded teeth (Murry, 1987; Heckert et al., 2006; Mueller and Parker, 2006). In *T. buettneri*, these teeth have cusps of subequal height

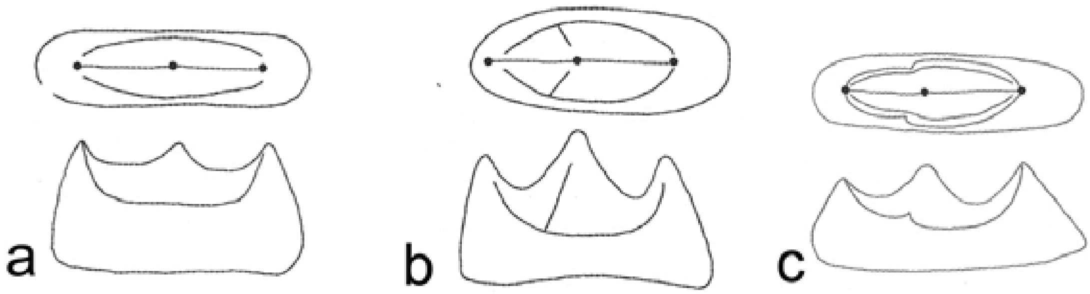


Fig. 4.6. Diagrammatic drawings of the teeth of three species of *Trilophosaurus*, labial to the left and lingual to the right (source: Mueller and Parker, 2006, fig. 4) *g*, *Trilophosaurus buettneri*; *h, Trilophosaurus jacobsi*; *i, Trilophosaurus dornorum.*

with the central cusp roughly equidistant between the labial and lingual cusps, cingula connecting the labial and lingual cusps but not connecting these cusps to the medial cusp (Fig. 4.6a). In *T. jacobsi*, the medial cusp differs from the condition in *T. buettneri* in being taller than the labial and lingual cusps and closer to the labial cusp than the lingual cusp, although the cingula connect only the labial and lingual cusps as in the type species (Fig. 4.6b). In *T. dornorum*, the cusps are of subequal height as in *T. buettneri*, but the cingula connect all three cusps unlike either of the other species (Fig. 4.6c-d). The teeth and jaws of *T. dornorum* are also larger and more robust than in the other species, and there are fewer teeth posterior to the lateral process of the maxilla than in *T. buettneri*.

Spielmann et al. (2007a) questioned the validity of *T. dornorum*, indicating that it was junior synonym of *T. jacobsi*. Their evidence (p. 239) is that "large isolated maxilla and dentary fragments" they had referred to *T. jacobsi* from the Kahle Quarry show all the diagnostic features of *T. dornorum*, including its relatively large size. However, they do not make clear why they assign these teeth to large individuals of *T. jacobsi* instead of recognizing *T. dornorum* as a valid species co-existing in the Kahle Quarry with *T. jacobsi*. Specimens showing an intermediate size and morphology between *T. jacobsi* and *T. dornorum* and/or a mosaic of characters from both species might indicate that *T. dornorum* falls within the range of variation of *T. jacobsi*, but Spielmann et al.'s (2007a) description seems to indicate that, specimens from the Kahle Quarry seem to fall fully into the distinct morphotypes used by Mueller and Parker (2006) to distinguish the species.

Nearly all *Trilophosaurus* material from the Dockum Group of southern Garza County comes from the Boren Quarry (MOTT 3869) at the base of the lower unit of the Cooper Canyon Formation, and this material was partly described by Mueller and Parker (2006). The Boren Quarry trilophosaur fauna is remarkably diverse. A couple specimens are referable to *Trilophosaurus buettneri* (TTU P-9495, TTU P-12401), with most other material that is specifically determinate being referable to *T. jacobsi* and *T. dornorum* (Mueller and Parker, 2006). There is also abundant postcranial material, but as there has not yet been a careful comparative study of the good postcranial material known for *T. buettneri* (Gregory, 1945) and *T. jacobsi* (Spielmann et al., 2005), most can only be referred to *Trilophosaurus* sp. The two unnamed trilophosaur taxa alluded to by Mueller and Parker (2006, p. 123) referred to informally as "*Trilophosaurus* new taxon A" and "*Trilophosaurus* new taxon B" in Appendix 3, are also from the Boren Quarry.

The remaining two localities in southern Garza County to produce *Trilophosaurus* material are the Post Quarry (MOTT 3624) and Lott Hill (MOTT 3878), the former of which is located near the top of the lower unit of the Cooper Canyon Formation, just below the Cooper Creek beds, and the latter of which comes from slightly higher in the section, not far below the Route 669 Roadcut sandstone. The only species that can yet be recognized is *Trilophosaurus dornorum* (Mueller and Parker, 2006), making this the highest ranging species in southern Garza County.

ARCHOSAURIFORMES Gauthier, 1984

(=ARCHOSAURIA *sensu* Benton, 1999)

ARCHOSAURIFORMES *incertae sedis*

cf. *Doswellia*

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869), lower unit of the Cooper Canyon Formation.

Discussion: Weems (1980) described the enigmatic basal archosauriform(?) *Doswellia kaltenbachi* from the Newark Supergroup of Virginia, and the taxon is also known from the Otis Chalk localities (Long and Murry, 1995). *Doswellia* is characterized in part by its extensive covering of osteoderms, in which the ornamentation is deeply "honeycombed" or "punctate" (Weems, 1990; Long and Murry, 1995). *Doswellia* also has pronounced tongue and groove articulations on its osteoderms, which Long and Murry (1995) suggested was similar to *Desmatosuchus*, although the tongue and groove articular surfaces in *Doswellia* seem to be somewhat more pronounced. Both the deeply punctuate ornamentation and pronounced tongue and groove articulations are evident in a fragmentary osteoderm from the Boren Quarry (TTU P-11518), which may belong to *Doswellia* or a related taxon.

ARCHOSAURIA Cope, 1869 *sensu* Gauthier, 1986

(=AVESUCHIA *sensu* Benton, 1999)

PSUEDOSUCHIA Zittel, 1890 *sensu* Gauthier, 1986

CRUROTARSI Sereno and Arcucci, 1990

PARASUCHIA Huxley, 1875 *sensu* Sereno, 1991

***PALEORHINUS* Williston, 1904**

***Paleorhinus scurriensis* Langston, 1949**

Occurrences in Southern Garza County: Lake Alan Henry-Cedar Hill (MOTT 3890), Boren Ranch sandstone.

Paleorhinus* cf. *P. sawini

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869), lower unit of the Cooper Canyon Formation.

***Paleorhinus* sp.**

Occurrences in Southern Garza County: OS Ranch (MOTT 3867), Boren Ranch beds.

Discussion: The crocodilian branch of crown-clade Archosauria (*sensu* Gauthier, 1986; =Avesuchia *sensu* Benton, 1999) is variously referred to as Pseudosuchia (Gauthier, 1986), Crurotarsi (Sereno and Arcucci, 1990), or Crocodylotarsi (Benton and Clark, 1988), was the dominant clade during most of the Late Triassic, and includes most of the Dockum Group archosaurs. The phytosaurs, usually accepted to be the most basal group within Pseudosuchia (e.g. Sereno, 1991; Juul, 1994; Gower and Wilkinson, 1996), are arguably the single most important vertebrate group in the Upper Triassic deposits of the western United States. This is not only because they are the most common, but because they are the primary basis for vertebrate biostratigraphy and biochronology (e.g. Camp, 1930; Colbert and Gregory, 1957; Gregory, 1972; Long and Ballew, 1985; Long and Padian, 1986; Hunt and Lucas, 1991; Long and Murry, 1995; Lucas, 1998; Lucas et al., 2007b).

Several phytosaur taxa exhibit features that are relatively plesiomorphic among phytosaurs (in other words, more like the "normal" condition seen in other archosaurs, and diapsids in general). These include a prenarial snout that is relatively short compared to the postnarial part of the skull, external nares positioned anterior to the antorbital fenestra, and a supratemporal fenestra that is entirely level with the skull roof. There has been a strong tendency to lump these basal phytosaurs into the genus *Paleorhinus* (Williston, 1904) or *Parasuchus* (Lydekker, 1885 *sensu* Chatterjee, 2001), but there is some measure of controversy about the exact number of species (Hunt and Lucas, 1991a; Hunt, 1994; Long and Murry, 1995; Lucas et al., 2007a). However, Hungerbühler (1998, 2001a, 2002a, b) and Fara and Hungerbühler (2000) have tended to remain fairly conservative by not lumping basal phytosaur genera.

Lucas et al. (2007a, p. 226) rejected what they described as a "cladotaxonomic" approach to basal phytosaur alpha taxonomy: "primitive phytosaurs lived during the Late Triassic and were unaware of subsequent *a posteriori* cladistic reasoning more than 200 million years later. Those primitive phytosaurs constituted a biological entity that merits a Linnaean name, as do all other diagnosable biotaxa, and that name is *Parasuchus*." However, if basal phytosaurs were unaware they were a metataxon, they were equally unaware that they were a genus, an artificial and arbitrary taxonomic rank if ever there was one.   Lucas et al. (2007a) are not clear on what they mean when they identify a genus as a "biological entity." They diagnose *Parasuchus* by a suite of inherited plesiomorphic features, some of which are shared by "*Angistorhinus*" (*Rutiodon sensu* Hungerbühler, 2001b), and choose, apparently arbitrarily, to consider features of variation among basal phytosaurs (e.g. Long and Murry, 1995; Axel Hungerbühler, personal communication) less important. They also do not take into account that intermediates between basal phytosaurs and more derived taxa certainly existed, so that the apparently sharp differences between *Parasuchus* and other phytosaurs is essentially an artifact of the fossil record which may be blurred with future discoveries (as has happened with *Pseudopalatus* and *Redondasaurus*; see below). Genera may be useful (if arbitrary and artificial) taxonomic ranks, but it is hard to see how selective character appraisal and an incomplete fossil record makes *Parasuchus* a "biological entity" any more real than a cladotaxon. Hungerbühler's conservative approach to basal phytosaur genera is preferred here pending a more detailed comparison between the neotype of *Parasuchus* (Chatterjee, 2001; Anonymous, 2003) and the American genoholotypes of *Paleorhinus* (Williston, 1904) and *Promystriosuchus* (Case, 1922).

Nearly all North American basal phytosaurs come from the Dockum Group of West Texas, including the types of *Promystriosuchus ehlersi* (Case, 1922) from Crosby County, *Paleorhinus sawini* (Long and Murry, 1995) from Borden County, and *Paleorhinus scurriensis* from Scurry County (Langston, 1949), and well as material referred to *Paleorhinus bransoni* from the Otis Chalk localities and Palo Duro Canyon (Hunt and Lucas, 1991a; Long and Murry, 1995). Four basal phytosaur skulls are known from southern Garza County (Fig. 4.7), all from the Boren Ranch sandstone/beds and lower unit of the Cooper Canyon Formation, and therefore probably slightly stratigraphically higher than the type specimen of *Paleorhinus scurriensis* (TTU P-8090)

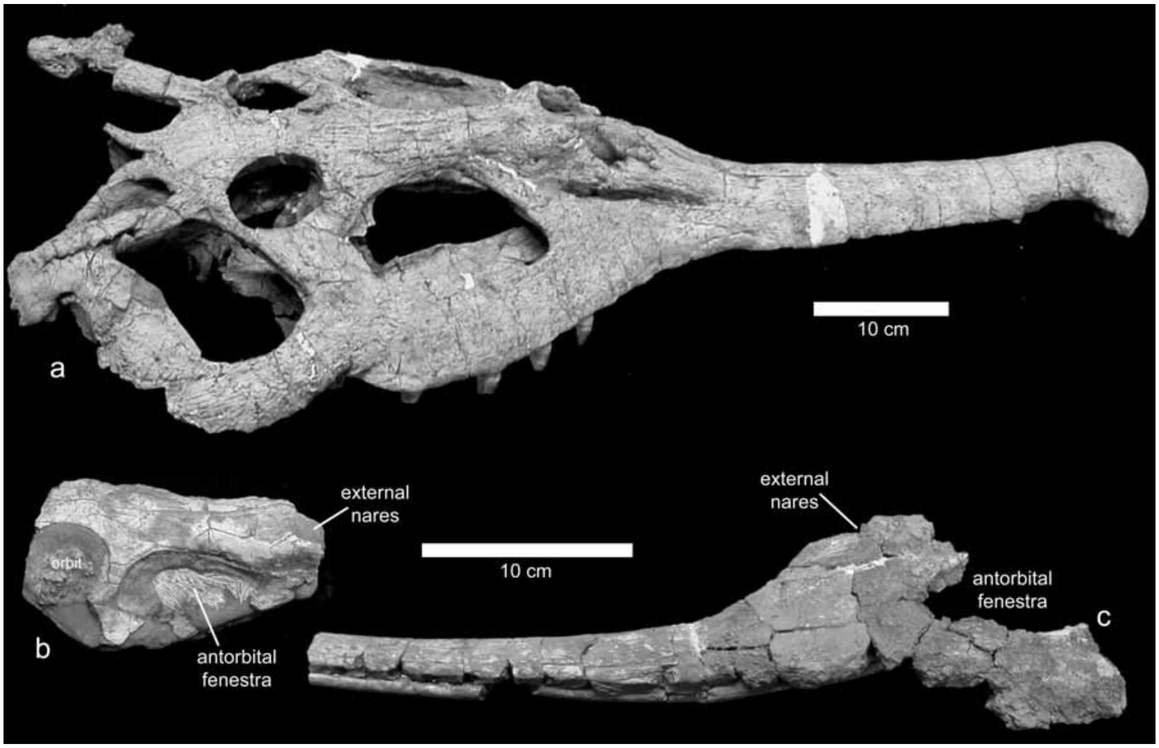


Fig. 4.7. *Paleorhinus*: *a*, skull of *Paleorhinus* cf. *P. sawini* (TTU P-9423) from the Boren Quarry in right dorsolateral view; *b*, partial skull of *Paleorhinus scurriensis* (TTU P-11422) from Lake Alan Henry-Cedar Hill in right dorsolateral view; c, partial skull of *Paleorhonus* sp. (TTU P-11706) from OS Ranch in left lateral view.

described by Langston (1949) from the Santa Rosa Sandstone(?) in adjacent Scurry County.

TTU P-9423 (Fig. 4.7a) is an excellent nearly complete skull with an associated mandible and considerable postcranial material, which was recovered from the Boren (Neyland) Quarry (MOTT 3869). It has anteriorly oriented external nares placed anterior to the antorbital fenestrae, an uncrested rostrum, large lateral temporal fenestrae, supratemporal fenestrae entirely contacting the skull roof, and short, truncated, and laterally ridged posterior squamosal processes, all of which characterize basal phytosaurs (e.g. Hunt and Lucas, 1991a; Long and Murry, 1995; Lucas et al., 2007a). The specimen lacks the extremely elongate snout and dorsally oriented orbits seen in *Promystriosuchus ehlersi* and *Ebrachosuchus neukami*, and also has a total upper tooth count smaller than these taxa (Gregory, 1962; Long and Murry, 1995). Although more similar to

Paleorhinus bransoni in possessing a prenarial and postnarial length that are roughly equal, dorsolaterally oriented orbits, and a tooth count of 42, the skull appears to be taller than is typical for that taxon and also has a ventrally convex maxilla and posteriorly enlarged aveoli in both the premaxilla and maxilla. This is more similar to the condition seen in the robust species, *Paleorhinus sawini* (Long and Murry, 1995), and it is tentatively assigned to *Paleorhinus* cf. *P. sawini*, although Axel Hungerbühler (personal communication, 2006) indicates the specimen may represent a new species. Another basal phytosaur skull from the Boren Quarry was recently found by Gretchen Gurtler, who is also preparing and describing it.

The other two partial basal phytosaur skulls are both from the Boren Ranch sandstone/beds. TTU P-11422 (Fig. 4.7b) is a partial skull roof from Lake Alan Henry (MOTT 3890), and TTU P-11706 (Fig. 4.7c) is a partial snout from the OS Ranch (MOTT 3867). Both are relatively small individuals with external nares which are distinctly placed anterior to the antorbital fenestrae. The orbits of TTU P-11422 appear to be dorsolaterally rather than dorsally oriented, and the posterior premaxillary teeth in TTU P-11706 do not appear to be enlarged, indicating that they are probably one of the more gracile species; Axel Hungerbühler (personal communication) and Michelle Stocker (personal communication) both consider TTU P-11422 referable to *Paleorhinus scurriensis*. I assign TTU P-11706 to *Paleorhinus* sp., as it is too incomplete for a more precise assignment.

LEPTOSUCHUS Case, 1922

Leptosuchus cf. _L. crosbiensis_

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

Discussion: The alpha taxonomy of phytosaurs more derived (and usually stratigraphically higher) than *Paleorhinus* and *Promystriosuchus* from the southwestern

United States has historically been highly confused. Most of these taxa share several derived features, including external nares that are not placed anterior to the antorbital fenestra, at least partial depression of the supratemporal fenestrae, and a long posterior process on the squamosal. They are distinguished from each other primarily by features of the temporal region, notably the width and surface morphology of postorbitosquamosal bar, the shape of the posterior process of the squamosal, and the degree of depression and narrowing of the supratemporal fenestra being particularly important (see particularly Camp, 1930; Ballew, 1989; Long and Murry, 1995; Hungerbühler, 2002b).

I follow the practice of several recent workers (e.g. Long and Murry, 1995; Hungerbühler, 2001b; Parker and Irmis, 2005, 2006) in applying the name *Leptosuchus* (Case, 1922) to many of the phytosaurs from western North America assigned to the *nomen nudum Machaeroprosopus* by Camp (1930), and the eastern North American taxon *Rutiodon* by others (e.g. Gregory, 1962; Westphal, 1976; Ballew, 1989; Hunt, 1994; Lucas et al., 2007b), although the latter genus may be a senior synonym of the western North American taxon *Angistorhinus* rather than *Leptosuchus* (Hungerbühler, 2001b). *Leptosuchus* is characterized by a deep, crested rostrum with a V-shaped cross section, the depression of the posterior rim of the posttemporal arch and supratemporal fenestrae below the level of skull roof, and a postorbitosquamosal bar which is still narrow compared to the more derived pseudopalatines (Long and Murry, 1995).

Only one skull from southern Garza County is currently referable to *Leptosuchus*: TTU P-9234 (Fig. 4.8) from the Post Quarry (MOTT 3624) (Lehman and Chatterjee, 2005). This skull is nearly complete except for the left side of the temporal region (Fig. 4.8a), although it is in bad need of extensive repreparation, and also includes most of both mandibles. This skull has previously been referred to *Nicrosaurus* (Chatterjee, 1986a; Simpson, 1998) due to the possession of a crest which extends all the way down the snout (Fig. 4.8b). However, although the laterally facing orbits, depressed supratemporal fenestra, and external nares positioned over the antorbital fenestra indicate this is a derived phytosaur, the specimen is clearly not a pseudopalatine (*sensu* Hungerbühler, 2002b). The supratemporal fenestra, although partly reconstructed, is clearly not as

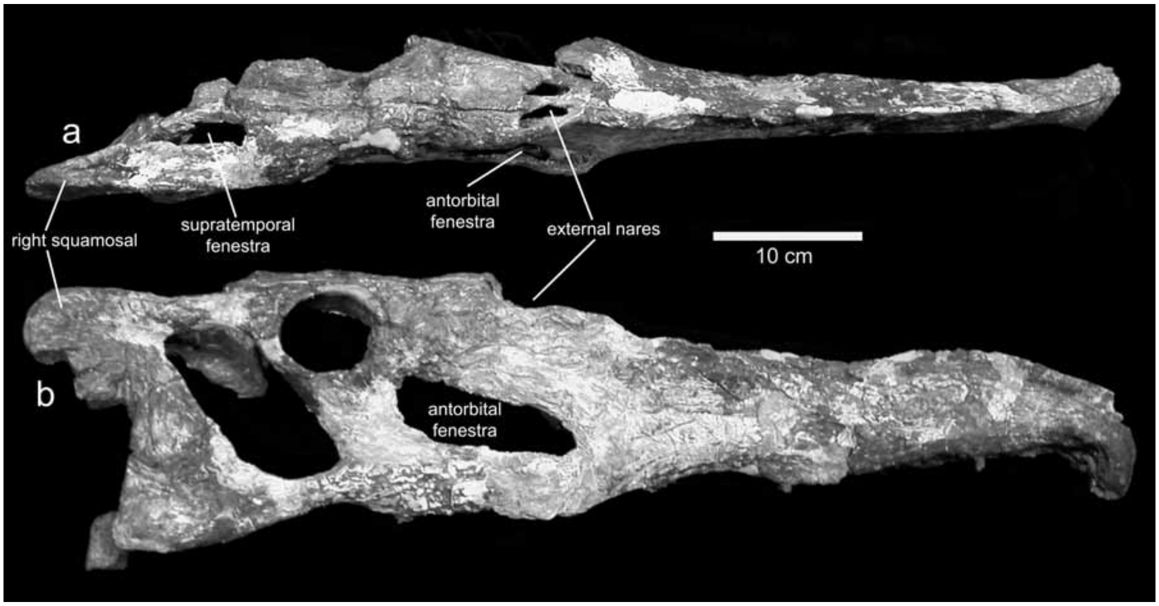


Fig. 4.8. *Leptosuchus* cf. *L. crosbiensis* (TTU P-9234) from the Post Quarry*: a,* dorsal view; *b,* right lateral view.

strongly depressed as in pseudopalatines, and the postorbitosquamosal bar is not as broad, indicating that the specimen is referable to *Leptosuchus* (Long and Murry, 1995). The skull lacks the somewhat dorsally oriented orbits and lateral temporal fenestrae of "*Smilosuchus*" (=*Leptosuchus*) *gregorii* (Long and Murry, 1995; Hungerbühler, 2001b) suggesting it is probably not a subadult of that taxon. The posterior ends of the squamosals are somewhat shallow in lateral view (Fig. 4.8b), and elongate and acutely tapering in dorsal view (Fig. 4.8a), which is characteristic of *Leptosuchus crosbiensis* (Ballew, 1989; Long and Murry, 1995). However, Axel Hungerbühler (personal communication) indicates that some features, including the fully crested snout, are unusual enough to make the referral to that species tentative.

PSEUDOPALATINAE Long and Murry, 1995 *sensu* Hungerbühler, 2002

***PSEUDOPALATUS* Mehl, 1928**

***Pseudopalatus buceros* Cope, 1887**

***Pseudopalatus pristinus* Mehl, 1928**

Occurrences in Southern Garza County: Lott Kirkpatrick (MOTT 3630) and Patricia Site (MOTT 3870), upper unit of the Cooper Canyon Formation.

Pseudopalatus sp. nov. Hungerbühler et al., in review

Occurrences in Southern Garza County: Patricia Site (MOTT 3870), upper unit of the Cooper Canyon Formation.

Pseudopalatus ("_Macysuchus_") sp. nov.

Occurrences in Southern Garza County: Macy Ranch (MOTT 3631) and Patricia Site (MOTT 3870), upper unit of the Cooper Canyon Formation.

Pseudopalatus sp.

Occurrences in Southern Garza County: Headquarters locality (MOTT 3892), middle unit of the Cooper Canyon Formation; Patricia Site (MOTT 3870), upper unit of the Cooper Formation.

Discussion: Long and Ballew (1985) and Ballew (1989) made an extremely important contribution to phytosaur systematics (and biostratigraphy) is the recognizing that the highly derived phytosaurs *Belodon buceros, Machaeroprosopus tenuis,* and *Pseudopalatus pristinus,* should be united within the genus *Pseudopalatus*. These phytosaurs had previously been lumped by Camp (1930) into *Machaeroprosopus,* and by Gregory (1962) and Westphal (1976) into *Rutiodon* with material now often assigned to *Leptosuchus* (Long and Murry, 1995; Hungerbühler, 2001b; Parker and Irmis, 2005, 2006). Unlike previous phytosaur systematic studies which tended to split phytosaurs into crested and non-crested forms (e.g. Case, 1929, Gregory 1962; Westphal, 1976; Hunt, 1994), Ballew's (1989) cladistic analysis, later corroborated by Hungerbühler

(2002b), showed that various crested and non-crested phytosaurs (particularly *Pseudopalatus pristinus* and *P. buceros*) shared a closer systematic relationship with each other than with other crested and non-crested forms.[3] *Pseudopalatus* is diagnosed in part by a suite of characters, many of which were originally identified by Camp (1930). These include: external nares which are elevated above skull roof, a postorbitosquamosal bar which is extremely broad, a descending process of squamosal which highly reduced, reduced posttemporal fenestra, parietal-supraoccipital complex shaped like an inverted "U" in posterior view, supratemporal fenestrae which are deeply depressed below skull roof with slit-like anterior borders, and parietal wings that are almost totally concealed in dorsal view (Long and Murry, 1995; Hungerbühler et al., in review).

Long and Murry (1995) acknowledged the separation between *Pseudopalatus* from *Leptosuchus*, although they assigned *Belodon buceros* and the crested forms from Canjilon Quarry that Lawler (1976) referred to *Rutiodon tenuis* to a new genus, *Arribasuchus*. However, most subsequent treatments of derived phytosaurs (Hungerbühler, 2002b; Lucas et al., 2002b; Zeigler et al., 2002a, b; Parker and Irmis, 2006) have accepted Ballew's (1989) referral of *Belodon buceros* and the crested forms from Canjilon Quarry to *Pseudopalatus*. In addition to *Pseudopalatus pristinus* and *P. buceros*, two other species have been referred to the genus: *P. maccauleyi* (Ballew, 1989) and *P. jablonskiae* (Parker and Irmis, 2006). Hungerbühler et al. (2003, in review) have identified a highly derived new species from the uppermost Cooper Canyon Formation which has characters also present in the derived pseudopalatine *Redondasaurus* (Hunt and Lucas, 1993a). As with other phytosaur taxa, these species are distinguished largely on characters of the temporal region, particularly the morphology of the postorbitosquamosal bar.

Colbert and Gregory (1957) and Gregory (1972) recognized that the vertebrate fauna of the uppermost Dockum Group and Chinle Formation of New Mexico contained a phytosaur which was more derived than any other taxon in having supratemporal fenestrae which were completely concealed in dorsal view, continuing the trend of

[3] Hungerbühler (2002a) noted that the degree of heterodonty in phytosaurs, a character loosely associated with rostral morphology, was also of dubious systematic value.

depressing and reducing the supratemporal fenestra seen in skulls now referred to *Leptosuchus* and *Pseudopalatus*. Hunt and Lucas (1993a) assigned these skulls to a new genus, *Redondasaurus*, consisting of the non-crested type species *R. gregorii* and the crested species *R. bermani*. Long and Murry (1995) sunk *Redondasaurus gregorii* and *R. bermani* into *Pseudopalatus pristinus* and "*Arribasuchus*" (*Pseudopalatus*) *buceros* respectively, claiming that the highly depressed supratemporal fenestra of *Redondasaurus* fell within the range of variation for *Pseudopalatus*. Although Hungerbühler (2002) and Lucas et al. (2007b) continued to use *Redondasaurus* as a distinct taxon from *Pseudopalatus*, Hungerbühler et al. (2003, in review) endorsed sinking *Redondasaurus* into *Pseudopalatus* (although retaining *P. gregorii* as a valid species), due to the new species of *Pseudopalatus* they described bridging the morphological gap between the genera, making distinction between them highly arbitrary.

Another *Pseudopalatus* specimen from southern Garza County (TTU P-10074) being described by Hungerbühler at al. (in review), and an undescribed species of *Pseudopalatus* also known from southern Garza County currently being described by Christina Chavez ("*Macysuchus brevirostris*" of McQuilkin, 1998) also show mosaics of characters seen in *Pseudopalatus buceros/P. pristinus* and more derived pseudopalatines (Axel Hungerbühler, personal communication). Even if *Redondasaurus* is retained as a valid genus arbitrarily divided from *Pseudopalatus*, these specimens from southern Garza County complicate exactly where the line between the genera should be drawn.

Another important taxonomic issue relates to the possibility that material now referred to *Pseudopalatus buceros* and *P. pristinus* are sexual dimorphs of the same species as suggested by Colbert (1947) and later by Zeigler et al. (2002b, 2003b), and endorsed by Hungerbühler et al.'s (2003, in review) work on the new species of *Pseudopalatus*. Irmis (2005) and Parker and Irmis (2005) considered the evidence for *Pseudopalatus pristinus* and *P. buceros* representing sexual dimorphs of the same species ambiguous, though entirely plausible, and I also consider it prudent to retain both as distinct *morphological* species that could potentially have belonged to the same *biological* species.

Some *Pseudopalatus* specimens from southern Garza County have squamosals with the knob-like posterior ends and pronounced lateral ridges shared exclusively by *Pseudopalatus buceros* and *P. pristinus* within the genus (Ballew, 1989; Parker and Irmis, 2006; Hungerbühler et al., in review). The lowest specimens of *Pseudopalatus* referable to this morphotype are TTU P-102 (Fig. 4.9e-f) and TTU P-11895 (4.9c-d), a partial skull and isolated squamosal from the Lott-Kirkpatrick Ranch locality (MOTT 3630) in the upper unit of the Cooper Canyon Formation. A partial skull (Fig. 4.9g-h), TTU P-11075 ("Shorty"), is known from the top of the Macy Ranch sandstone at the Patricia Site (MOTT 3870). Both TTU P-102 and TTU P-11075 are missing the region of the skull immediately anterior to the external nares, so it is unknown if these specimens are referable to *Pseudopalatus buceros* or *P. pristinus*.

The new derived species of *Pseudopalatus* being described by Hungerbühler et al. (2003, in review), and "*Macysuchus brevirostris*" (McQuilkin, 1998; Christina Chavez, in prep) appear higher in the higher in the section than specimens with the postorbitosquamosal bar morphology distinctive of *Pseudopalatus buceros* and *P. pristinus*. *Pseudopalatus* sp. nov. (Hungerbühler et al., 2003, in review) is known from two skulls; a non-crested specimen (Fig. 4.10a-b; TTU P-10076, "Papa John") and a crested specimen (Fig. 4.10c; TTU P-10077, "Andy"), both from the Macy Ranch sandstone at the Patricia Site (MOTT 3870). "*Macysuchus*" (McQuilkin, 1998) is known from an excellent articulated and nearly complete skeleton with a strikingly truncated skull (Fig. 4.10d; TTU P-9425) from the Macy Ranch locality (MOTT 3631) several meters below the Macy Ranch sandstone, and from an excellent crested skull (TTU P-11423, "Spike") from the Patricia Site.

The stratigraphically lowest *Pseudopalatus* specimen is a fragmentary squamosal (Fig. 4.9a-b), TTU P-11880, from the Headquarters Site (MOTT 3892) in the middle unit of the Cooper Canyon Formation. Although it can be identified as pseudopalatine, it is too incomplete to assign to a particular species.

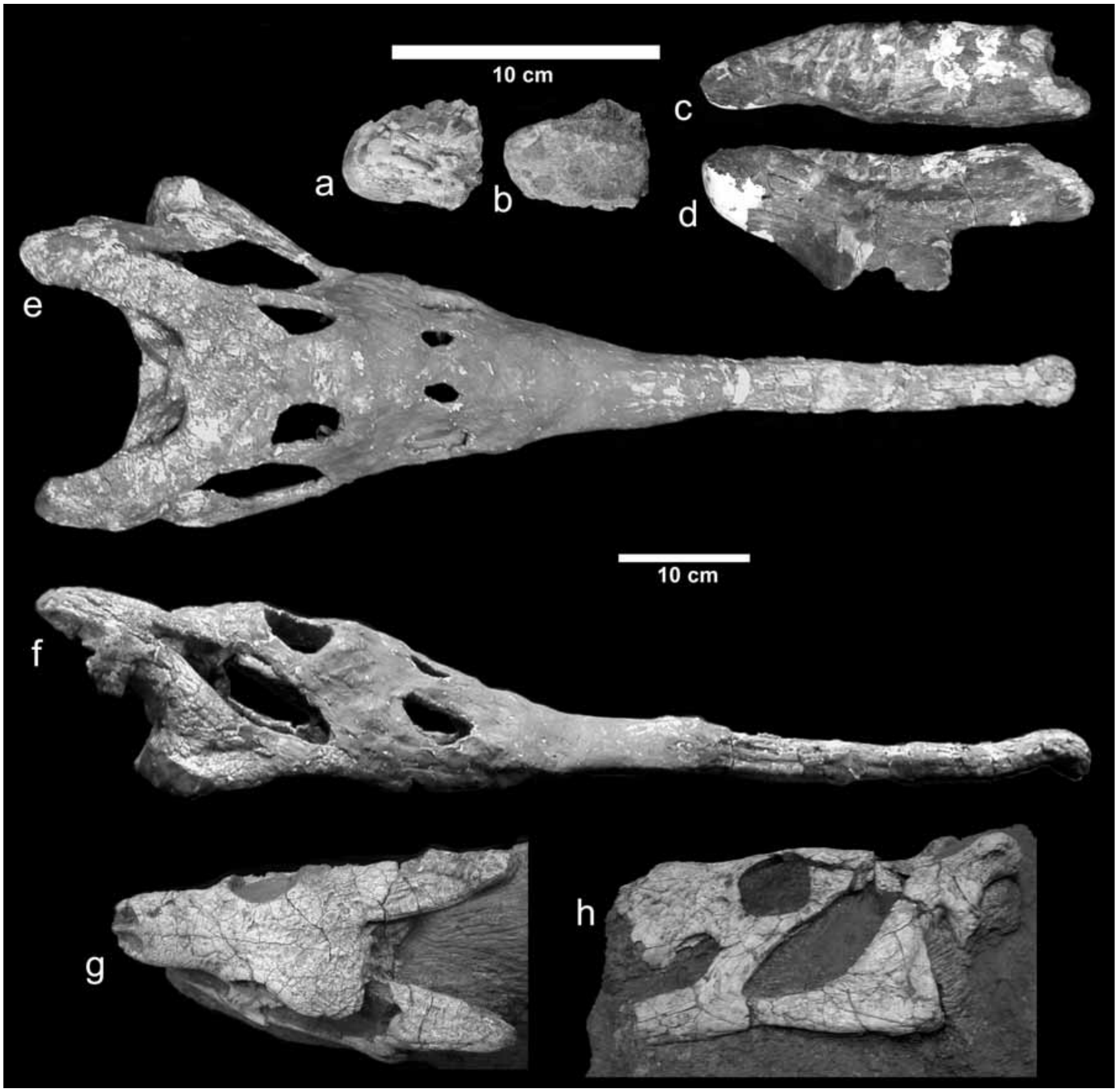


Fig. 4.9. *Pseudopalatusbuceros* and/or *P. pristinus*: *a*, isolated squamosal referable to *Pseudopalatus* sp. (TTU P-11880) from the Headquarters Site in dorsal view and; *b*, ventral view; *c*, isolated right squamosal (TTU P-11895) referable to *Pseudopalatus buceros* or *P. pristinus* from the Lott Kirkpatrick locality in *c*, dorsal view and; *d*, lateral view; partial skull (middle section reconstructed) of *Pseudopalatus buceros* or *P. pristinus* (TTU P-102) from the Lott Kirkpatrick locality in *e*, dorsal view and; *f*, right lateral view; partial skull of *Pseudopalatus buceros* or *P. pristinus* (TTU P-11075, “Shorty”) from the Patricia Site in *g*, dorsal view and; *h*, left lateral view.

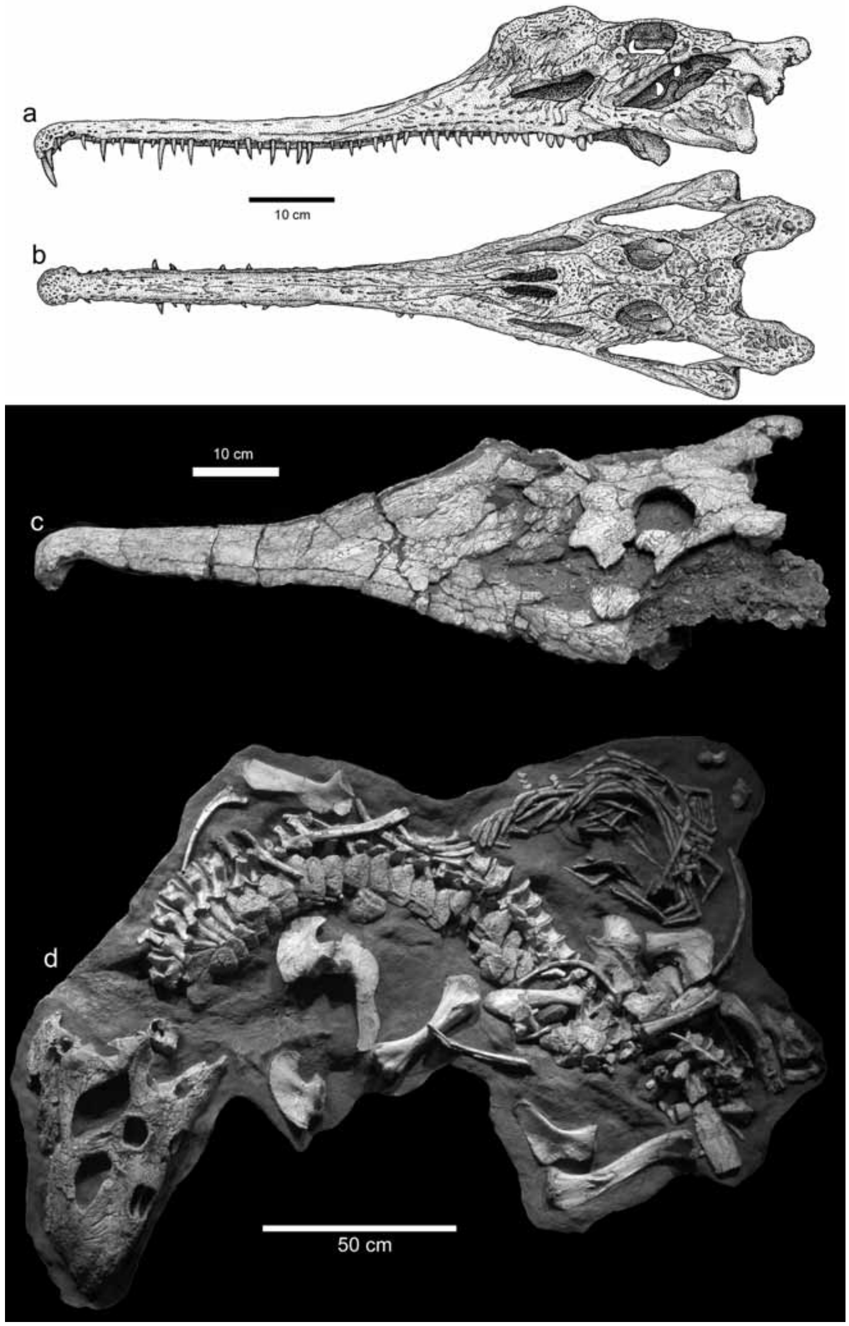


Fig. 4.10. Derived species of *Pseudopalatus*: *a*, skull reconstruction of the gracile morph of *Pseudopalatus* nov. sp., based mostly on TTU P-10076 (“Papa John”) in left lateral view and; *b*, dorsal view (drawn by the author for Hungerbühler et al., in review); c, skull of the crested morph of *Pseudopalatus* nov. sp. TTU P-10077 (“Andy”) in left dorsolateral view; *d*, wall mount made from a cast of the skull and semi-articulated partial skeleton of *Pseudopalatus* (“*Macysuchus*”) nov. sp. (TTU P-9425) from the Macy Ranch locality (photograph courtesy Bill Mueller).

PARASUCHIA *incertae sedis*

Occurrences in Southern Garza County: Eastern Garza (MOTT 3928), OS Ranch (MOTT 3867), OS Roadside (MOTT 3910), OS Ranch Fish (MOTT 3702) and OS

Ranch Giants (MOTT 3704), Boren Ranch beds; Boren Quarry (MOTT 3869) and Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation; Headquarters (MOTT 3892), Headquarters South (MOTT 3898), Green Tooth Arroyo (MOTT 3901), middle unit of the Cooper Canyon Formation; K.W. Flats (MOTT 3908), Squeak Site (MOTT 3909), Lott-Kirkpatrick (MOTT 3635), Problematic Hill (MOTT 3921), Macy Ranch (MOTT 3631) "Macy Ranch" (MOTT 3924), Macy Ranch Debbie (MOTT 3925), Macy Ranch 3926 (MOTT 3926), Patricia Site (MOTT 3870), Richard's Skull (MOTT 3913), Far East (MOTT 3884), Caterpillar Canyon (MOTT 3891), Audad Bluff (MOTT 3895), Big Hill Road (MOTT 3896), and Sandstone Alley (MOTT 3920), upper unit of the Cooper Canyon Formation.

Discussion: Phytosaurs are, stratigraphically, the most consistently represented vertebrates in the Dockum Group in southern Garza County, with at least fragmentary material being known from almost every vertebrate locality, from the lowest (a single cervical vertebra from Eastern Garza County, MOTT 3928) to the highest (the abundant pseudopalatine material at the Patricia Site, MOTT 3870 and associated localities). Unfortunately, phytosaur alpha taxonomy is based primarily on the temporal region of the skull, and most of the remainder of the skull, mandible, and postcranial skeleton is usually considered undiagnostic with the exception of a few attempts to identify diagnostic variation in the postcrania (e.g. Hunt, 1994; Lucas et al., 2002a). Consequently, most of the phytosaur material recovered from southern Garza County is undiagnostic, although it stands to reason that most of the abundant postcranial material known from the Patricia Site (MOTT 3870) and associated localities is probably referable to *Pseudopalatus*, as that is the only phytosaur known from diagnostic cranial material in the Macy Ranch sandstone.

At least one gigantic phytosaur skull, which has not yet been recovered, is present at the OS Ranch Giants locality (MOTT 3704), which probably lies in the uppermost Boren Ranch beds or lowermost lower unit of the Cooper Canyon Formation. The size of the mandibular material recovered from the specimens suggests they may be referable to *Leptosuchus*, which would be an important range extension for the genus in the southern Garza County, or "*Angistorhinus*" (referable to *Rutiodon* according Hungerbühler, 2001b), which would be a new occurrence in southern Garza County. However, the skull briefly described by Lucas et al. (2007a) indicates that basal phytosaurs also reached gigantic sizes, so the biostratigraphic significance of the OS Ranch Giants material remains unclear.

SUCHIA Krebs, 1974 *sensu* Benton and Clark, 1988
AETOSAURIA Marsh, 1884, *sensu* Parker, 2007
STAGONOLEPIDIDAE Lydekker, 1887, *sensu* Heckert and Lucas, 2000
AETOSAURINAE Marsh, 1884 *sensu* Heckert and Lucas, 2000
cf. *STAGONOLEPIS*?

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869), lower unit of the Cooper Canyon Formation.

Discussion: Pseudosuchians more derived than phytosaurs, the "rauisuchians," aetosaurs, and crocodylomorphs, are sometimes united as Suchia, although the precise interrelationships, and indeed monophyly, of these three groups is more controversial (e.g. Gauthier, 1986; Sereno, 1991; Parrish, 1993; Gower and Wilkinson, 1996; Gower, 2002; Benton, 2004; Gower and Nesbitt, 2006; Weinbaum and Hungerbühler, 2007). Aetosaurs were quadrupedal, heavily armored, herbivorous or omnivorous pseudosuchians. Along with metoposaurs and phytosaurs, they are one of the most frequently encountered tetrapods in Upper Triassic strata in the southwestern United States. The osteoderms (often referred to as "plates" or "scutes") of aetosaurs, especially the paramedian osteoderms extending down the midline of the back, and the lateral osteoderms articulating with the lateral ends of the paramedians, show considerable taxonomic variation and are the primary means by which aetosaurs are identified and classified (e.g. Long and Ballew, 1985; Long and Murry, 1995; Heckert and Lucas, 2000; Parker, 2007), an unfortunate situation given the high degree of homoplasy that seems to be present in aetosaur osteoderms (Martz and Small, 2006; Parker, 2007). I follow Long and Murry (1995) and Parker (2007) here in using the term “paramedian” rather than “dorsal paramedian” for any of the paired osteoderms along the dorsal midline of the body, restricting the term “dorsal paramedian” for those covering the dorsal vertebrae. The phylogenetic framework of Parker (2007) is also more consistent with my own observations of aetosaur morphology and variation than other phylogenetic studies (Parrish, 1994; Heckert and Lucas, 1999, 2000; Harris et al., 2003), and is used here.

The Aetosauria branches into two clades, the Aetosaurinae and the Desmatosuchinae (defined phylogenetically by Heckert and Lucas, 2000). The aetosaurines have a dorsal boss on the paramedian osteoderms which is closer to the medial edge than the lateral edge, lateral osteoderms in which the dorsal flange is smaller than the lateral flange, and lack desmatosuchine apomorphies such as the thickened tongue and groove articulations and elongate cervical paramedians with dorsal bosses. The Aetosaurinae consists of the Typothoracsinae and a sister clade formed by all other aetosaurines (Parker, 2007).

TTU P-11750 is a specimen from the Boren Quarry (MOTT 3869) from the base of the lower unit of the Cooper Canyon Formation consisting of two osteoderms, a lateral osteoderm, and a nearly complete caudal paramedian osteoderm with a raised anterior bar, a medially offset pyramidal boss that contacts the posterior margin of the osteoderm, a very faint ventral strut, and rather faint and indistinct ornamentation. This specimen is probably an aetosaurine, and the extremely weak ornamentation and blunt (rather than pyramidal) dorsal boss suggests it may be a non-typothoracisine form allied to *Stagonolepis* (personal observation)

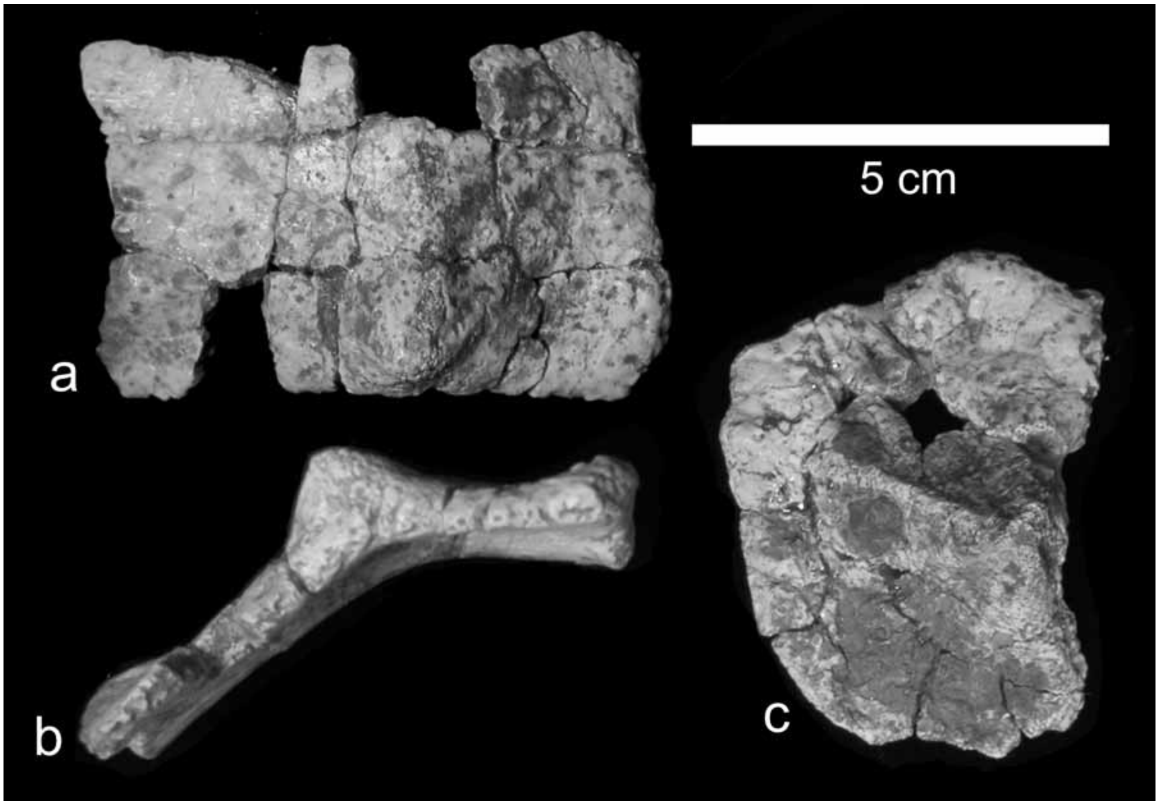


Fig. 4.11. cf. *Stagonolepis*? (TTU P-11750) from the Boren Quarry: *a*, caudal paramedian osteoderm in dorsal view and; *b*, posterior view; *c*, possible lateral osteoderm.

TYPOTHORACISINAE Parker, 2007

***TYPOTHORAX* Cope, 1874**

***Typothorax coccinarum* Cope, 1874**

Occurrences in Southern Garza County: Rocker A Oilfield (MOTT 3614), lower unit? of the Cooper Canyon Formation; Headquarters locality (MOTT 3882), middle unit of the Cooper Canyon Formation; Patricia Site (MOTT 3870), Audad Bluff (MOTT 3895), and Bauchier-Crenshaw (MOTT 3885), upper unit of the Cooper Canyon Formation.

***Typothorax* sp.**

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

Discussion: The Typothoracsinae consists of aetosaurs with paramedian osteoderms that are very wide compared to their length, and lateral osteoderms with a fairly distinctive suite of characters, including a dorsal flange that is triangular or tongue-shaped (Parker, 2007). Two typothoracisine aetosaur genera with wide dorsal paramedian osteoderms are present in the Dockum Group of southern Garza County: *Typothorax* and *Paratypothorax*. *Typothorax* is characterized in part by its distinctively pitted paramedian osteoderms, a strongly developed ventral strut on the paramedians, and lateral osteoderms with a triangular-shaped dorsal flange (Long and Ballew, 1985; Long and Murry, 1995; Heckert and Lucas, 2000; Martz, 2002). In addition to the type species *Typothorax coccinarum*, there are two other putative species recognized by some at least some workers: *Typothorax* (*"Redondasuchus"*) *reseri* (Hunt and Lucas, 1991b; Heckert et al., 1996; Martz, 2002) and *T. antiquum* (Lucas et al., 2002c).

"*Redondasuchus*" *reseri* was named for small, isolated osteoderms from the Redonda Formation of New Mexico, and was considered a distinct genus by Hunt and Lucas (1991b), Heckert et al. (1996), and Spielmann et al. (2006b). However, Long and Murry (1995), Small (1998), Martz (2002), and Parker (2006) sunk *Redondasuchus* into *Typothorax*. Martz (2002) noted that the paramedians of both genera were actually "arched" closer to the medial edge of the paramedian in both taxa[4]. However, Martz (2002) maintained it as a distinct species, *Typothorax reseri*, based in part on its small size, and also on its stratigraphic separation from definite adult *T. coccinarum* material, which provided circumstantial evidence that *T. reseri* was not a juvenile of *T. coccinarum.*

[4] Hunt and Lucas (1991b), Heckert et al. (1996), and Heckert and Lucas (2000) thought that the "flexing" occurred closer to the lateral edge in *Redondasuchus*, a mis-orientation of the holotype osteoderm corrected by Martz (2002). Spielmann et al. (2006) found Martz's reinterpretation compelling and graciously conceeded that it had merit.

Spielmann et al. (2006) disagreed with the sinking of *Redondasuchus* into *Typothorax* by Long and Murry (1995) and Martz (2002). They agreed with Long and Ballew (1985) and Martz (2002, pp. 32, 34) that the "arching" in the paramedians of *Typothorax* is natural and not due to post-mortem distortion as claimed by Long and Murry (1995). However, Spielmann et al. (2006) also argued that there was an important difference in the transverse shape of the paramedians in *Typothorax* and *Redondasuchus*. They used the term "flexed" to describe an abrupt bending at the center of ossification in *Redondasuchus*, and restricted the term "arched" to describe a more continuous transverse curvature in *Typothorax,* indicating that this difference was sufficient to maintain a genus distinction. I agree with Spielmann et al. (2006) that it is useful to distinguish these conditions, and by their definition there is indeed transverse curvature extending the width of at least some caudal paramedians of *Typothorax* best described as "arching" rather than "flexing."

However, in the widest (mid-dorsal) paramedians of *Typothorax*, there is clearly a more distinct flexing at a point closer to the medial edge than the lateral edge where the ventral strut is thickest and the ornamentation is finest, with the osteoderm being distinctly flatter medial and lateral to the region, although as noted by Martz (2002) the flexing is more subtle than in *Redondasuchus.* In particular, this flexing is present in the dorsal paramedian of TTU P-9214 figured by Martz (2002, fig. 3.1) and claimed by Spielmann et al. (2006) to have been distorted because they could discern from the photograph that the specimen has cracks. The specimen does indeed contain cracks (like most vertebrate fossils), but there is no evidence that the shape of the osteoderm has been distorted, and other mid-dorsal paramedian osteoderms from TTU P-9214, as well as other mid-dorsal paramedian osteoderms of *Typothorax* from Canjilon Quarry and Petrified Forest National Park show the distinct flexing at the same point in the osteoderm, with the osteoderm being more flattened laterally and medially. The same condition is clearly present in the paramedians of *Typothorax* and *Redondasuchus* regardless of what terms are used, and I continue to regard *Redondasuchus* a junior synonym of *Typothorax*. The only described aetosaur material I have personally examined in which the paramedian osteoderms of the *pre*-caudal region are truly "arched" (transversely curved across their entire width) is *Aetosaurus ferratus* (Schoch, 2007). There is probably a continuum between "arching" and "flexing."

Spielmann et al. (2006) named a new species of *Redondasuchus*, *R. rineharti*, based on isolated and incomplete paramedian osteoderms from the Redonda Formation, which they claimed shared the flexing of the paramedian osteoderms and pitted ornamentation which diagnoses "*Redondasuchus*" *reseri*, but is larger and possesses a circular boss at the point of flexure. Given that the flexing, pitted ornamentation, and boss at the point of flexion are all present in *Typothorax* (e.g. Long and Ballew, 1985; Martz, 2002) it is not clear how a large specimen of *Redondasuchus* is supposed to differ from *Typothorax coccinarum*. I am also extremely dubious about naming a new species based on isolated and incomplete paramedian osteoderms (Martz and Small, 2006), although I am reluctant to pass full judgment on "*Redondasuchus*" *rineharti* without having seen the material firsthand.

Typothorax antiquum (Lucas et al., 2002c) is based on more complete material (especially for the holotype specimen), from the lower part of the Dockum Group (Los Esteros Member of the Santa Rosa Formation and "Garita Creek Formation") in New Mexico. The osteoderms of *T. antiquum* were diagnosed and distinguished from those of the type species in part by Lucas et al. (2002c, p. 222) in that the paramedian osteoderms were relatively narrow with "coarser", "shallower", and "less dense" ornamentation, and that the lateral osteoderms have "more pronounced radial ridges" and "broader, shallower, and less numerous pits." Lucas et al. (2002c) also maintained that there is a stratigraphic separation between *Typothorax coccinarum* and *T. antiquum*. The possibility that *Typothorax antiquum* might represent a juvenile of *T. coccinarum*, with the differences between the species being ontogenetic, was not discussed by Lucas et al. (2002c), but the possibility is suggested by the fact that the *T. antiquum* material, including the holotype, is smaller than adult *Typothorax coccinarum* material (personal observation of some of the holotype material; Bill Parker, personal communication). Parker (2007) considered *Typothorax antiquum* to be a junior synonym of *T. coccinarum*.

There are several specimens of *Typothorax* from southern Garza County (Figs. 4.12-4.13), and some of these specimens, and a few from elsewhere, suggest that *Typothorax coccinarum* and *Typothorax antiquum* may have occurred in the same (or at least correlative) strata, which would lend circumstantial support to the possibility that the latter is an immature form of the former. TTU P-9209 (Fig. 4.12a), from the "Rocker A Oil Field" (MOTT 3614) in southern Garza County, consists of two partial dorsal paramedian osteoderms indistinguishable from Canjilon Quarry *Typothorax coccinarum* material. Unfortunately, the precise locality for this material came from is hard to determine, as this locality name "Rocker A Oil Field" has been used for both the OS Ranch and for the area to the east of the Post Quarry. However, both of these areas lie stratigraphically within or below the Dalby Ranch sandstone, and indicate that TTU P-9209 was probably recovered from either the lower unit of the Cooper Canyon Formation, or the Boren Ranch sandstone/beds. Moreover, another specimen (TTU P-9208) consisting of three superimposed dorsal paramedian osteoderms which appear to be referable to *Typothorax coccinarum*, comes from the L-7 Ranch locality in Crosby County (MOTT 3617) near Cedar Hill, in the Tecovas Formation. Although these specimens are not represented by extensive material, they do suggest that *Typothorax coccinarum*, or at least a species with indistinguishable dorsal paramedian osteoderms, was present in the lower part of the Dockum Group in strata correlative with that which produced Lucas et al.'s (2002c) *Typothorax antiquum* material.

Additionally, a very small specimen of *Typothorax* (PEFO 33980) possessing the osteoderm characters Lucas et al. (2002c) used to diagnose *T. antiquum* (relatively narrow dorsal paramedians, coarse pitting on the dorsal paramedians, and deeply incised ornamentation on the lateral osteoderms) is known from the Giving Site in the Petrified Forest Member (=Painted Desert Member) of the Chinle Formation, and probably represents a juvenile of *T. coccinarum* (Parker and Irmis, 2005, p. 50). This suggests that, even if the species is valid, *Typothorax antiquum* may be difficult to distinguish from young individuals of *T. coccinarum*.

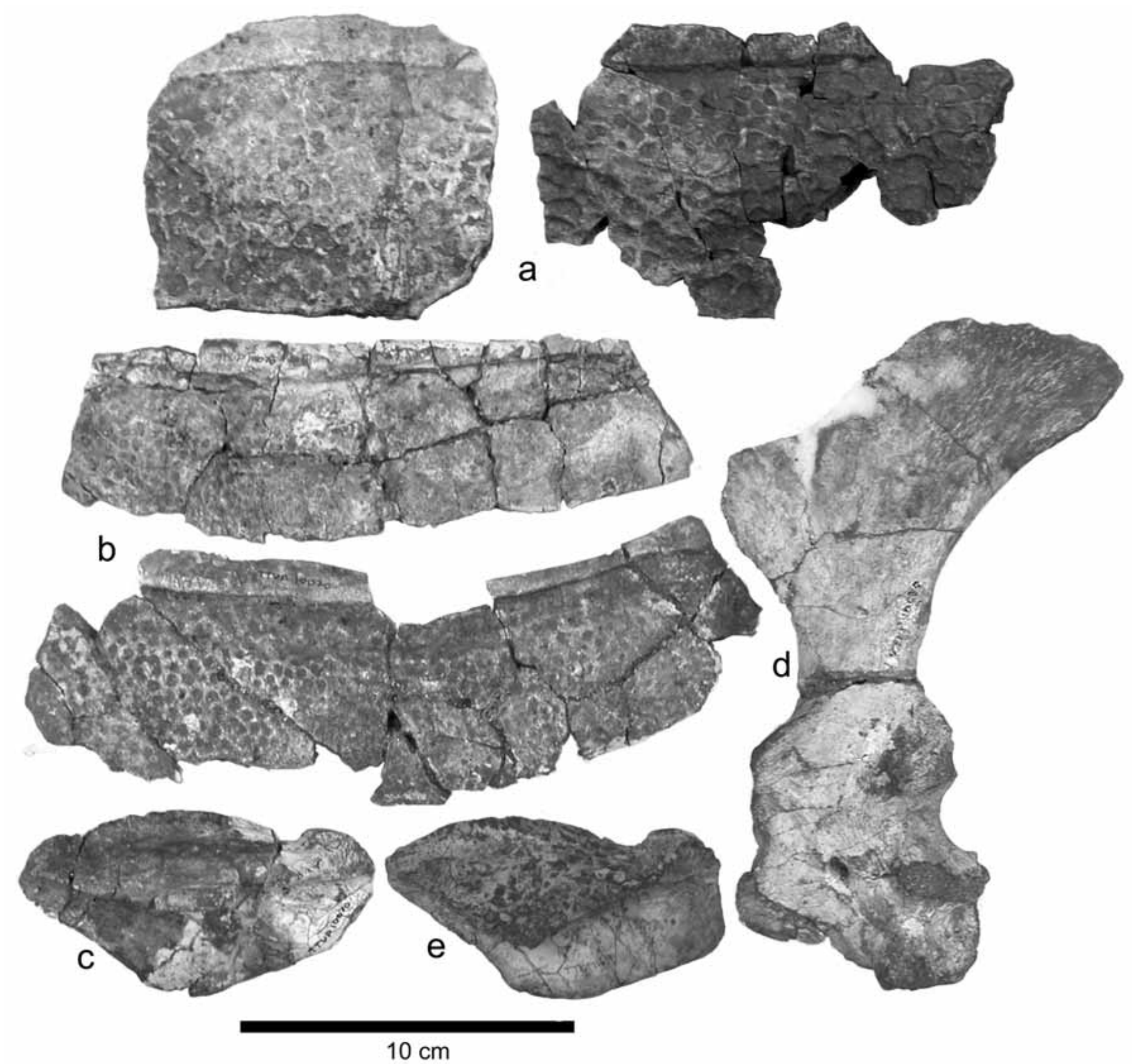


Fig. 4.12. *Typothorax coccinarum*: a, partial paramedian osteoderms (TTU P-9209) from Rocker A Oil Field; *b*, TTU P-10070 from the Patricia Site, consisting of two anterior dorsal paramedians in dorsal view; *c*, a left lateral osteoderm in dorsal view, and; *d*, a left scapulocoracoid in lateral view; *e*, a complete left lateral osteoderm (TTU P-11591) in dorsal view from the Patricia Site.

TTU P-9214 (Fig. 4.13a-c), from the Post Quarry in the lower unit of the Cooper Canyon Formation, is a small specimen of *Typothorax* described previously by Small (1989b) and Martz (2002) and considered by both to represent a sub-adult of *T. coccinarum*. The specimen seems to show the same osteoderm characters considered by Lucas et al. (2002c) to distinguish *T. antiquum* from *T. coccinarum*, in particular

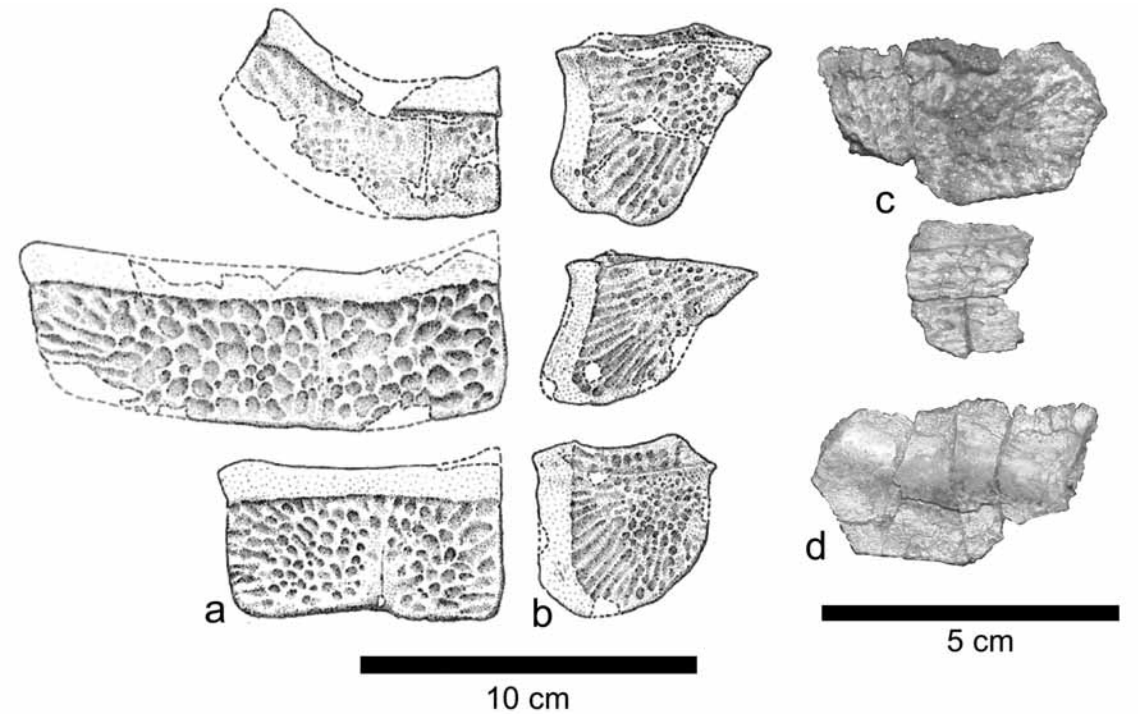


Fig. 4.13. Small individuals of *Typothorax*: *a*, left paramedian osteoderms of TTU P-9214 from (top to bottom) the anterior dorsal, mid or posterior dorsal, and caudal regions, all in dorsal view; *b*, left lateral osteoderms of TTU P-9214 from the same regions in lateral view; *c*, fragmentary paramedian osteoderms possibly representing a juvenile of *Typothorax* (TTU P-10448) from the UU Railroad Flats locality in dorsal view; *d*, larger fragment in ventral view, showing the ventral strut.

paramedians that are not as wide compared to their length as in the larger species, the presence of relatively wide and less numerous pits on both the paramedian and lateral osteoderms, and more deeply incised grooves (forming more pronounced ridges in between) on the lateral osteoderms (see Martz, 2002, figs. 4.28 c-d, 4.34 a, e, and 4.35 a, e). Although these features all show anterior-posterior variation in aetosaur osteoderms (e.g. Walker, 1967; Long and Ballew, 1985; Parker, 2007), osteoderms from the equivalent regions of the carapace in the Canjilon Quarry *Typothorax coccinarum* specimens show they differ in these characters from TTU P-9214 (Martz, 2002). Martz (2002) suggested some of these differences represented ontogenetic changes within *Typothorax coccinarum*, citing the relatively small size, incompletely fused neurocentral sutures (particularly in the cervical vertebrae) and the incompletely ossified laterosphenoid in TTU P-9214 as suggesting it had not achieved full size.

However, Irmis (2007), based on his extensive observations of neurocentral suture closure in other pseudosuchian archosaurs, considered the dorsal and caudal vertebrae neurocentral sutures of TTU P-9214 to be fully closed. He noted that this pattern of neurocentral closure in crocodilians (Brochu, 1996) and other archosaurs is more consistent with TTU P-9214 being an animal approaching maturity than with a juvenile or subadult. It may therefore be that TTU P-9214 was approaching a full adult size considerably smaller than adults of *Typothorax coccinarum*, and lends support to *T. antiquum* being a valid taxon. Ongoing histological work by Randy Irmis may help resolve the stage of maturity, and therefore taxonomic status, of TTU P-9214 and *Redondasuchus reseri*.

Incomplete osteoderms probably referable to *Typothorax coccinarum* include the two partial paramedians from the Rocker A Field (Fig. 4.12a; TTU P-9209) in the lower unit of the Cooper Canyon Formation or Boren Ranch sandstone, an incomplete paramedian (TTU P-12108) from the Headquarters Site (MOTT 3882) in the middle unit of the Cooper Canyon Formation, and several fragmentary paramedian and lateral osteoderms from the Patricia Site (MOTT 3870), Audad Bluff (MOTT 3895), and the Bauchier-Crenshaw Site (MOTT 3885), all located in the Macy Ranch sandstone in the upper unit of the Cooper Canyon Formation. Better material is represented by two specimens from the Patricia Site: a complete lateral osteoderm (Fig. 4.13e; TTU P-11591), and two anterior dorsal paramedian osteoderms and a lateral osteoderm associated with a scapulocoracoid (Fig. 4.12b-d; TTU P-10070), all identical to the Canjilon Quarry material (Martz, 2002).

There are also postcranial elements from the Patricia Site (MOTT 3870) and Patty East Site (MOTT 3880) which probably also belonged to *Typothorax coccinarum*, including a cervical vertebra (TTU P-11589), a proximal humerus (TTU P-11536), proximal femur (TTU P-11590), distal femur (TTU P-11593), and astragalus (TTU P-10868). These elements are all identical with elements from Canjilon Quarry or with

TTU P-9214 (except for being larger than the latter), but are tentatively assigned to Aetosauria *incertae sedis* until more detailed comparative studies of aetosaur postcranial anatomy are available. In summary, *Typothorax coccinarum*, or at least a large species of that genus, was apparently present at least as far down as the middle unit of the Upper Cooper Canyon Formation, and possibly as low as the lower unit, but the taxon was most abundant in the upper unit Cooper Canyon Formation during deposition of the Macy Ranch sandstone.

One of the more interesting specimens is the fragmentary remains of a small juvenile aetosaur (TTU P-10448), including fragmentary paramedians (Fig. 4.13d-e), some tiny limb elements, and tiny dorsal vertebra centra with un-attached neural arches, from the UU Railroad Flats locality (MOTT 3883) in the middle unit of the Cooper Canyon Formation. The paramedian osteoderms have a very thick ventral strut, raised anterior bar, and somewhat pitted ornamentation, and may represent a baby *Typothorax*. Finally, the excellent partial skeleton (TTU P-9214) described by Small (1989b) and Martz (2002) from the Post Quarry (MOTT 3624) in the lower unit of the Cooper Canyon Formation, representing either a juvenile of *Typothorax coccinarum* or a juvenile *Typothorax antiquum*, is assigned to *Typothorax* sp. until the species can be more thoroughly re-evaluated. No other *Typothorax* specimens small enough to be assigned as either *Typothorax antiquum* or a juvenile of *T. coccinarum* are known from southern Garza County.

PARATYPOTHORACISINI Parker, 2007

***PARATYPOTHORAX* Long and Ballew, 1985**

***Paratypothorax* sp.**

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation; Macy Ranch Debbie (MOTT 3925), upper unit of the Cooper Canyon Formation.

PARATYPOTHORACISINI *incertae sedis*

Occurrences in Southern Garza County: Headquarters NW (MOTT 3899) Problematic Hill (MOTT 3921), middle unit of the Cooper Canyon Formation.

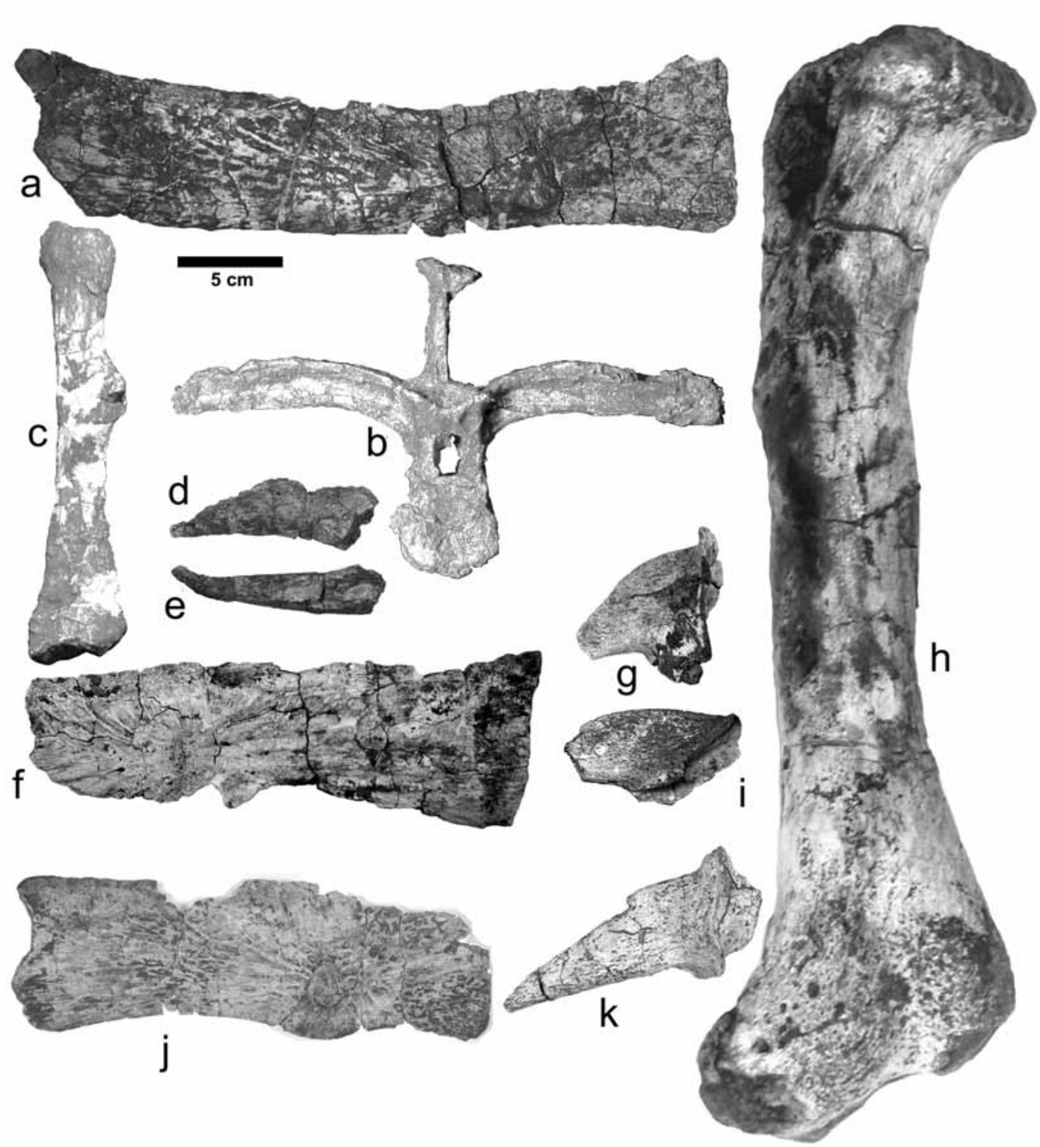
Discussion: The Paratypothoracisini is a clade within the Typothoracsinae in which the dorsal eminence on the paramedian osteoderms rarely contacts the posterior margin of the osteoderm, and is strongly offset medially, and the lateral osteoderms have a pronounced, dorsoventrally flattened horn and a tongue-shaped dorsal flange (Martz and Small, 2006; Parker, 2007). Long and Ballew (1985) named the genus *Paratypothorax* for extensive paramedian and lateral osteoderm material from the German Stubensandstein. Although this material has been discussed briefly in subsequent papers (e.g., Long and Murry, 1995; Lucas et al., 2006a), a thorough description of the type material is still wanting. *Paratypothorax* material is also known from western North America, with numerous, mostly incomplete and isolated osteoderms having been identified from the Chinle Formation and Dockum Group (e.g., Long and Ballew, 1985; Long and Murry, 1995, p. 235). In addition to possessing the apomorphies of the Paratypothoracisini given above, *Paratypothorax* is characterized in part by paramedian osteoderms that are extremely wide compared to their length, and in having distinctly radiating ornamentation of grooves and pits on the paramedians, an anterior bar which is only weakly raised, and a prominent dorsal boss on the paramedians (Long and Ballew, 1985; Hunt and Lucas, 1992; Long and Murry, 1995; Heckert and Lucas, 2000; Martz and Small, 2006; Lucas et al., 2006a).

In addition to a partial carapace of *Paratypothorax* collected from the Sonsela Member of the Chinle Formation (Hunt and Lucas, 1992; Lucas et al., 2006a), the best North American material for *Paratypothorax* comes from the Post Quarry (MOTT 3624). This locality has produced one of the most extensive collections of aetosaur material in North America, including the largest and most diverse collection of aetosaur cranial material from a single locality on the continent. Material has been recovered for multiple individuals of the large aetosaurs *Paratypothorax* and *Desmatosuchus*, as well as for a small specimen of *Typothorax* (TTU P-9214, already discussed above), and two paramedian osteoderms possibly representing a fourth taxon (discussed below). In addition to MOTT material, the Dallas Museum of Natural History made an important collection of *Paratypothorax* and *Desmatosuchus* remains from the Post Quarry in 1977 (Small, 1985, 1989a, b; Long and Murry, 1995).

The Post Quarry *Paratypothorax* material received only brief discussion by Small (1989b), who did not assign it to a particular species. Long and Murry (1995, pp. 108-114) provided a more thorough description of the DMNH Post Quarry *Paratypothorax* material, including the postcranial material, and also compared the Post Quarry osteoderms with those of PEFO 3004 and the German genoholotype material. Long and Murry (1995, p. 114) noted that the German type material differs from the Post Quarry and Petrified Forest material in having much larger and more bulbous bosses on the dorsal paramedian osteoderms, and that the Post Quarry material differed from the German and Petrified Forest specimens in having more elongate and recurved horns on the lateral osteoderms. They considered PEFO 3004 to be intermediate in form between the German and Post Quarry material due to its possession of relatively small dorsal paramedian bosses and modest-sized lateral horns. Long and Murry (1995), like Small (1989), preferred to remain conservative and assigned the North American material to *Paratypothorax* sp., as Long and Ballew (1985) had before them for the more fragmentary material they described. Having examined the German genoholotype, the Petrified Forest specimen, and the Post Quarry material, I agree with Long and Murry (1995) that they are not referable to *Paratypothorax andrssorum*, and refer to them as *Paratypothorax* sp. following Small (1989) and Long and Murry (1995).

As aetosaur taxonomy is based almost entirely on osteoderm characters, sorting out which cranial and postcranial skeletal material belongs with which aetosaur taxon in the Post Quarry can be somewhat problematic. This is especially true given the disarticulated nature of the material (Chatterjee, 1985; Small, 1989a), and that only a few quarry maps and notes exist to give some idea of exactly how cranial and postcranial skeletal material was associated with more diagnostic osteoderms. This problem is slightly alleviated by the fact that all *Typothorax* material seems to have come from a single specimen (TTU P-9214; Small, 1989b; Martz, 2002) which considerably smaller than the *Paratypothorax* and *Desmatosuchus* material, which was collected from a relatively confined area (Bryan Small, personal communication; Sankar Chatterjee unpublished field notes). This makes the problem primarily one of distinguishing *Paratypothorax* and *Desmatosuchus* cranial and post-cranial skeletal material. Until the available field notes, quarry maps, and photographs for the Post Quarry excavation can be analyzed in more detail, and the available aetosaur material prepared and described more thoroughly, the referral of much non-osteoderm aetosaur material to particular taxa must be taken with caution. In particular, some of the Post Quarry's excellent aetosaur cranial material that was referred to *Desmatosuchus* (Small, 1985, 2002) may belong to *Paratypothorax*.

Paratypothorax osteoderms were collected at Post Quarry by Texas Tech University throughout the 1980s and (most notably) in 1993. TTU P-9169 (Fig. 4.14a) is the single best paramedian osteoderm of *Paratypothorax* in the Texas Tech collection, but TTU P-12540 and DMNH 9942 (Long and Murry, 1995) are more important specimens, represented by multiple paramedian and lateral osteoderms, and some other postcranial material. TTU P-12540 originally had lateral and paramedian osteoderms in articulation (Sankar Chatterjee field notes, 1993), but was unfortunately dumped after being jacketed. Once prepared and reconstructed, the specimen promises to be one of the best available for the genus. Other material assigned to TTU P-9416 was found in close proximity to the osteoderms of TTU P-12540 and probably belonged to the same individual; in particular, a dorsal vertebrae (Fig. 4.14b) assigned to TTU P-9416 has greatly elongated transverse processes as are also seen in *Typothorax* (Martz, 2002; Lucas et al., 2002c) and a fibula (Fig. 4.14c) assigned to the same number is much more slender than those assigned to *Desmatosuchus* by Long and Murry (1995) from the *Placerias* Quarry. Both elements can tentatively be identified on the field sketch for TTU P-9416 and TTU P-12540 (Sankar Chatterjee, 1993 field notes) in close association



Next page: Fig. 4.14. Paratypothoracisini: *a*, left dorsal paramedian osteoderm of *Paratypothorax* (TTU P-9169) from the Post Quarry in dorsal view; b, dorsal vertebra of *Paratypothorax* (TTU P-9416) from the Post Quarry in anterior view; *c*, fibula of same specimen; *d*, partial horn of a lateral osteoderm of *Paratypothorax* (TTU P-9215) from Post Quarry identified by Small (1989b) as a dentary in dorsal? view and; *e*, posterior view; *Paratypothorax* specimen (TTU P-12547) from the Macy Ranch Debbie Site, consisting of: *f*, a partial dorsal paramedian osteoderm; *g*, a partial left lateral osteoderm, and; *h*, a gigantic right femur; *i*, lateral osteoderm (TTU P-11885) of a paratypothoracisine aetosaur from the Problematic Hill locality in dorsal view *j*, dorsal paramedian osteoderms of an aetosaur with similarities to *Rioarribasuchus* (TTU P-10449) from the UU Sand Creek locality; *k*, lateral osteoderms of same specimen in dorsal view.

with the latter. As noted by Martz (2002), the “dentary” of TTU P-9215 (Fig. 4.14d-e) referred to *Paratypothorax* by Small (1989b) is a lateral osteoderm horn of that taxon.

The lateral end of a paramedian osteoderm (TTU P-12546) from the Headquarters NW locality (MOTT 3899) probably belongs to *Paratypothorax* in having a weakly raised anterior bar, and also a sheared-looking posterolateral edge as in *Paratypothorax* and *Tecovasuchus* (Martz and Small, 2005); this latter character may be an apomorphy for the mid-dorsal paramedians of paratypothoracisines associated with the tongue-shaped dorsal flange of the lateral osteoderms. A partial lateral horn (Fig. 4.14i; TTU P-11885) from Problematic Hill (MOTT 3921) and two paramedian osteoderms (one in excellent condition), a partial lateral osteoderm, and a gigantic and beautifully preserved associated femur (Fig. 4.14f-h; TTU P-12547) known from the Macy Ranch Debbie Site (MOTT 3925), are all probably referable to *Paratypothorax*. The latter specimen is the stratigraphically highest paratypothoracisine in southern Garza County.

cf. *Rioarribasuchus*

Occurrence in Southern Garza County: UU Sand Creek (MOTT 3882) and UU RR Flats (MOTT 3883), middle unit of the Cooper Canyon Formation.

Discussion: The type specimen of the procolophonid *Libognathus sheddi* (Small, 1997) recovered from the UU Sand Creek locality (MOTT 3882) was found encased within a partially articulated aetosaur carapace including paramedian and lateral osteoderms (Fig. 4.14j-k), probably mostly representing the pre-caudal region, with associated ribs and chevrons (Martz et al., 2003; in prep). The taxon has similarities to both paratypothoracisine and desmatosuchine aetosaurs, an interesting problem given the probable phylogenetic disparity of these clades and their constituent taxa (Parker, 2007).

The wider paramedian osteoderms of the Sand Creek aetosaur (Fig. 4.14j), probably from the dorsal region, strongly resemble those from the mid-dorsal region of the paratypothoracisine *Rioarribasuchus* (Lucas et al., 2006b; =*Heliocanthus*, Parker, 2007; "Andysuckus," Lucas personal communication to Parker) in having a high width-length ratio, medially offset dorsal bosses and radial ornamentation, and a posteriorly directed tongue behind the dorsal boss; additionally some of the lateral osteoderms (Fig. 4.14k, bottom) are very similar to the "Type F" lateral osteoderms of *Rioarribasuchus* (Parker, 2007) except for the absence of a posterior emargination. However, the paramedian osteoderms also possess depressed anterior laminae rather than raised bars, osteoderms possibly representing cervical paramedians that are longer than wide, and lateral osteoderms unlike any described for *Rioarribasuchus* which have large lateral horns and extremely broad flanges which are much larger than the highly reduced lateral flanges (Fig. 4.14j, top). These characters are apomorphies of the Desmatosuchinae (Parker, 2007; Bill Parker, personal communication, 2007). The strong similarities of the specimen to *Rioarribasuchus* suggest they may be co-generic, or at least closely allied, so TTU P-10449 is most likely a paratypothoracisine with a few convergent desmatosuchine-like features.

A fragment of a paramedian osteoderm (TTU P-11858), including the dorsal boss, is known from the UU Railroad Flats locality a short distance from the UU Sand Creek locality, and at very close to the same stratigraphic level. It is identical to the same region of the some of the dorsal paramedians of TTU P-10449, and may belong to the same taxon.

AETOSAURINAE *incertae sedis*

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation; Headquarter locality (MOTT 3892), middle unit of the Cooper Canyon Formation.

Discussion: There are several aetosaur osteoderms from southern Garza County which cannot be assigned confidently to an alpha taxon, and in fact most of them (discussed later) can only be referred to Aetosauria *incertae sedis*. However, a few can at least be referred to the Aetosaurinae. Two paramedian osteoderms from the Post Quarry included in TTU P-9420, which were originally brought to my attention by Bill Parker (personal communication), cannot be confidently assigned to either *Desmatosuchus* or *Paratypothorax*. Although they have not been prepared, these osteoderms have a weakly raised anterior bar, radiating ornamentation, a gently sinuous profile in posterior view, and are surprisingly thick. This is especially true of the medial part of the posterior half, where there is a pronounced swelling differing from the distinct dorsal bosses in known osteoderms of either *Desmatosuchus* or *Paratypothorax*. Little can be said with certainty about this specimen other than that it probably is an aetosaurine; it could represent a poorly known part of the carapace of *Paratypothorax* (I suspect this is the case), or a distinct taxon. The possibility can also not be discounted that these osteoderms are pathological.

TTU P-11664 from the Headquarters Site (MOTT 3892) is a small partial lateral osteoderm with a raised anterior bar, an asymmetrical dorsal flange with elongate pitting, and a long ridge-like eminence which peaks posteriorly. It may belong to a small individual of *Typothorax*.

DESMATOSUCHINAE Parker, 2007

***DESMATOSUCHUS* Case, 1920**

***Desmatosuchus smalli* Parker, 2005**

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

DESMATOSUCHINAE *incertae sedis*

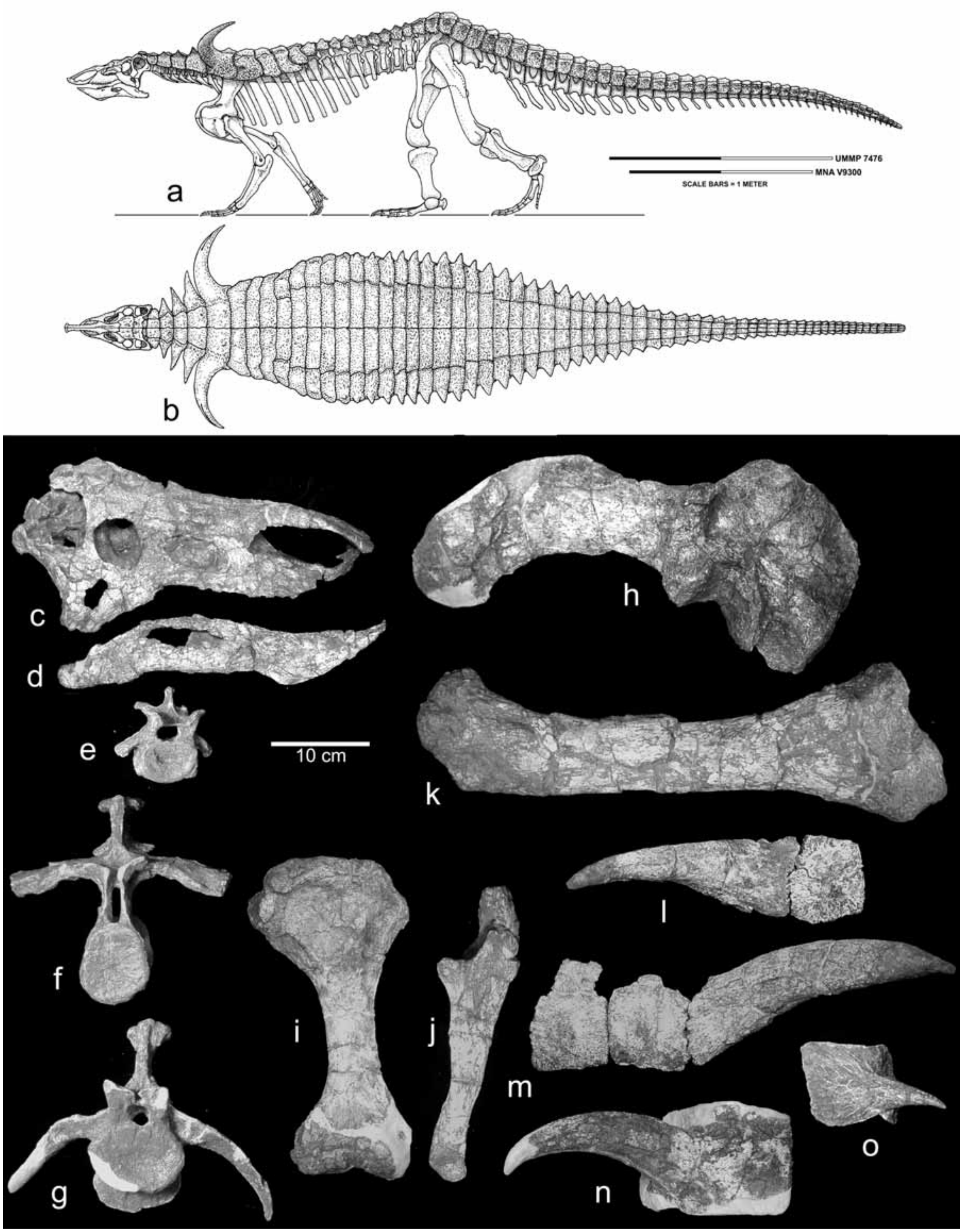
Occurrence in Southern Garza County: Rocker A Oil Field (MOTT 3614), lower unit of the Cooper Canyon Formation.

Discussion: The Desmatosuchinae is a clade of aetosaurs united by several characters, including paramedian osteoderms which have thickened "tongue and groove" articulations for the lateral osteoderms, cervical paramedians that are longer than wide, and lateral osteoderms which almost all possess elongate horns and have a dorsal flange larger than the lateral flange (Long and Ballew, 1985; Long and Murry, 1995; Parker, 2007). The genus *Desmatosuchus* has generally been thought to be composed of a single species, *D. haplocerus* (Gregory, 1953; Long and Ballew, 1985; Small, 1985, 1989b, 2002; Long and Murry, 1995; Heckert and Lucas, 2000), but recent work by Parker (2003, 2005, in prep) has shown that there are probably three species in western North America, assigning most of the material traditionally referred to *D. haplocerus* to *D. spuriensis* (Fig. 4.15a-b; Case, 1922), and a new species based on the Post Quarry material, *D. smalli* (Fig. 4.15d-o; Parker, 2005), with the species *D. haplocerus* being tentatively retained only for the type specimen (Cope, 1892).[5]

In addition to the desmatosuchine apomorphies given above, *Desmatosuchus* is a large aetosaur (adult length four meters or more) diagnosed in part by an edentulous premaxilla, an oval and reduced infratemporal fenestra (Fig. 4.15c), a small external

Next page: Fig. 4.15. *Desmatosuchus*: *a*, skeletal reconstruction of *Desmatosuchus spuriensis* in lateral view and; *b*, dorsal view (drawn by the author for Parker, in prep); selected elements of holotype of *Desmatosuchus smalli* (TTU P-9024); *c*, skull in right lateral view; *d*, right mandible in right lateral view; *e*, cervical vertebra in anterior view; *f*, dorsal vertebra in anterior view; *g*, anterior caudal vertebra in anterior view; *h*, right scapulocoracoid in lateral view; *i*, left humerus in anterior view; *j*, right ulna in medial view; *k*, right humerus in anterior view; *l*, articulated left cervical paramedian and lateral osteoderms interpreted by Parker (2005, fig. 2A) as being fourth or fifth; *m*, articulated right cervical paramedian and lateral osteoderms interpreted by Parker (2005, fig. 2B) as being sixth; *n*, fused left cervical paramedian and lateral osteoderm interpreted here as being sixth (last); *o*, left anterior caudal lateral osteoderm figured by Parker (2005, fig. 5A) .

[5] A fourth alleged species, *Desmatosuchus chamaensis* (Ziegler et al., 2002; Heckert et al., 2003) has was recognized by Parker (2003) to represent a new genus more closely related to *Paratypothorax*. Parker's extensive (2007) redescription of the material provided the new genus name *Heliocanthus*. However, Lucas et al. (2006) produced a 1 ¼ page paper immediately before Parker's providing the name *Rioarribasuchus*. Lucas has claimed that he assumed Parker never intended to actually name the material himself.


a
UMMP 7476
MNA V9300
SCALE BARS = 1 METER
b
c
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mandibular fenestra (Fig. 4.15d), a humerus with an ectepicondylar foramen, a last presacral vertebra which is a dorsosacral fused to the sacrum, paramedian and lateral osteoderms with depressed anterior laminae rather than raised anterior bars, paramedian osteoderms with a randomly pitted pattern and a dorsal boss usually situated in the middle of the osteoderm, and lateral spines which are especially massive and recurved in the cervical series (Fig. 4.15l-n), and to a lesser extent in the sacral region (Fig. 4.15o) (e.g. Long and Ballew, 1985; Small, 2002; Long and Murry, 1995; Parker, 2005).

Small (1985, 1989b, 2002) described the excellent Post Quarry *Desmatosuchus* material, recognizing that there were differences between in the cranial material and osteoderms between these specimens and material generally referred to *D. haplocerus*. Parker (2003, 2005) considered these differences sufficient to erect a new species, *Desmatosuchus smalli*. This species is diagnosed by the absence of a shallow transverse sulcus between the supratemporal fenestrae, a highly reduced antorbital fossa, a shallow median pharyngeal recess, a large gap between the basal tubera and basipterygoid processes, exoccipitals that do not meet on the floor of the braincase, a maxillary tooth count of 10-12, anterior cervical lateral osteoderms with extremely elongate lateral spines (Fig. 4.15l-n), and recurved spines on the posterior lateral osteoderms (Fig. 4.15o)(Small, 1989b, 2002; Parker, 2005).

Parker's (2005) holotype for *Desmatosuchus smalli* (TTU P-9024), and a referred specimen (TTU P-9023), both include excellent skull with extensive postcranial material (including paramedian and lateral osteoderms) described by Small (1985, 2002) and Parker (2005), and there is also an unpublished quarry map for the holotype showing that this material was associated. TTU P-9204, TTU P-9226, TTU P-9229, and TTU P-9419 consist of associated osteoderm and other postcranial material of varying degrees of completeness. Other cranial (TTU P-9025, TTU P-9420, TTU P-9207) and postcranial material (TTU P-9225, TTU P-9416, TTU P- 10083) from the TTU collections, mostly lacking osteoderms, are tentatively assigned to the same taxon based on similarities with TTU P-9023 and TTU P-9024 (Small, 1985, 2002; Long and Murry, 1995; Parker, 2005). TTU P-9416 includes *Paratypothorax* material (already discussed), but also a string of vertebrae and an associated scapulocoracoid (Sankar Chatterjee field notes, 1993) probably referable to *Desmatosuchus* by comparison with the holotype material. The Dallas Museum of Natural History houses considerable *Desmatosuchus smalli* material from the Post Quarry (Parker, 2005), the most important of which is perhaps a partial pelvis (DMNH 9939; Long and Murry, 1995). This material is all in dire need of extensive repreparation, redescription, and careful reevaluation; it is likely that some skull and skeletal material will ultimately prove referable to *Paratypothorax*.

Parker (2005, fig. 2B) interpreted the largest of the cervical lateral spikes of TTP-9204 (Fig. 4.15m) as being the sixth and last of the cervical series, homologous with the massive recurved lateral spines of *Desmatosuchus spuriensis* (Fig. 4.15a-b), although he noted that the cervical spines of *D. smalli* were less recurved. Unlike the last cervical row of *D. spuriensis* (Parker, 2003, in prep), the lateral horn in TTU P-9204 is also not fused to its adjacent paramedian. However, TTU P-9204 does possess a cervical lateral horn which is shorter than Parker's putative last cervical spike, but also strongly recurved and strongly fused to its adjacent paramedian (Fig. 4.15n). This row may actually be the one which is homologous with the massive shoulder spike in the last cervical row in *D. spuriensis*, and the longer but unfused and less recurved lateral spike may be the penultimate (fifth) row instead.

The only other probable desmatosuchine material from southern Garza County consists of two robust lateral horns (TTU P-9228), probably from the anterior cervical region, collected by Malcom Neyland from the "Rocker A Oil Field" (MOTT 3614). As already discussed, this field number covers a broad area, but all material probably comes from the lower unit, or possibly the Boren Ranch sandstone/beds.

AETOSAURIA *incertae sedis*

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869) and Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation; Lott Hill (MOTT 3878), UU Railroad Flats (MOTT 3883), middle unit of the Cooper Canyon Formation; Patricia Site

(MOTT 3870), and Patty East (MOTT 3880), upper unit of the Cooper Canyon Formation.

Discussion: There are numerous fragmentary osteoderms from southern Garza County which can only be assigned to Aetosauria *incertae sedis*. There are a few tantalizing fragmentary osteoderms from the Boren Quarry (MOTT 3869). TTU P-10747 is a paramedian fragment with a faint and somewhat conical boss and faint, distinctly radiating ornamentation, TTU P-11148 is an oddly shaped paramedian with a massive pyramidal boss and a raised anterior bar, TTU P-10406 consists of paramedian fragments, including one with a dorsal boss, and others showing a raised anterior bar and both pitted and grooved ornamentation, and TTU P-12447 is an incomplete dorsal boss from a paramedian.

Much material from the Post Quarry can also not be clearly associated with osteoderms or identifiable postcranial material, although based on size they are almost certainly referable to either *Desmatosuchus* or *Paratypothorax*. This includes a basicranium (TTU P-9206), an axis (TTU P-9205), metapodials and phalanges (TTU P-9227). There is also a small ulna (TTU P-9171) referred by Small (1989) to *Desmatosuchus*, although this elements may not even be aetosaur; if it is, its size suggests it probably belongs to the little *Typothorax* specimen. TTU P-11564 is a partial possible lateral osteoderm from UU Railroad Flats locality (MOTT 3883) which includes a pyramidal horn and traces of radiating ornamentation. TTU P-10490 from the Lott-Kirkpatrick (MOTT 3635) locality is the partial skeleton of a very small aetosaur. The osteoderms are fragmentary, unprepared, and not very well preserved, but may prove diagnostic with preparation.

PARACROCODYLOMORPHA Parrish, 1993

RAUISUCHIA Bonaparte, 1982

RAUISUCHIDAE Huene, 1942

POSTOSUCHUS Chatterjee, 1985

***Postosuchus kirkpatricki* Chatterjee, 1985**

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

RAUISUCHIDAE *incertae sedis*

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869), lower unit of the Cooper Canyon Formation; Patricia Site (MOTT 3870), upper unit of the Cooper Canyon Formation.

POPOSAUROIDEA Nopsca, 1928
***sensu* Weinbaum and Hungerbühler, 2007**

POPOSAURIDAE Nopsca, 1928

***sensu* Weinbaum and Hungerbühler, 2007**

***POPOSAURUS* Mehl, 1915**

***Poposaurus* sp.**

Occurrences in Southern Garza County: OS Ranch Brazos (MOTT 3705), middle unit of the Cooper Canyon Formation.

SHUVOSAURIDAE Chatterjee, 1993 *sensu* Nesbitt, 2007

***SHUVOSAURUS* Chatterjee, 1993**

***Shuvosaurus inexpectus* Chatterjee, 1993**

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

SHUVOSAURIDAE *incertae sedis*

Occurrences in Southern Garza County: OS Flat Road (MOTT 3872), Boren Ranch beds; Boren Quarry (MOTT 3869) and Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation; Lott Hill (MOTT 3878), Headquarters (MOTT 3892), Headquarters South (MOTT 3898), middle unit of the Cooper Canyon Formation; Patricia Site (MOTT 3870), upper unit of the Cooper Canyon Formation.

Discussion: Within the "Rauisuchia" (in its broad usage, *sensu* Bonaparte, 1984; Chatterjee 1985; Long and Murry, 1995; Gower, 2000; *contra* Parrish, 1993); the taxa *Postosuchus kirkpatricki* (Chatterjee, 1985), *Shuvosaurus inexpectus* (Chatterjee, 1993), and *Chatterjeea elegans* (Long and Murry, 1995) have had a complex taxonomic history. Indeed, much considerable confusion regarding rauisuchian systematics has stemmed from the type material of these taxa (all from the Post Quarry), and their relationship to the genus *Poposaurus* (Mehl, 1915) (see Long and Murry, 1995; Gower, 2000 for summaries).

Postosuchus kirkpatricki (Fig. 4.16) is a large (about 6-9 meters long) carnivorous rauisuchian characterized by a massive, mediolaterally compressed skull with recurved, serrated, and somewhat heterodont teeth, a key-hole shaped orbit with a stepped postorbital bar, a subnarial fenestra between the premaxilla and maxilla, an infratemporal fenestra divided by a forward process on the squamosal and quadratojugal, a long, rod-like pubis and ischium with a well-developed pubic foot, a pelvis with two sacral vertebrae and a sub-horizontally oriented illium, cervical vertebra that are much taller than long and have hypapophyses, caudal vertebrae with two neural spines, and a single row of small paramedian osteoderms (Chatterjee, 1985; Long and Murry, 1995; Peyer, 2001; Weinbaum, 2002, 2007). Several of these characters led Long and Murry (1995) and Weinbaum (2002, 2007), who have done the most recent detailed studies of the excellent holotype and paratype material (TTU P-9000 and TTU P-9002), to assign *Postosuchus* to the family Rauisuchidae, a group which includes most of the large Late Triassic rauisuchians. The tiny manus, a forelimb which is extremely short compared to the hindlimb (Fig. 4.16a), and vertebral column in which the anterior dorsal vertebrae are

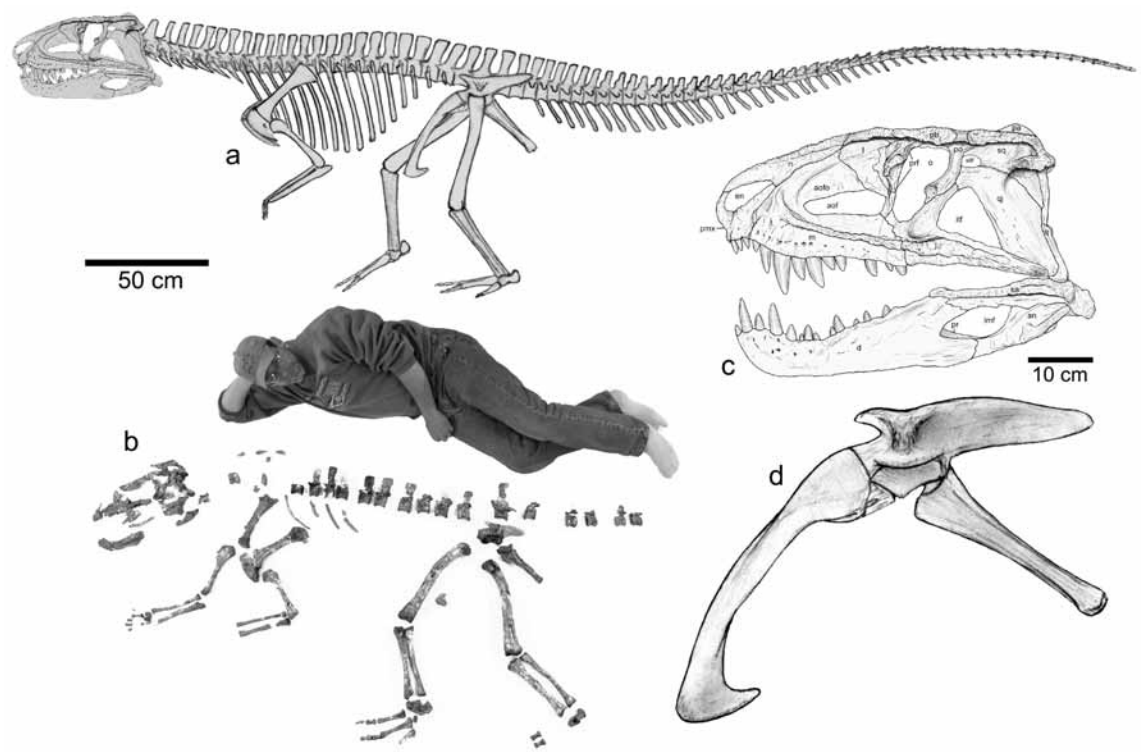

Fig. 4.16. The large rauisuchid *Postosuchus kirkpatricki* from the Post Quarry; *a*, skeletal reconstruction scaled to the holotype, TTU P-9000 (source: Weinbaum, 2007, fig. 5.27); *b*, paratype skeleton and flying chimp to same scale; *c*, skull reconstruction mostly based on holotype (source: Weinbaum, 2007, fig. 3.1); *d*, reconstruction of pelvis in left lateral view (source: Weinbaum, 2007, fig. 5.19, left).

much smaller than the posterior dorsals, probably indicate that *Postosuchus* was bipedal, and its massive, superficially tyrannosaur-like skull indicates it was probably the top terrestrial predator of its time (Chatterjee, 1985; Weinbaum, 2002, 2007).

The Post Quarry holotype and paratype material (TTU P-9000 and TTU P-9002) is the only extensive material from southern Garza County material referable to *Postosuchus kirkpatricki* (Chatterjee, 1985; Long and Murry, 1995; Weinbaum, 2002, 2007). A right ectopterygoid (TTU P-9626) and two tibias (TTU P-11612 and TTU P-11686) from the Patricia Site (MOTT 3870) are virtually identical to the Post Quarry material. However, I am uncomfortable assigning isolated elements to a particular alpha taxon, especially given the thickness of strata between the Post Quarry (at the top of the lower unit of the Cooper Canyon Formation) and Patricia Site material (near the top of

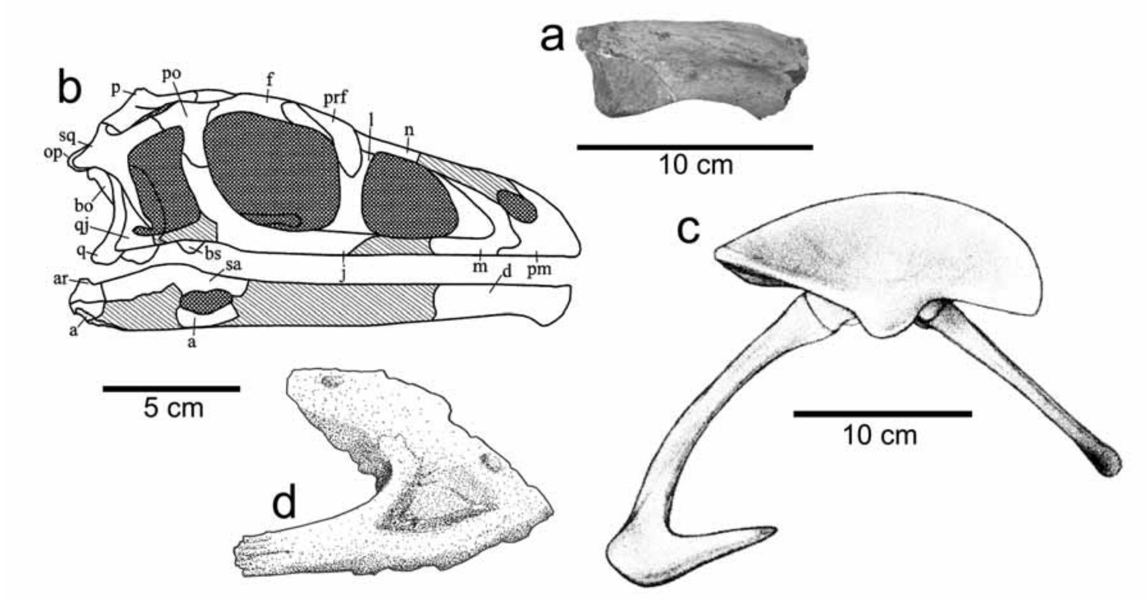

Fig. 4.17. Poposauroid rauisuchians: *a*, postacetabular process of a right illium of *Poposaurus* (TTU P-11524) from the OS Ranch Brazos locality to the same scale; *b*, skull reconstruction of *Shuvosaurus inexpectus* (source: Lehane, 2005, fig. 32A); *c*, pelvis of *Shuvosaurus inexpectus* (=*Chatterjeea elegans*) in left lateral view (source: Weinbaum, 200, fig. 6.1); *d*, large right maxilla of indeterminate shuvosaurid (TTU P-9605) from OS Flat Road locality in lateral view (source: Lehane, 2005, fig. 38A).

the upper unit). I prefer to refer these isolate elements to Rauisuchidae *incertae sedis*, although they may very well be referable to *Postosuchus* (Jonathan Weinbaum, personal communication). Isolated teeth (TTU P-10444, TTU P-10512) from the Boren Quarry (MOTT 3869) near the bottom of the lower unit may also belong to rauisuchids (Bill Mueller, personal communication).

The small rauisuchian *Poposaurus* (Mehl, 1915) is not known from the Post Quarry, although Chatterjee's (1985) comparison of this animal with *Postosuchus* is the source of some of the taxonomic confusion regarding the difference between rauisuchids and poposaurids (Long and Murry, 1995; Weinbaum, 2002). Weinbaum and Hungerbühler (2007) recently reviewed the genus, and an upcoming description of an amazingly complete postcranial skeleton from the Chinle Formation of Utah will shed additional light on this animal. The only material from southern Garza County referable to *Poposaurus* is a post-acetabular process of a right illium and a badly preserved associated vertebra (TTU P-11524; Fig. 4.17a) collected from the OS Ranch Brazos locality (MOTT 3705), supposedly within the Dalby Ranch sandstone (Bill Mueller, personal communication).

Long and Murry (1995) recognized that the postcranial material from the Post Quarry which Chatterjee (1985) had considered to be juveniles of *Postosuchus* were actually a distinct, much smaller rauisuchian taxon allied to *Poposaurus*, which they named *Chatterjeea* (holotype TTU P-9001). They also suggested that the bizarre, edentulous, ornithomimid-like skull from the Post Quarry that Chatterjee (1993) had named *Shuvosaurus* (holotype TTU P-9280; Fig. 4.17b) actually belonged with the *Chatterjeea* postcrania. Although Chatterjee (1993), Rauhut (1997, 2003), and Lehane (2006) all noted features of the *Shuvosaurus* cranial material which argued for theropod affinities, the recent discovery of an articulated specimen of a closely related taxon, *Effigea okeefei* (Nesbitt and Norell, 2005; Nesbitt, 2007) shows clearly that *Shuvosaurus* and *Chatterjeea* are the same animal.

Shuvosaurus is a small (about 2 m long) rauisuchian with edentulous jaws, a smooth and unornamented skull roof, greatly elongated parabasisphenoid, elongate cervical vertebrae, three or more sacral vertebrae, a vertically oriented illium with a long preacetabular process, a slightly perforate acetabulum, and enormous pubic boot (Fig. 4.17c) (Chatterjee, 1993; Long and Murry, 1995; Nesbitt, 2007). It's bizarre edentulous jaws indicate that may have been herbivorous (Chatterjee, 1993). Nesbitt (2007) placed *Shuvosaurus* and *Effigea* within Chatterjee's (1993) family Shuvosauridae.

As with *Postosuchus*, the only extensive cranial and postcranial material of *Shuvosaurus* from southern Garza County is the Post Quarry material described by Chatterjee (1993), Long and Murry (1995) and Lehane (2004). The Post Quarry postcranial material is currently being reprepared and redescribed by Jeremiah Kokes. A massive edentulous maxilla (TTU P-9605; Fig. 4.17d) probably belonging to a shuvosaurid (Lehane, 2004) is known from the OS Flat Road locality (MOTT 3872) in the uppermost Boren Ranch beds, and isolated postcranial elements (TTU P-11601, TTU P-11865, TTU P-11414, TTU P-10783) are known from the Lott Hill (MOTT 3878), Headquarters and Headquarters South (MOTT 3892, 3898), and Patricia Site (MOTT 3870) localities in the middle and upper units of the Cooper Canyon Formation (Jeremiah Kokes, in prep).

CROCODYLOMORPHA Hay, 1930 *sensu* Walker, 1970
SPHENOSUCHIDAE Haughton, 1924
SPHENOSUCHIDAE *incertae sedis*

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation; Headquarters South (MOTT 3898), middle unit of the Cooper Canyon Formation.

Discussion: Sphenosuchian material from the Dockum Group is known from the Los Esteros Member and Redonda Formation of New Mexico, and the Tecovas Formation of Texas (Colbert, 1952; Parrish, 1991; Long and Murry, 1995; Clark et al., 2000; Nesbitt et al., 2005). Most sphenosuchian material from both the Chinle Formation and Dockum Group has been assigned to *Hesperosuchus agilis* (Parrish, 1991; Long and Murry, 1995; Clark et al., 2000), although Long and Murry (1995) named the taxon *Parrishia mccreai* for more robust vertebrae from low in the Chinle Formation and Dockum Group, and *Redondavenator quayensis* from the Redonda Formation is a particularly massive taxon with a skull length alone probably reaching 60 cm (Nesbitt et al., 2005).

In southern Garza County, sphenosuchian limb elements (TTU P-11443, TTU P-11444, TTU P-11277) and a premaxilla (TTU P-9466) are known from the Post Quarry (MOTT 3624) (Jonathan Weinbaum and Bill Mueller, personal communication). However, the best specimen by far is an excellent semi-articulated specimen including a skull, both mandibles, and most of the postcranial skeleton (TTU P-10927) from the Headquarters South locality (MOTT 3898). This specimen currently is undergoing preparation by Doug Cunningham. Isolated sphenosuchian elements are also known from Headquarters South (TTU P-11279 and TTU P-11623).

SUCHIA incertae sedis

***REVUELTOSAURUS* Hunt, 1989**

***Revueltosaurus callenderi* Hunt, 1989**

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869), lower unit of the Cooper Canyon Formation.

Discussion: Hunt (1989b) named *Revueltosaurus callenderi* (Fig. 4.18) for isolated teeth from the Bull Canyon Formation of New Mexico with similarities to those of ornithischian dinosaurs, and several other putative ornithischian taxa have also been based on teeth (e.g. Chatterjee, 1984; Hunt and Lucas, 1994; Heckert, 2002, 2004). However, Parker et al. (2005) provided a preliminary description of extensive skeletal material of *Revueltosaurus* from the Painted Desert Member of the Chinle Formation of Arizona which revealed that it is a pseudosuchian archosaur, as demonstrated in part by the presence of a postfrontal, a crocodile-normal ankle, and paramedian osteoderms resembling those of aetosaurs. Irmis et al. (2006) and Nesbitt et al. (2007) considered several other "ornithischian" tooth taxa to be diagnostic as alpha taxa, although they emphasized that the recent revision of *Revueltosaurus* casts doubt on their identification as ornithischians.

Heckert (2002, 2004) provided the most recent overview of these putative ornithischian tooth taxa. They share crowns that are non-recurved, roughly triangular in labial view but asymmetrical in mesial and distal views, possess large denticles at an angle of 45° or more to the mesial and distal edges, and a well developed neck. The teeth of *Revueltosaurus callenderi* are distinguished from these other putative ornithischians by the height of the crown (7-15 mm), a large number of denticles (more than seven per carina) that are short and well worn by occlusion, and premaxillary crowns that are approximately twice as tall as those of the maxilla and dentary (Heckert, 2002, 2004).

Only a single tooth from southern Garza County may be tentatively assigned to *Revueltosaurus callenderi*, a complete root and crown (TTU P-10423; Fig. 4.18) from the

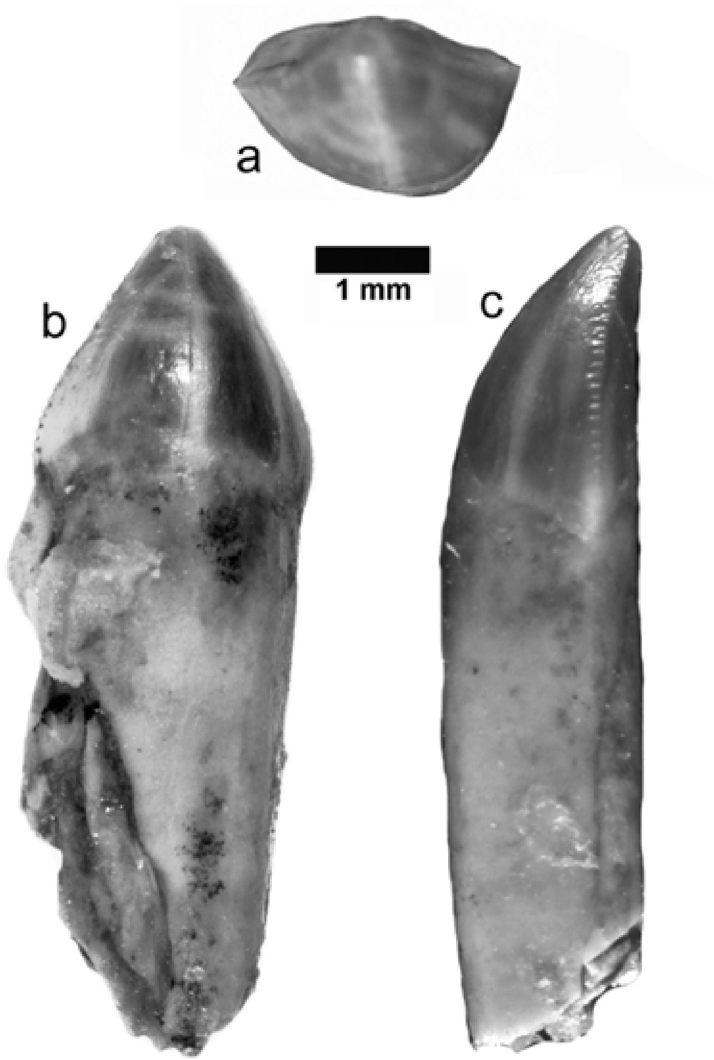

Fig. 4.18. Tooth of *Revueltosaurus callenderi* (TTU P-10423) from the Boren Quarry; *a*, occlusal view; *b*, labial view; *c*, messial view (**photos courtesy Bill Mueller**).

Boren (Neyland) Quarry (MOTT 3869) at the base of the lower unit of the Cooper Canyon Formation. The denticles of this tooth are considerably finer than others referred the taxon (Hunt, 1989; Heckert, 2002, 2004) so the referral must be considered tentative. However, the specimen still resembles *R. callenderi* more than any other known taxon.

ORNITHOSUCHIA Huene 1907-1908 *sensu* Gauthier, 1986

ORNITHODIRA Gauthier, 1986

“*PTEROMIMUS*” Atanassov, 2002

“*Pteromimus longicollis*” Atanassov, 2002

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869) and Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

“*PROCOELOSAURUS*” Atanassov, 2002

“*Procoelosaurus brevicollis*” Atanassov, 2002

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869) and Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

cf. “*Procoelosaurus*”

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869) and Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation; UU Sand Creek (MOTT 3882) and Headquarters (MOTT 3892), middle unit of the Cooper Canyon Formation.

Discussion: Atanassov (2002) described two small reptiles with somewhat similar procoelous vertebrae, “*Procoelosaurus*” and “*Pteromimus*” (Fig. 4.19), from Dockum Group of western Texas. Most material for both taxa (including the holotypes, TTU P-10085 and TTU P-10110) comes from the Post Quarry (MOTT 3624), where isolated vertebrae and some associated material were fantastically abundant (Sankar Chatterjee, unpublished field notes), with additional material coming from the Boren Quarry (MOTT 3869). Incomplete procoelous vertebra (TTU P-10777 and TTU P-10836) from Headquarters (MOTT 3892) and UU Sand Creek (MOTT 3882), both slightly below the Miller Ranch sandstone, may belong to *Procoelosaurus* or a closely related form. These specimens are the stratigraphically highest representatives of either taxon.

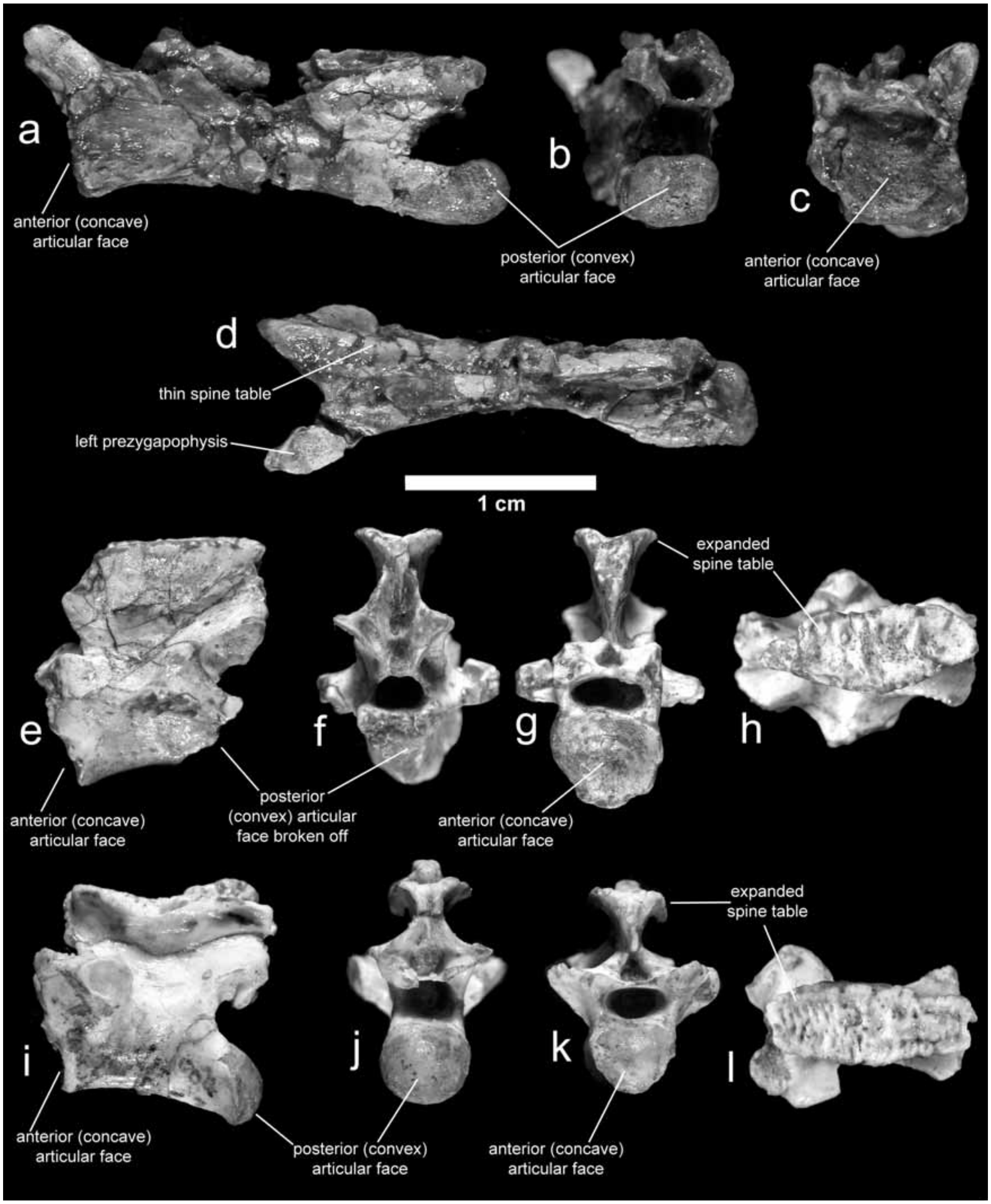

Fig. 4.19. Vertebrae of "*Pteromimus longicollis*" and "*Procoelosaurus brevicollis*"; *a*, cervical vertebra of "*Pteromimus*" (TTU P-10085) from the Post Quarry in left lateral view; *b*, posterior view; *c*, anterior view, and; *d*, dorsal view; *e*, dorsal vertebra of "*Procoelosaurus*" (TTU P-1 0216) from the Boren Quarry in left lateral view; *f*, posterior view; *g*, anterior view, and; *h*, dorsal view; *i*, dorsal vertebra of "*Procoelosaurus*" (TTU P-10213) from the Boren Quarry in left lateral view*; j*, posterior view; *k*, anterior view and; *l*, dorsal view.

Both holotypes are based on associated but disarticulated material, and most referred specimens are isolated vertebrae (Sankar Chatterjee, unpublished field notes). The type and referred material of "*Pteromimus*" consists of considerable disarticulated cranial material. The skull was reconstructed as tall and anteriorly tapering, with conical, distally fluted teeth with subthecodont implantation. The cervical vertebrae are elongate and procoelous with anterior centrum faces that are subhexagonal, and also possess a ventral keel, and long and low neural arches with narrow and smooth-surfaced spine tables (Atanassov, 2002).

The vertebrae of the type and referred specimens of "*Procoelosaurus*" differ from those of "*Pteromimus*" in being shorter, lacking a ventral keel, and having tall neural arches with a broad and heavily ornamented spine table. The transverse processes on the caudal vertebrae are very wide. The illia have a short preacetabular process and a long postacetabular process, the ischium is robust and plate-like. The holotype includes an almost complete hindlimb with the femur, tibia, a distally tapering fibula, and an advanced mesotarsal ankle in which the astraglaus has an ascending process and the calcaneum is reduced and lacks a tuber (Atanassov, 2002). The hindlimb morphology and tooth implantation of "*Procoelosaurus*" and "*Pteromimus*" caused these taxa to fall out as ornithodirans allied to pterosaurs in Atanassov's (2002) phylogenetic analysis.

A few vertebrae identified in more recent years from both the Post Quarry and Boren Quarry differ from the material described by Atanassov (2002) and may belong to different but closely related taxa (Momchil Atanassov, personal communication). There are also partial procoelous vertebrae (TTU P-10777, TTU P-10836) from the UU Sand Creek (MOTT 3882) and Headquarters (3892) localities possibly referable to "*Procoelosaurus*", the stratigraphically highest known specimens potentially referable to either taxon.

DINOSAUROMORPHA Benton, 1985 *sensu* Sereno, 1991

***DROMOMERON* Irmis et al., 2007**

***Dromomeron* sp.**

Occurrences in Southern Garza County: Boren Quarry (MOTT 3869), lower unit of the Cooper Canyon Formation; Headquarters South locality (MOTT 3898), middle unit of the Cooper Canyon Formation.

DINOSAURIFORMES Novas, 1992
***TECHNOSAURUS* Chatterjee, 1984**
***Technosaurus smalli* Chatterjee, 1984**

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

DINOSAURIFORMES *incertae sedis*

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

DINOSAURIA Owen, 1842 *sensu* Gauthier, 1986
SAURISCHIA Seeley, 1887 *sensu* Gauthier, 1986
SAURISCHIA *incertae sedis*

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation; Headquarters NW (MOTT 3899), middle unit of the Cooper Canyon Formation.

THEROPODA Marsh, 1881 *sensu* Gauthier, 1986
THEROPODA *incertae sedis*

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation; Lott-Kirkpatrick (MOTT 3634) and Patricia Site (MOTT 3870), upper unit of the Cooper Canyon Formation.

COELOPHYSOIDEA Nopsca 1928 sensu Holtz, 1994

COELOPHYSOIDEA *incertae sedis*

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

COELUROSAURIA? Huene, 1914

COELUROSAURIA *incertae sedis*

***PROTOAVIS* (in part) Chatterjee, 1991**

***Protoavis texensis* (in part) Chatterjee, 1991**

Occurrences in Southern Garza County: Post Quarry (MOTT 3624), lower unit of the Cooper Canyon Formation.

Discussion: The Upper Triassic dinosauromorph fossil record has, until recently been considered to lie almost exclusively within crown-clade Dinosauria, and more specifically within the clades Ornithischia, Theropoda, and Sauropodomorpha (e.g. Hunt et al., 1997), with the possible exception of the herrerasaurids (Gauthier, 1986; Langer, 2004). However, recent work indicates the presence of a variety of basal saurischians (Langer and Benton, 2006; Nesbitt et al., 2007) basal dinosauriforms (Dzik, 2003; Ezcurra, 2006; Nesbitt et al., 2007) and basal dinosauromorphs (Irmis et al., 2007) being present in the Late Triassic. Much of this material from North America was previously considered to be theropod (e.g. Sullivan and Lucas, 1999; Heckert et al., 2003; Hunt et al., 1997) but lacks theropod and/or dinosauriform apomorphies (Ezcurra, 2006; Nesbitt et al., 2007).

A handful of limb elements of basal saurischians, basal dinosauriforms and basal dinosauromorphs from southern Garza County have been identified and are currently being described (Nesbitt et al., 2007; Nesbitt and Chatterjee, in prep). Several partial limb bones from the Neyland Quarry (MOTT 3869) and Headquarters South (MOTT 3898) localities are referable to the basal dinosauromorph *Dromomeron* (Nesbitt and Chatterjee, in prep), and a basal dinosauriform tibia (TTU P-11127) is known from the Post Quarry (MOTT 3624). Basal saurischians are represented by a partial pelvis (TTU P-10082) from the Post Quarry (Nesbitt and Chatterjee, in prep) previously identified by Lehman and Chatterjee (2005) as *Coelophysis*, and a tibia from the Headquarters NW locality (MOTT 3899) (Nesbitt and Chatterjee, in prep).

True theropods present in western North America during the Late Triassic, and with the possible exception of the putative herrerasaurid *Chindesaurus* (Long and Murry, 1995), all identifiable theropod material probably belongs to the basal theropod clade Coelophysoidea (Hunt et al., 1997; Heckert et al., 2003; Langer, 2004; Tykoski and , 2004; Rauhut, 2003; Nesbitt et al., 2007). In southern Garza County, basal theropod material probably belonging to coelophysoids is known from the Lott-Kirkpatrick (MOTT 3634), Post Quarry, and Patricia Site (MOTT 3870) localities (Nesbitt et al., 2007; Nesbitt and Chatterjee, in prep). The Lott-Kirkpatrick material consists of a partial skeleton (TTU P-10072), while the Post Quarry material consists of an a illium (TTU P-10071) previously referred to *Coelophysis* by Lehman and Chatterjee (2005) and a tibia (TTU P-11044), and the Patricia Site element is a tibia (TTU P-10534) previously identified as ornithischian by Cunningham et al. (2002; "TTUP unnumbered" of Nesbitt et al., 2007).

Chatterjee (1991, 1999) identified the putative bird *Protoavis texensis* from the Post Quarry in southern Garza County, suggesting that surprisingly early radiation for coelurosaurian theropods. It is a commonly stated opinion that *Protoavis* is a chimera (e.g. Ostrom, 1991; Chiappe, 1995; Paul, 2002), although even if true, this does not discount the possibility that at least some of the material might indeed be avian (Witmer, 1991). At the very least, some of the *Protoavis* material is theropod. The femur of TTU

P-9200 and the astragalus and calcaneum of TTU P-9201 are probably basal theropod and possibly coelophysoid (Paul, 1988; Hunt et al., 1998; Irmis et al., 2007).

Renesto (2000) made the very tentative suggestion that *Protoavis* might be a drepanosaur based on similarities, particularly in the cervical vertebrae, with the Italian drepanosaur *Megalancosaurus*. This suggestion was voiced with more confidence by Paul (2002), who revised his previous opinion (Paul, 1988) that *Protoavis* was a peculiar basal theropod. However, Renesto (2000) was cautious about making these comparisons, acknowledging that he had not seen *Protoavis* in person and was basing his comparisons on Chatterjee's (1991, 1999) description and drawings. The identification of the cervicals of *Protoavis* as belonging to a drepanosaur, though entirely possible (especially given the identification of other drepanosaur postcranial material at the Post Quarry), must remain tentative, especially given that the Italian drepanosaurs material is crushed two-dimensionally, making comparisons with the elements of *Protoavis* problematic (Momchil Atanassov, personal communication)

Paul's (2002, p. 172) claim that "Renesto (2000) noted numerous skull similarities between *Megalancosaurus* and '*Protoavis*'" is an exaggeration. Renesto only noted that, presumably in comparison to Chatterjee's (1991, 1999) reconstruction of the skull of *Protoavis*, both had a pointed snout, an inflated postorbital region, and a downturned anterior mandible.[6] Paul (2002) himself made no additional comparison between the skulls of *Protoavis* and the Italian drepanosaurs aside from a similarity in the shape of the quadrate. Indeed, as with the vertebrae, such a comparison is difficult given the two-dimensional crushing of the skulls in the Italian material (e.g. Renesto, 2000; Renesto and Binelli, 2006; Momchil Atanassov, personal communication). This makes description of the braincase, a critical region of the skull in *Protoavis*, problematic. The only particular reason to consider the cranial material of *Protoavis* drepanosaurid is the association with (possibly) drepanosaur-like cervical vertebrae, but if *Protoavis* is indeed a chimera, there is no particular reason to assume the cranial material is drepanosaurid

[6]It is worth pointing out that these are the same similarities that Feduccia (1996) used to compare *Megalancosaurus* with *Archaeopteryx*.

even if the cervical vertebrae are. Indeed Witmer (1991), Currie and Zhao (1993), and Currie (1995) have noted striking similarities in the braincase with various derived coelurosaurs, and Witmer (2002) offered the opinion that *Protoavis* does in fact represent a range extension for the Coelurosauria, although he considered its avian affinities unproven.

Putative ornithischians from the Upper Triassic of North America have mostly been based on teeth (Hunt, 1989; Hunt and Lucas, 1994; Heckert, 2002, 2004), and as already discussed at least some of these tooth taxa are probably pseudosuchians, or at least archosauriforms of uncertain affinity (Parker et al., 2005; Irmis et al., 2006; Nesbitt et al., 2007). Another putative ornithischian, *Technosaurus smalli* (Chatterjee, 1984) from the Post Quarry in southern Garza County, was based on a partial mandible containing teeth and several fragmentary cranial and postcranial elements (TTU P-9021). This specimen may be a chimera (Sereno, 1991; Hunt and Lucas, 1994; Nesbitt et al., 2007), but the premaxilla and tooth-bearing partial mandible have similarities to the basal dinosauriform *Silesaurus* (Dzik, 2003), and *Technosaurus* may belong to the same family (Nesbitt et al., 2007).

Vertebrate Localities

The Texas Tech vertebrate collections from the Dockum Group of southern Garza County are vitally important, as they include not only some extraordinarily rich and diverse sites, but because these localities (Figs. 1.5, 2.3c) are distributed throughout the Dockum Group section. With the establishment of a lithostratigraphic section in which important units are not only identified but mapped in order to corroborate their geographic and superpositional relationships, this makes it possible to place the vertebrate localities in superpositional order (Fig. 4.20), and therefore to establish a detailed and testable biostratigraphic framework for the vertebrate taxa discussed above that are found at these localities. Stratigraphic sections for most of these localities may be found in Appendix 1.

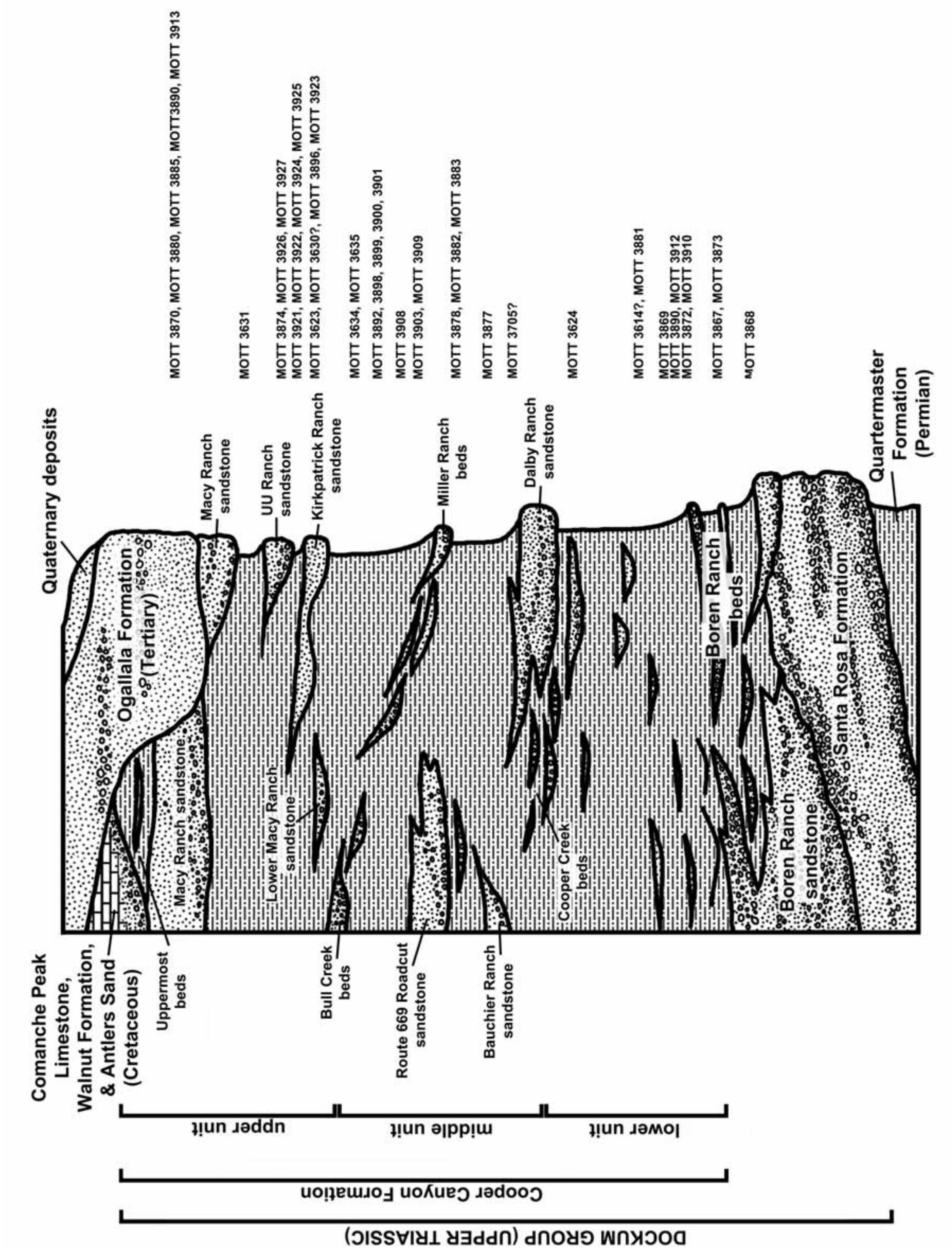

Fig. 4.20. Vertebrate localities in the Dockum Group of southern Garza County placed (approximately) in superpositional order.

The Boren Ranch Sandstone/Beds

OS Ranch and associated localities

Most vertebrate localities from the Boren Ranch beds come from the OS Ranch localities, which are located on property belonging to Giles McCrary near the eastern edge of Garza County south of Highway 380, in the hilly area on the south side of the North Fork of the Double Mountain Fork of the Brazos River. Most of these localities were found and collected by Father Malcom Neyland and Bill Mueller. Due to the complex stratigraphic relationships of sandstones, mudstones, and conglomerates at the OS Ranch, the precise superpositional relationships of these localities with each other, even over a short area, is sometimes hard to determine, and will probably not be fully resolved without very fine-scale mapping. As already discussed, the lower (grayish) part of the Boren Ranch beds at OS Ranch are interpreted as probably being largely lacustrine, while the upper (more reddish) part of the sequence probably represents predominantly overbank deposits (Fig. 2.16a). The OS Ranch localities, especially those at MOTT 3867 and MOTT 3873, are the stratigraphically lowest Upper Triassic vertebrate localities known in southern Garza County.

The OS Ranch locality (MOTT 3867) and the associated "Petrified Grove" (MOTT 3868) are located in the grayish, mudstone dominated beds possibly representing lacustrine deposition. The lower Boren Ranch sandstone exposed here is probably the same one present in the OS Ranch Gully section (Fig. 2.14), and the fossil localities are therefore probably about 15-18 meters (50'-60') above the base of the Boren Ranch beds. The fossil localities are mostly lie close to the level of a distinctive bed of tan-colored limestone or dolomite. Site 1 is directly beneath the carbonate bed, at the base of the southeast side of a hill capped by an upper Boren Ranch sandstone which is referred to informally as "Dicynodont Hill" (Fig. 2.16a; the Jacob's staff is resting against the carbonate bed). Site 2 is directly beneath the carbonate bed about 200 meters east of Site 1, and Site 3 is probably slightly higher, about 100 meters east of Site 1. These localities, and the surrounding area, have produced abundant fragmentary material of large metoposaurs, a small partial skull of a basal phytosaur (*Paleorhinus* sp.; Fig. 4.7c), unidentified phytosaur postcrania, and dicynodont postcranial material (Mueller and Chatterjee, 2007). The "Petrified Grove" of upright *Araucarioxylon* tree stumps (Lehman and Chatterjee, 2005, p. 333; Fig. 2.17a) was discovered by Jonathan Weinbaum and Kyle McQuilkin on the north side of the Dicynodont Hill, stratigraphically lower than the vertebrate localities within the lower grayish beds.

The OS Ranch East locality (MOTT 3873) is located just to the east of OS Ranch Site 2. The material recovered from this locality, consisting of indeterminate large metoposaur and phytosaur material, also comes from the lower grayish beds, and in fact from directly above a tan colored carbonate bed which appears to be the same one linking the main OS Ranch localities. Carbonaceous plant material and indeterminate large metoposaur material was observed in sandstone exposed in the gully below the locality, probably at roughly the same level as the "Petrified Grove."

OS Flat Road locality (MOTT 3872) is a roadside ditch in a conglomeritic upper Boren Ranch sandstone, with a couple of thin sandstone beds being exposed a few meters higher. These higher thin sandstones can be roughly traced north to the escarpments along the North Fork of the Double Mountain Fork, and at about the same stratigraphic level as the upper Boren Ranch sandstone capping exposures along the creek. This locality is therefore probably slightly higher than the OS Ranch and OS Ranch East localities to the east, even though they are at a lower elevation, due to the westerly dip of the Boren Ranch beds. This locality produced the large shuvosaurid maxilla (Shuvosauridae *incertae sedis*; Fig. 4.17d) described and figured by Lehane (2005, fig. 38) as well as indeterminate metoposaur and phytosaur material.

The OS Roadside locality (MOTT 3910) is located at another roadside ditch in a conglomeritic upper Boren Ranch sandstone not far from the main OS Ranch localities. A thin sandstone in the hillside above the ditch appears to be at about the same stratigraphic level as the upper Boren Ranch sandstone capping the escarpments along the North Fork a short distance to the north, and the locality therefore lies at about the same level as the OS Flat Road locality, and a little higher than the OS Ranch and OS Ranch

East localities. The site produced indeterminate metoposaur and phytosaur material, and scraps of large metoposaurs have been found in other conglomeritic beds at close to the same level on both the north and south sides of the North Fork.

Unrelocated localities at OS Ranch

Several localities collected by Father Malcom Neyland in and around OS Ranch have not yet been re-located or placed precisely stratigraphically. However, they lie somewhere near the North Fork of the Double Mountain Fork, possibly just west of the main OS Ranch localities, and therefore should fall somewhere in the Boren Ranch beds or the lower unit of the Cooper Canyon Formation. These localities include "OS Ranch" (MOTT 3701), OS Ranch Fish (MOTT 3702), and OS Ranch Giants (MOTT 3704). "OS Ranch" has mostly produced indeterminate phytosaur and metoposaur material. However, OS Ranch Fish is the only locality in southern Garza County to yield diagnostic fish material (Fig. 4.1a), referable to the palaeoniscid *Turseodus dolorensis* (Schaffer, 1967), as well as unusually preserved phytosaur material (Parasuchia *incertae sedis*). The material from OS Ranch Giants consists of skull material from at least two gigantic phytosaurs, of which only the mandibles have yet been collected.

Boren Ranch Sandstone localities along Lake Alan Henry

Both vertebrate localities known from the Boren Ranch Sandstone along the lake, Lake Alan Henry-Cedar Hill (MOTT 3890) and Dorward Field 114 (MOTT 3912), come from near the top of the Boren Ranch Sandstone. Although precise correlation between the different levels within the Boren Ranch Sandstone with those in the Boren Ranch beds at the OS Ranch is problematic, the Boren Ranch sandstone localities may lie stratigraphically higher than all the OS Ranch area localities. This supported by the gamma-ray log for Humble Oil and Refining Company No. 1 Irene Rodgers (Fig. 2.32d), located near the Lake Alan Henry-Cedar Hill locality in the Sam Wahl Recreational Area, which allows the basal contact of the Boren Ranch sandstone to be placed about 40 meters (about 135') below the locality.

The Lake Alan Henry-Cedar Hill locality has produced a small partial skull of a basal phytosaur (Fig. 4.7b) referable to *Paleorhinus scurriensis* (Axel Hungerbühler and Michelle Stocker, personal communication), which was collected by Cory MacEwen in 2002. The Dorward 114 locality is a conglomeritic bed at the top of the Boren Ranch sandstone further south which has produced fragmentary metoposaur and phytosaur material. The conchostrachan locality mentioned briefly in Chapter 2 probably comes from somewhere in the Boren Ranch sandstone stratigraphically lower than the vertebrate localities, but has not been relocated.

The Lower Unit of the Cooper Canyon Formation

There are few vertebrate localities in the lower unit of the Cooper Canyon Formation, but they are biostratigraphically significant ones. This is not only because they produce diagnostic (and in some cases, spectacularly diverse) material, but because the lower unit is equivalent stratigraphically to the Tecovas Formation of southern Crosby County, and these localities (along with those in the Boren Ranch sandstone/beds) should therefore be roughly equivalent to well-known localities in the area around Kalgary, Cedar Hill, Negro Hill, White River Reservoir, Rotten Hill, and Sierrita de la Cruz Creek (e.g. Case, 1922; Murry, 1989; Long and Murry, 1995; Heckert, 2004). Material is rarely collected from the monotonous overbank mudstones dominating this part of the Cooper Canyon Formation, but instead from interbedded sandstones and conglomerates representing channel and lacustrine deposits (Lehman and Chatterjee, 2005).

The Boren Quarry

The Boren Quarry localities (MOTT 3869, also known as the Neyland Quarry) includes three sites collected by Father Neyland identified in the MOTT collections database as Rocker A Field (MOTT 3625), Rocker A/Kirkpatrick (MOTT 3869a), and Rocker A Oil Field (MOTT 3869b). This locality is located near the very base of the lower unit of the Cooper Canyon Formation, not far stratigraphically above the top of the Boren Ranch sandstone, which is exposed a short distance to the north along Lake Alan Henry. This site was described and mapped by Edler (1999) and Lehman and Chatterjee (2005), and the vertebrate material from the site will be discussed in detail in Bill Mueller's dissertation.

Lehman and Chatterjee (2005, pp. 337-338) interpreted the flats at the base of the section as lacustrine deposits, in which centripetally dipping sheet sandstones define small lacustrine basins. These beds have produced most of the large vertebrates from the Boren Quarry locality. The flats have also produced abundant limonized tree trunks, silicified burrows, and concretions (Edler, 1999; Lehman and Chatterjee, 2005). Most of material from higher in the section consists of microvertebrate material, and was recovered from conglomerates in overbank deposits above the lacustrine beds. Due to the regular visits of Bill Mueller over the past decade, the Boren Quarry is one of the most intensely collected Upper Triassic vertebrate sites in North America.

The extremely rich and diverse macrovertebrate and (especially) microvertebrate fauna includes includes two excellent skulls referable to *Metoposaurus bakeri* (Houle and Mueller, 2005; Fig. 4.2b-d), and cranial and postcranial dicynodont material (Fig. 4.4a-d; Edler, 1999; Lehman and Chatterjee, 2005, p. 340), some of which will assigned to a new taxon (Mueller, 2007; Mueller and Chatterjee, in prep). There is sphenodontid and drepanosaur material (Nick Fraser, personal communication), and postcranial material of the controversial small protorosaur? *Malerisaurus* (Lehman and Chatterjee, 2005, p. 342). *Trilophosaurus* is more diverse here than anywhere else in southern Garza County, with *T. buettneri, T. jacobsi, T. dornorum*, and two undescribed species being present (Mueller and Parker, 2006; Lehman and Chatterjee, 2005, p. 342).

A single osteoderm of the enigmatic archosauriform? *Doswellia* and a single tooth of the pseudosuchian pseudodinosaur *Revueltosaurus callenderi* (Fig. 4.18) have been recovered here, and are not known from anywhere else in southern Garza County.

Phytosaur material is abundant and includes an excellent skull and partial skeleton of *Paleorhinus* cf. *P. sawini* (Fig. 4.7a). Aetosaur material has been recovered here, and although it cannot be identified with certainty, at least some is aetosaurine and may belong to *Stagonolepis* or a closely related form (Fig. 4.11). A few probable rauisuchid teeth and shuvosaurid postcranial elements have also been recovered. Numerous distinctive vertebrae of the enigmatic possible ornithodirans "*Procoelosaurus brevicollis*" (Fig. 4.19e-l) and "*Pteromimus longicollis*" were described by Atanassov (2002), and Sterling Nesbitt (personal communication) has identified limb elements of the basal dinosauromorph *Dromomeron*.

The Meyer's Hill and Rocker A Oil Field localities

These two localities are not close together geographically within the study area, but material from both comes from about 25 meters (80') below the Dalby Ranch sandstone, stratigraphically between the more productive Boren Quarry and the Post Quarry localities within the lower unit of the Cooper Canyon Formation. Meyer's Hill (MOTT 3881) is one of two well-exposed hills lying just west of Highway 84 near the southern edge of Garza County, immediately below low cliffs capped by the Dalby Ranch sandstone, below the much higher cliffs capped by Cretaceous strata in this area. The bone bed itself is a conglomeritic low order sandstone bed which has produced an excellent dicynodont humerus (Mueller, 2007; Mueller and Chatterjee, in prep).

Rocker A Field (MOTT 3614) is another locality collected by Father Neyland which has not been relocated with certainly, although it probably lay a few kilometers east of the Post Quarry at the base of a mesa capped by the Dalby Ranch sandstone, a bit lower stratigraphically than the Post Quarry. The locality is important for having produced identifiable *Typothorax coccinarum* osteoderms (Fig. 4.13a), which may be the lowest in the southern Garza County, and also lateral spines probably belonging to a desmatosuchine aetosaur.

The Post Quarry

The Post Quarry (Figs. 2.7a, 2.28; MOTT 3624), also known as the Miller Quarry (e.g. Long and Murry, 1995), is one of the most remarkable Late Triassic localities in the world. It has produced one of the most diverse collections of Triassic vertebrates anywhere, and is also extraordinary in terms of the number of partial skeletons of rauisuchians and aetosaurs, including some exceptional cranial material. The main bone bed is located in overbank deposits about 8 meters below a sandstone ledge (Chatterjee, 1986a) which is part of the Cooper Creek beds, roughly equivalent to the Dalby Ranch sandstone, while the *Protoavis* material came from several meters above this (Chatterjee, 1986a, 1991; unpublished field notes). The rauisuchian and aetosaur skeletons were disarticulated but associated, and microvertebrates mostly consist of isolated elements scattered among larger skeletons (Chatterjee, 1985; Small, 1989a; Lehman and Chatterjee, 2005).

Temnospondyls are represented by the small metoposaur *Apachesaurus* (Fig. 4.2e; called "*Dictyocephalus*" by Davidow-Henry, 1989) and the enigmatic small temnospondyl *Rileymillerus cosgriffi* (Bolt and Chatterjee, 2000; Fig. 4.3). Both been suggested as being more terrestrial in habit than large metoposaurs (Hunt, 1994; Bolt and Chatterjee, 2000), consistent with the overall terrestrial aspect of the overbank deposits and fauna. Therapsids are represented by a dicynodont femur (Mueller, 2007) and teeth and jaws probably belonging to a trithelodontid ("*Pachygenelus milleri*" of Chatterjee, 1983; Fig. 4.4g-h). Sphenodontid material, including a premaxilla possibly referable to *Clevosaurus* is being described by Nick Fraser (personal communication). At least one cervical vertebra probably referable to *Malerisaurus* has been recognized. Good drepanosaur postcrania is also known from the quarry (Bill Mueller and Sankar Chatterjee, in preparation), and *Trilophosaurus dornorum* also occurs here (Mueller and Parker, 2006).

The quarry contains the only verified occurrence of *Leptosuchus* in southern Garza County (Fig. 4.8; Lehman and Chatterjee, 2005, p. 344). Aetosaur material is extremely common, especially for the very large taxon *Desmatosuchus smalli* (Fig.

4.15c-o; Small, 1985, 1989b, 2002; Parker, 2005), but also including abundant material for a new species of *Paratypothorax* (Fig. 4.14a-e; Small, 1989b; Long and Murry, 1995; Parker and Martz, in prep), and a small specimen either representing a juvenile of *Typothorax coccinarum* (Fig. 4.13a-c; Small, 1989b; Martz, 2002), or *T. antiquum*. The lectotype and paralectotype of the large rauisuchid *Postosuchus kirkpatricki* both include excellent cranial and postcranial material (Fig. 4.16; Chatterjee, 1985; Weinbaum, 2002, 2007), and the small poposauroid *Shuvosaurus inexpectus* (=*Chatterjee elegans*; Fig. 4.17b-c; Long and Murry, 1995; Nesbitt and Norell, 2005) is represented by some cranial material (Chatterjee, 1993; Rauhut, 1997; Lehane, 2006) and more extensive postcranial material (Chatterjee, 1985; Long and Murry, 1995; Jeremiah Kokes, in prep). Sphenosuchian postcranial material is also known from the quarry (Jonathan Weinbaum, personal communication).

The procoelous vertebrae of the small enigmatic possible ornithodirans "*Procoelosaurus*" and "*Pteromimus*" (Fig. 4.19a-d) are fantastically abundant in the quarry, mostly found as isolated elements, although cranial and appendicular material which was probably associated with these distinctive vertebrae is also known (Sankar Chatterjee, unpublished field notes; Atanassov, 2002). The Post Quarry also has the most diverse dinosauromorph assemblage in southern Garza County, containing basal dinosauriformes (including the possible silesaurid *Technosaurus*, Chatterjee, 1984; Nesbitt et al., 2007), basal saurischians, and basal theropods (Lehman and Chatterjee, 2005; Nesbitt and Chatterjee, in prep).

The Middle Unit of the Cooper Canyon Formation

OS Ranch Brazos and Lott Hill

OS Ranch Brazos (MOTT 3705) produced a single specimen of *Poposaurus* (Fig. 4.17a) supposedly found by Rick Caylor on top of one of the cliffs capped by the Dalby Ranch sandstone west of the OS Ranch localities, making it the lowest locality in the middle unit of the Cooper Canyon Formation. Probably slightly higher stratigraphically are the Lott Tree (MOTT 3877) and Lott Hill (MOTT 3878) localities, which are located on along the South Fork of the Double Mountain Fork, in the southwestern region of the study area. Lott Tree is an area producing petrified wood from the top of the Bauchier Ranch sandstone (Bill Mueller, personal communication). Lott Hill is capped by a locally traceable low order sandstone with abundant associated sheet sands, lying a short stratigraphic distance above the Bauchier Ranch sandstone but slightly below the Route 669 Roadcut sandstone. The locality has produced the highest known specimen of *Trilophosaurus dornorum* (Muller and Parker, 2006) from the study area, a calcaneum identical to that of the Post Quarry *Shuvosaurus* material (Jeremiah Kokes, in prep), and indeterminate phytosaur and aetosaur material.

UU Ranch

Other localities in the middle unit of the Cooper Canyon Formation are particularly difficult to order superpositionally, because most of them are placed stratigraphically relative to the Miller Ranch sandstone. This unit is, in places, a complex and somewhat discontinuous unit of several closely associated sandstone lenses which changes drastically in elevation between the northern part of the study area and its southwestern termination along Middle Creek. It is not entirely clear how this drastic change in elevation relates to stratigraphic position. However, the major high order sandstones in the area (the Dalby Ranch sandstone, Route 669 sandstone, and Macy Ranch sandstone) remain at almost constant elevation throughout thier exposure. This suggests that the degree of dip in the middle and upper units of the Cooper Canyon Formation is very slight (as discussed in Chapter 2). It is therefore hypothesized that the upward change in elevation of the Miller Ranch sandstone represents a change in stratigraphic position. Consequently, localities which lie about the same distance below the Miller Ranch sandstone in the northern and southern part of the study area may in fact lie at slightly different stratigraphic levels, and localities just *above* the Miller Ranch sandstone in the northern part of the study area may in fact lie stratigraphically *below* localities below the Miller Ranch sandstone along Middle Creek. The relative positions of these localities shown in Fig. 4.20 must therefore be taken with caution.

The UU Sand Creek (MOTT 3882) and UU Railroad Flats (MOTT 3883) localities lie a few kilometers from each other on either side of Highway 84, just southeast of Post. In this area, the Miller Ranch sandstone caps small hills and mesas (Fig. 2.30), and also appears to consist of multiple closely associated sandstone and conglomerate lenses. The UU Sand Creek locality, just north of Highway 84, lies in a low order conglomeritic sandstone just a little lower than the Miller Ranch sandstone capping the mesas along the highway. It has produced three very important specimens: the holotype of the procolophonid *Libognathus sheddi* (Fig. 4.5; Small, 1997) an aetosaur with apparent affinities to *Rioarribasuchus chamaensis* (Fig. 4.14j-k; Martz et al., 2003) and a tiny procoelous vertebra possibly referable to the putative ornithodiran "*Procoelosaurus*" (Atanassov, 2002).

The UU Railroad Flats localities are located between Highway 84 and the railroad, in flats a short distance from a northwest-facing escarpment exposing a section of complexly interbedded sandstone and mudstone. This interbedded unit is mapped as part of the Miller Ranch sandstone (Fig. 2.4a), but lies slightly lower than the sandstone unit capping roadcuts to the north along Highway 84 just southeast of Post. The fossil localities are in overbank deposits with interbedded conglomerates below the escarpment, at close to the same level as the UU Sand Creek locality. These localities have produced some tantalizing aetosaur material, including a possible juvenile specimen of *Typothorax* (Fig. 4.13c-d) and a fragment possibly belonging to the aetosaur from UU Sand Creek (cf. *Rioarribasuchus*). There are also several reptile teeth which may belong to theropods, and an un-recovered phytosaur skull (Bill Mueller, personal communication).

Big Red Mud localities

Big Red Mud, the name given to most of the area along the southwestern edge of the Caprock Finger, exposes the top of the lower unit of the Cooper Canyon Formation, and the entire thickness of the middle and upper units up to the Macy Ranch sandstone, which is partly to completely truncated in this area. Most vertebrate localities in this area (Lily Pad, MOTT 3904; Point Site, MOTT 3905; and Pump Jack 32-2, MOTT 3906) were found by Doug Cunningham and have not been precisely placed yet geographically or stratigraphically, although most probably lie in the middle unit below the Miller Ranch sandstone. The Red Mud Metoposaur locality (MOTT 3903) lies several meters below the Miller Ranch sandstone, and has produced *Typothorax* osteoderms and uncollected metoposaur material.

K.W. Flats and the Squeak Site

The K.W. Flats (MOTT 3908) and Squeak Site (MOTT 3909) localities are located to the northeast of the Caprock Finger in overbank deposits composed of complexly interbedded mudstones, intrabasinal conglomerates, and sheet sands, immediately above the Miller Ranch sandstone. The Squeak Site is located in a small, well exposed draw directly above cliffs capped by the Miller Ranch sandstone, and the K.W. Flats locality lies in a broad, well exposed drainage to the northwest. Both localities have produced indeterminate phytosaur material. Due to the sharp upward climb of the Miller Ranch sandstone southwest of the Caprock Finger, these localities may be close to the same level, or even a little lower, than the Headquarters localities.

The Headquarters localities

The Headquarters locality (MOTT 3892) and closely associated Headquarters South (MOTT 3898), Headquarters NW (MOTT 3899), Headquarters North (MOTT 3900) and Green Tooth Arroyo (MOTT 3901) localities are located immediately below the Miller Ranch sandstone in overbank mudstones complexly interbedded with low order sandstones and sheet sands. The Headquarters and Headquarters South localities both lie in the lateral sheet flood deposits of the same low order channel sandstone (Fig. 2.24). Both localities mostly produce isolated elements. The Headquarters locality lies slightly closer to the channel and yields large vertebrate elements, while the Headquarters

South locality which lies several meters further away from the channel, mostly produces microvertebrates; this is presumably due to the power of the sheet floods which transported the material decreasing away from the channel during flooding. The Headquarters and Headquarters South localities have produced the lowest known material *Pseudopalatus* (Fig. 4.9a-b) and the possibly the lowest definite material of *Typothorax coccinarum* (depending on whether the Rocker A Oil Field specimen really came from the lower unit of the Cooper Canyon Formation or not). They have also produced abundant drepanosaur material, isolated shuvosaurid elements, and an excellent semi-articulated skull and sphenosuchian skeleton being prepared by Doug Cunningham.

The Headquarters North and Headquarters NW localities, located less than a kilometer from the first two localities, have produced a proximal femur referable to *Malerisaurus*, the lateral end of an aetosaur osteoderm probably belonging to *Paratypothorax*, and a basal saurischian tibia (Sterling Nesbitt, personal communication). Green Tooth Arroyo, located in the first major drainage to the east of the one containing the other localities, occurs at roughly the same stratigraphic level and has produced fragmentary metoposaur and phytosaur material.

Upper Unit of the Cooper Canyon Formation

Localities near Post

Two localities within a few kilometers of Post lie high in the upper unit of the Cooper Canyon Formation, not far below the Macy Ranch sandstone. Problematic Hill (MOTT 3921) is located on UU Ranch immediately west of where the UU Ranch sandstone forms a prominent cliff (Fig. 2.31). Most of the hill is made of complexly interbedded overbank mudstones and low order sandstones and conglomerates, most of which are thin. There is a particularly thick, reddish sandstone which strongly resembles the Kirkpatrick Ranch sandstone and occurs at about the same stratigraphic level. The few isolated elements recovered from the site, indeterminate phytosaur elements and a partial paratypothoracisine lateral osteoderm (Fig. 4.14i), were recovered as float weathered from the Kirkpatrick Ranch sandstone(?) or slightly higher.

The Simpson Ranch locality (MOTT 3874; Fig. 2.26c) is on property belonging to R.L. and Jimella Simpson just west of Post, in a well exposed gully of reddish mudstone overbank deposits with drab-colored mottling, intensely interbedded with low order conglomeritic sandstones. The latter produce the vertebrate material. The conglomerates, located about 21 meters (70 feet) below the Macy Ranch sandstone, are mostly composed of reworked sedimentary rock clasts, although some are siliceous. Nearly all specimens are isolated elements of the procolophonid *Libognathus sheddi* (Muller and Chatterjee, 2003).

Localities within or below the Kirkpatrick Ranch sandstone near Highway 669

The Lott-Kirkpatrick Ranch locality (Fig. 2.19a; MOTT 3634 and MOTT 3635) is a hill capped by the Ogallala Sandstone and Macy Ranch sandstone located between the Patricia Site and the Highway 669. The Kirkpatrick Ranch sandstone is exposed in the hillside, and is a relatively thin reddish sandstone layer only about a meter thick. The locality was one of the first collected by Sankar Chatterjee in West Texas, and his unpublished 1980 field notes and photographs indicate that the specimens collected here came from the very base of the hill, about 10 m meters below the Kirkpatrick Ranch sandstone. This material consists of fragmentary specimens and a partial skeleton identified by Lehane (2004) as *Shuvosaurus* and Lehman and Chatterjee (2005) as *Coelophysis*, although it can probably only be referred to Theropoda *incertae sedis* (Nesbitt and Chatterjee, in prep).

The Lott Kirkpatrick locality (MOTT 3630) on the *eastern* side of Highway 669, is another locality discovered and excavated by Sankar Chatterjee in 1980. It has not yet been precisely relocated, but what information is available on its location (Sankar Chatterjee, unpublished field notes; Doug Cunningham and Bill Mueller, personal communication) indicates it probably lies less than two kilometers from MOTT 3634 and close to the same stratigraphic level, not far below the Kirkpatrick Ranch sandstone. This locality produced a partial phytosaur skull (Fig. 4.9e-f) and isolated phytosaur squamosal (Fig. 4.9c-d), both referable to *Pseudopalatus buceros* or *P. pristinus.*

The Big Hill Road locality (MOTT 3896) is located not far north of the Lott-Kirkpatrick localities. A single phytosaur skull, which has not yet been recovered, is weathering out of the Kirkpatrick Ranch sandstone, as is another unrecovered phytosaur skull from an unnamed locality immediately to the north.

Macy Ranch localities between the Macy Ranch sandstone and the Lower Macy Ranch sandstone

The Macy Ranch "*Macysuchus*" Quarry (MOTT 3631) is located on Macy Ranch about 9 meters (30') below the Macy Ranch sandstone. It has produced one of the most spectacular phytosaur specimens in the MOTT collections (Fig. 4.10d), an almost complete skull and semi-articulated skeleton of an undescribed new species of *Pseudopalatus* collected in 1996 ("*Macysuchus brevirostris*" of McQuilkin, 1998). Fragmentary indeterminate phytosaur material has recently collected from the locality and from the immediate area.

Recent exploration by Doug Cunningham and Bill Mueller in the drainage of the South Fork of the Double Mountain Fork of the Brazos River in the area around the "*Macysuchus*" locality and Cowhead Mesa, has produced several scattered localities between the Macy Ranch sandstone and Lower Macy Ranch sandstone. Most of these localities lie stratigraphically a little lower than the "*Macysuchus*" Quarry, and have mostly produced indeterminate phytosaur material. Macy Ranch Cowhead Mesa (MOTT 3923) rests almost directly on top of the Lower Macy Ranch sandstone, while Macy Ranch Gail (MOTT 3922), "Macy Ranch" (MOTT 3924) and Macy Ranch Debbie (MOTT 3925), Macy Ranch 3926 (MOTT 3926) and Macy Ranch 3927 (MOTT 3927), are all lie a little higher, about 21-24 meters (70'-80') below the Macy Ranch sandstone. The Macy Ranch Debbie Site is important for also having produced the stratigraphically highest *Paratypothorax* material in southern Garza County (Fig. 4.14f-h), incomplete paramedian and lateral osteoderms associated with an enormous femur rivaling the *Desmatosuchus* material from Post Quarry in size.

The Patricia Site and associated localities in the Macy Ranch sandstone

The Patricia Site (MOTT VPL 3870) consists of several sites in a single gully, all located in the Macy Ranch sandstone, a few kilometers east of Highway 84. At the Patricia Site, the Macy Ranch sandstone is unusually muddy, and has been interpreted as abandoned channel (oxbow lake) deposits (Lehman and Chatterjee, 2005). Thin coal seams and concretions containing plant material are locally abundant in the lower half of the Patricia Site section. These lower beds have produced vertebrate material, but most comes from higher in the section, immediately below a conglomeritic unit at the top of the Macy Ranch sandstone.

At the Patricia Site locality, and at localities in the surrounding area (most of which are also within the Macy Ranch sandstone), phytosaur material is fantastically abundant. The only recovered and identified phytosaur skulls (and therefore, the only specimens which can be assigned to an alpha taxon), are from the Patricia Site itself, and all are referable to *Pseudopalatus*, including both *P. buceros* (Fig. 4.9g-h) and a new species with affinities to *Redondasaurus* (Fig. 4.10a-c) but the site has also produced excellent postcranial material probably referable to *Pseudopalatus* (Cunningham et al., 2002; Hungerbühler et al., 2003). Other material from the Patricia Site includes an unidentified but well-preserved mass of fish bones and scales (Fig. 4.1b), an interclavicle and associated centrum from a large metoposaur, paramedian and lateral osteoderms with an associated scapulocoracoid referable to the aetosaur *Typothorax coccinarum* (Fig. 4.12b-e; Martz, 2002), isolated postcranial elements which probably also belonging to *T. coccinarum*, isolated rauisuchid elements probably belonging to *Postosuchus*, shuvosaurid limb material, and a theropod tibia (Cunningham et al., 2002; Irmis et al., 2007).

The Patty East Site (MOTT 3880) is located immediately east of Site 1 of the Patricia Site in the same oxbow lake deposits, and indeed material seems to be weathering from precisely the same layers. Material from Patty East includes the partial skull of a large metoposaur (Metoposauridae *incertae sedis*), a phytosaur illium and unrecovered phytosaur skull probably belonging to *Pseudopalatus*, and an aetosaur astragalus probably belonging to *Typothorax coccinarum*.

Several localities found and collected by Doug Cunningham within several kilometers of the Patricia Site have not been precisely located, geographically or stratigraphically, aside from that they lie somewhere high in the upper unit of the Cooper Canyon Formation. These localities include Far East (MOTT 3884), Caterpillar Canyon (MOTT 3891), Patty Far East (MOTT 3894), Big Hill Road (MOTT 3896), Lower Far East (MOTT 3902), and Sandstone Alley (MOTT 3920). Most of the material collected from these localities can only be referred to Parasuchia *incertae sedis*, although most of it probably belongs to *Pseudopalatus*. Richard's Skull (MOTT 3913) is located in the Macy Ranch sandstone and contains an unrecovered crested phytosaur skull probably belonging to *Pseudopalatus*, and Audad Bluff (MOTT 3895), which probably also lies in the Macy Ranch sandstone and has produced a large metoposaur centrum, an indeterminate phytosaur ulna, and a partial paramedian osteoderm of *Typothorax coccinarum*.

Bauchier-Crenshaw (MOTT 3885), located in southwestern Garza County not far from the Borden County line, was discovered by Wade Crenshaw of Post. The material is all fragmentary and was recovered from the Macy Ranch sandstone and from the overbank deposits below it, although the latter material all appeared to be float, and so probably came from the Macy Ranch sandstone itself. The only diagnostic material consists of fragmentary aetosaur osteoderms referable to *Typothorax coccinarum*.

CHAPTER 5

VERTEBRATE BIOSTRATIGRAPHY AND BIOCHRONOLOGY: HISTORY, CONCEPTS, AND DEFINITIONS

Lucas (1990) presented the goal of a global Upper Triassic biochronology, stressing the need to establish a robust terrestrial biochronology for the Upper Triassic before correlating it to the marine record. Lucas (1990, p. 37) warned against building a biochronology from the "top down", by starting with "long lasting chronofaunas… [which] thereby produces rather monolithic ('monobiochronologic'!?) entities not easily subdivided." Instead, he argued, biochronologies should be built from the bottom up based on "short lived taxa and assemblages". Lucas considered the broad global characterizations of Romer (1975), Anderson and Cruickshank (1978) and Ochev and Shiskin (1984), which combined Late Triassic vertebrates into a single "epoch" or "empire", to represent such unhelpful monolithic entities. My primary objective in this dissertation was to build a such a detailed and testable biostratigraphic framework for the Upper Triassic strata of a particular region (southern Garza County), which can then be compared to other detailed local biostratigraphic schemes in order to test the broad validity of the Late Triassic Land Vertebrate Faunachrons, and also recognize regional differences in faunal composition and change during the Late Triassic.

Before considering the biostratigraphy and biochronology of the Dockum Group vertebrates, it is important to review some fundamental biostratigraphic and biochronological concepts, and how they apply to Upper/Late Triassic biostratigraphy and biochronology. It is also worth comparing the historical development of Upper/Late Triassic biostratigraphy/biochronology to that of the North American Land Mammal "Ages" (NALMAs), one of the most well developed systems of terrestrial vertebrate biostratigraphy/biochronology in existence. In the century or so since mammalian biostratigraphy in the western United States began to be described in detail, and the sixty years since the NALMAs were formulated by Wood et al. (1941), they have undergone many changes as more detailed lithostratigraphic, biostratigraphic, magnetostratigraphic, and radiometric date information has become available. Moreover, how the NALMAs are actually defined, and what they are understood to represent, has also been the subject of much debate (e.g. Tedford, 1970; Walsh, 1998, 2000; Woodburne, 2004). It is worth considering the lessons learned in the development of the NALMAs when attempting similar levels of biochronological resolution for the Late Triassic.

This chapter, and most of the following, will be primarily concerned with biostratigraphic zonation and biochronology within western North America, which must be done with care and detail before discussing attempts at intercontinental correlation. The biostratigraphic and chronostratigraphic correlation of the Dockum Group to Upper Triassic marine strata correlated by invertebrate biostratigraphy to the Carnian, Norian, and Rhaetian stages, will be discussed briefly at the end of the next chapter.

Biostratigraphy and Biochronology: Terms, Concepts, and Definitions

The difference between biostratigraphic and biochronologic terms and concepts is often blurred in the literature. This is due in no small part to confusion over the varied usage of many terms, which are constantly defined and redefined in various ways, or simply applied without an explicit explanation for how the term is being used. One of the most important of these confusions is whether or not a term refers to a stratigraphic concept based on fossil datums, or a temporal concept based on biological events (discussed by Arkell, 1933; Berry, 1966; Ludvigsen et al., 1986; Walsh, 1998).

Another source of confusion is the frequent failure to appreciate that our knowledge of the ranges of fossil taxa is, and probably always will be, incomplete. Not only are a small percentage of organisms ever preserved as fossils, but most of the fossils that are preserved either remain buried, are destroyed by erosion, or for some other reason are unknown or unavailable to the biostratigrapher (e.g. Smith, 1994, pp. 107-124). Consequently, the known stratigraphic range for a fossil, and the time which has elapsed during the deposition of that stratigraphic interval, is almost certainly shorter than the total amount of time during which a taxon actually existed (e.g. Johnson, 1979;

Marshall, 1998). It is therefore important to distinguish between the true stratigraphic and temporal ranges of taxa, and the shorter apparent ranges available to us through the imperfect fossil record.

Walsh (1998, p. 151) described this as the difference between *ontology*, the world as it actually is that we could see if we had unlimited data and infallible methodologies with which to reveal it (something inherently unrecognizable to fallible human beings with limited data), and *epistemology*, the world as it appears to be through the limitations of scientific data and methodology (the imperfect worldview that is constructed by fallible scientists, which may or may not approximate the ontological reality). Differing concepts of what biostratigraphic and biochronologic terms actually represent often depend on if the terms are ontological or epistemological in nature. An important point that must be made, and will be returned to later, is that all stratigraphic and temporal units actually identified and utilized by paleontologists *must* be epistemological in nature. They can be nothing else, unless the paleontologist utilizing them is omnipotent. This apparently common-sense observation is not always reflected in the way biostratigraphic and biochronological units based on vertebrates are discussed.

The following discussion of various biozone and biochron concepts will make much reference to the 1st and 2nd editions of the International Stratigraphic Guide (hereafter Hedberg, 1976, and Salvador, 1994 respectively), and the 1983 edition of the North American Stratigraphic Code (hereafter NACSN, 1983). It will also make heavy reference to Walsh's (1998, 2000) and Woodburne's (2004) discussions of various concepts for biostratigraphic and biochronologic units, which were primarily concerned with their application to the North American Land Mammal "Ages."

Biozones vs. Biochrons

Biozones and Biochronozones

A biostratigraphic unit, or biozone is defined by NACSN (1983) as "a body of rock defined and characterized by its fossil content," and the definitions of Hedberg

(1976) and Salvador (1994) are consistent with this. Historically, the meaning of the term has been more confused. Although the term “zone” originally had a clear stratigraphic intent (discussed by Arkell, 1933), the term “biozone” was originally used to refer to a unit of time (e.g. Buckman, 1902) and has been used that way intermittently even since. Walsh (1998, 2000) therefore suggested the substitution of the term “fossizone” or “fossilzone” for “biozone.” However, in light of the explicit stratigraphic connotations of the term “biozone” by most authors (e.g. Arkell, 1933; Hedberg, 1976; Salvador, 1994; NACSN, 1983; Woodburne, 2004), it is preferred here. Following Arkell (1933) and Walsh (1998), the suffix “-zone” applied to a unit has an explicitly stratigraphic rather than temporal connotation.

A biostratigraphic unit or biozone is a material thing, a body of rock strata. A biozone can be seen, photographed, and walked on. You can break off a piece of a biozone and look at it with a hand lens. Biostratigraphic units are made out of precisely the same materials as lithostratigraphic and chronostratigraphic units (*sensu* Hedberg, 1976; Salvador, 1994; NACSN, 1983): sedimentary rocks and whatever else they contain. Indeed, a particular stratum is usually part of more than one of these units (e.g. a stratum may be part of the biostratigraphic *Parasuchus* taxon range zone, the lithostratigraphic Santa Rosa Formation of the Dockum Group, and the chronostratigraphic Triassic System). Biozones differ from lithostratigraphic and chronostratigraphic units in that they are characterized and often bounded by fossil datums, rather than lithologic or age characteristics.

How a biozone should be bounded is debatable. Salvador (1994, p. 56) implies that the lower or upper boundary of a biozone must be a “biohorizon,” or “a stratigraphic boundary, surface or interface across which there is a change in biostratigraphic character.” Usually (but not always), this is the lowest or highest known stratigraphic occurrence of one or more fossil taxon. However, Hedberg (1976) and the NACSN (1981) indicate with their figures (although less explicitly in the text) that some assemblage biozones have boundaries that are *not* based on the lower or upper limits of one or more taxon’s stratigraphic range.

Walsh (2000) also discussed the difference between what he called "eubiostratigraphic units," which are bounded by biohorizons, and "quasibiostratigraphic units," which are bounded by some other criterion, such as an unconformity or lithologic change, or may even have no formal boundaries at all. Both eubiostratigraphic and quasibiostratigraphic units, being at least recognized and characterized by their fossil content, are accepted here to be types of biozones. As biozones may be defined by some sort of empirically determinable boundary (based on a fossil datum or otherwise), they are usually explicitly epistemological units that can actually be recognized and used.

A closely related concept to the biozone is that of the biochronozone, considered by Walsh (1998) to be a unit of strata bounded by the stratigraphic equivalents of paleobiological events. In other words, the boundaries of a biochronozone are layers of strata being deposited when a taxon evolved, went extinct, or migrated in or out of a particular area. As these events do not necessarily leave any fossil marker detectable to the biostratigrapher (and in fact, are unlikely to), and are unknowable as such even if they are found, this means that biochronozones not only are ontological in nature (purely theoretical units which cannot be recognized), but are not even biozones.

Biochrons

A "biochronologic unit" or "biochron" is generally agreed to represent some elapsed passage of time relating to a fossil taxon, not a material entity (Hedberg, 1976; Salvador, 1994; Walsh, 1998; Woodburne, 2004). As such, the boundaries of a biochron are events, rather than observable markers such as fossils or lithologic boundaries, and following Arkell (1933) and Walsh (1998), the suffix "-chron" is used to designate a unit of time rather than strata. However, the understanding of what sort of events are used to bound biochrons, and therefore what exactly the unit of elapsed time represents, tends to be far more contentious and confused than for biozones.

A biochron is identified by both editions of the International Stratigraphic Guide (Hedberg, 1976; Salvador, 1994) as a unit of time corresponding to the duration of a biozone. This would make at least some biochrons epistemological in nature, direct temporal reflections of empirically recognizable biozones, and their boundaries would represent the time of *burial* of the *known* fossil datums that form the biozone boundaries. However, Walsh (1998) used the term "fossilzone-chron" to refer to the time equivalent of a biozone (what he referred to as a fossil-zone), and used the term "biochron" in a very different way. According to Walsh (1998), a biochron is an exclusively ontological concept, the temporal equivalent of a biochronozone. The boundaries of a biochron represent the emigration, evolution, immigration, or extinction of a taxon, paleobiological events that will probably leave no trace in the fossil record, and therefore cannot be recognized by paleontologists.

Ontology and Epistemology in the Recognition of Biostratigraphic and Biochronologic Datums, Events, and Units.

In order to illustrate the importance of distinguishing ontology and epistemology in biostratigraphy and biochronology, we will consider the history of a hypothetical taxon both in a particular area (Fig. 5.1), and across its total range. We will consider historical events relating to this taxon and how they are recorded in the rock record, both from the perspective of an omnipotent observer and from that of a fallible biostratigrapher who has only the rock record to reconstruct the past. As has long been noted by biostratigraphers (e.g. Arkell, 1933), extinct taxa did not necessarily appear or disappear everywhere across their geographic range at the simultaneously; e.g. their first and last appearances in different areas are likely to be diachronous. Consequently, terms are needed not only to distinguish ontological and epistemological concepts, but first and last appearances (both real and perceived) on the local and regional level. With a few exceptions, these terms are largely adopted from Walsh (1998, 2000), although (as discussed in a footnote below) a variety of terms have been applied to the same datums, events, and units. For the purpose of this example, we will also assume that sedimentary deposition is perfectly uniform, without unconformities, so that stratigraphic thickness is a uniform measure of time.

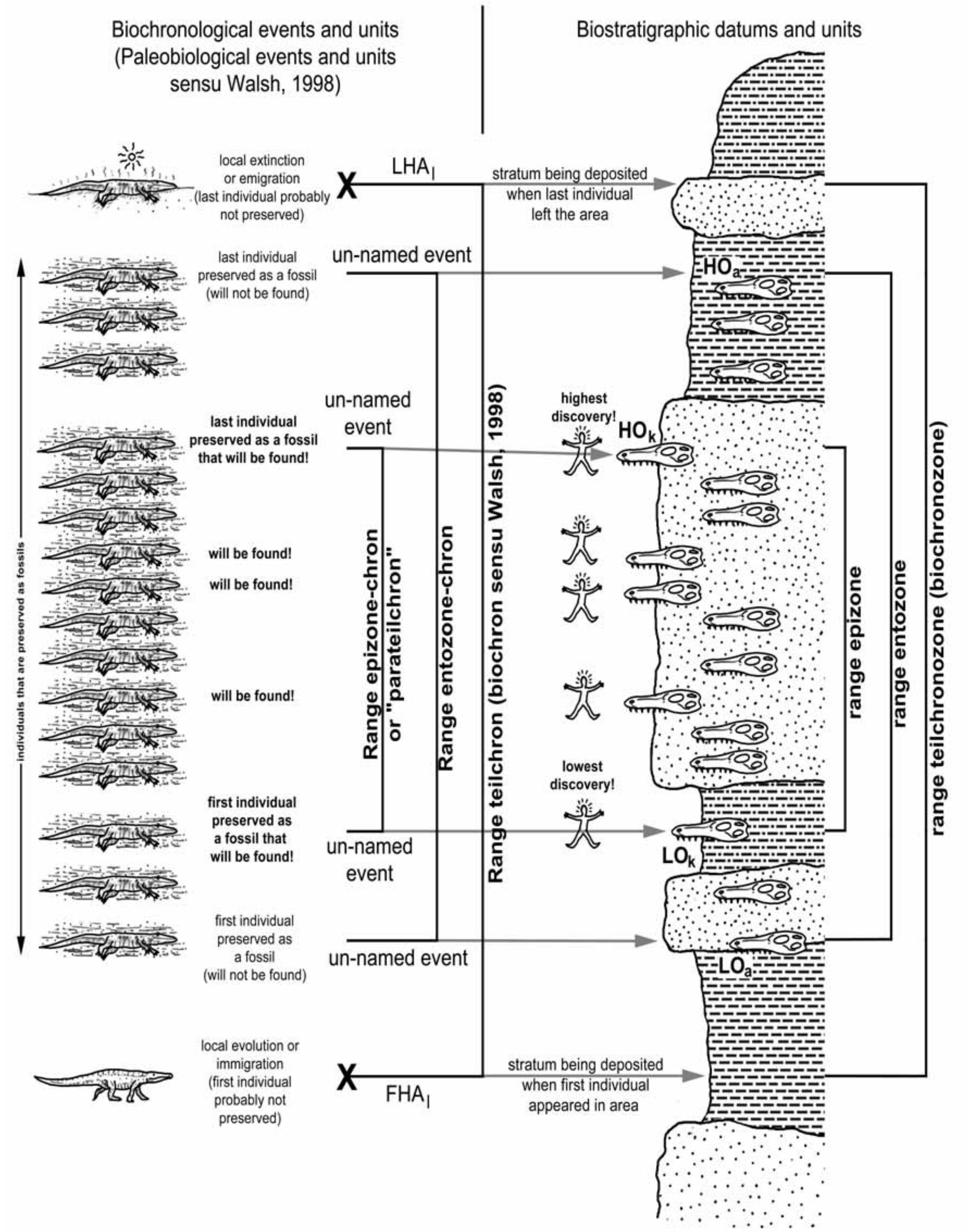

Fig. 5.1. Hypothethical example illustrating theoretical and practical biochronologic and biostratigraphic events, datums, and units.

When a taxon enters a particular area for the first time, either because it evolves there or immigrates from somewhere else, this moment in time (paleobiological event) is the *first local historical appearance* (FHA_l) for that taxon. If the taxon appears in this particular area before anywhere else (presumably having evolved there), this particular FHA_l is also the *oldest first historical appearance* (FHA_o) of that taxon. If this is the last area across its geographic range that the taxon ever immigrated to, the immigration event is instead the *time of complete dispersal* (FHA_{cd}). Woodburne and Fisher (1991) used the term "dispersal lag" to describe the time between the FHA_o and $FHA_{cd,}$ the time it takes a taxon to disperse completely across its geographic range after it evolves.

At some later point in time, the taxon will leave an area, either because the last individual in that area went extinct, or because it emigrated to somewhere else. This paleobiological event was described by Walsh (1998) as the *last local historical appearance* (LHA_l). If this is the *first* area in which the taxon went extinct or emigrated away from it is also the *oldest last historical appearance* (LHA_o). If this is the last area the taxon ever went extinct in, it is the *time of complete extinction* (LHA_{ce}). Walsh (1998) used the term *teilchron* to describe the biochron representing the time between the FHA and LHA in a particular area (in other words, the total amount of time that a taxon actually lived in a particular area), and the term *holochron* to describe biochron representing the time between an FHA_o and LHA_{ec} (in other words, the total time that a taxon existed anywhere). The strata deposited during a teilchron is a *teilchronozone*, and the strata deposited during a holochron is a *holochronozone* (Walsh, 1998).

Unfortunately, it is unlikely that FHAs and LHAs will leave any trace in the fossil record. The first and last individuals of a taxon to evolve, go extinct, or immigrate in or out of a region will most likely not be preserved as fossils. Consequently, a fallible biostratigrapher is incapable recognizing either a teilchron (*sensu* Walsh, 1998) or holochronozone. An omnipotent observer could point to the layers of strata being deposited during these events, but to a fallible real life paleontologist, they and the units they bound are unidentifiable, and ontological in nature.

At some point after the first member of a taxon entered a particular area, perhaps immediately, or perhaps after many generations, individuals in that area will start to be preserved as fossils. The first fossil of a taxon to actually be preserved after its FHA is *the lowest actual occurrence* (LO_a), and the last fossil of a taxon to ever be preserved is the *highest actual occurrence* (HO_a). However, just as most organisms that ever live die and deteriorate without leaving any trace in the fossil record, most of the organisms that are preserved will not be known to the biostratigrapher either because they remain buried or have eroded out and been destroyed (Smith, 1994, Chapter 5; Marshall, 1998), and the stratums containing the LO_a and HO_a are, therefore, ontological datums known or recognized for what they are only to the omnipotent observer, just as with the strata corresponding to the FHA and LHA. Walsh (1998) referred to an ontological (theoretical biozones) bounded by these unrecognized fossil occurrences as an *entozone*.

The oldest (stratigraphically lowest) fossil of a taxon actually known to the fallible biostratigrapher from a particular area is the *lowest known occurrence* (LO_k) [7]. If this is the oldest known individual of a taxon known from *anywhere* across its geographic range, this occurrence is also the *oldest known record* (OKR). At some later time, an organism in this area will die and be preserved whose remains will be the stratigraphically highest (youngest) known to the biostratigrapher, the *highest known occurrence* (HO_k) of that taxon. If this is the youngest known individual of a taxon known from anywhere across its geographic range, this is also the *youngest known record* (YKR).

[7] *First appearance datum* (*FAD*), and *last appearance datum* (*LAD*) are well known terms that have been used in a number of different ways. Many authors used them to describe what the lowest *known* fossil occurrence of a taxon in a particular stratigraphic section (e.g. Berggren and Van Couvering, 1978, pp. 44-47; Salvador, 1994, p. 56; Schoch, 1989, p. 201), while other authors used them to describe biochronologic events. Lindsey and Tedford (1990) used the term "FAD" to describe the oldest known record in a particular geographic area, which departs considerably from other uses of the term. For the lowest and highest known stratigraphic datums, Walsh (1998) preferred the terms *lowest known stratigraphic datum* (LSD_k) and *highest known stratigraphic datum* (HSD_k) following Opdyke et al. (1977) and Lindsay and Tedford (1990), and later (Walsh, 2000) emended these terms to *lowest known occurrence* (LO_k) and *highest known occurrence* (HO_k) following Bergren and Kent (1995) for purely semantic reasons. Pickford and Morales (1994) used the terms *Earliest Known Record (EKR)* and *Latest Known Record (LKR)* to refer repectively to the oldest and youngest known record of a taxon in a geographic region. Walsh (1998) preferred the terms *Oldest Known Record (OKR)* and *Youngest Known Record (YKR)* for these datums.

As known fossil occurrences are biohorizons, sections of strata bounded by them are true eubiostratigraphic biozones (fossil-zones sensu Walsh, 1998). Walsh (1998) proposed the term *epigone* for a biozone bounded by known occurrences. Arkell (1933) used the term *teilzone* for a local biozone for a particular area, and I use it here in that sense. Walsh (1998) suggested the term *paraholochronozone* for a stratigraphic interval bounded the OKR and/or YKR of one or more taxon. If extremely good non-biostratigraphic (e.g. magnetostratigraphic) correlation and dating techniques are available, it is hypothetically possible for even the fallible biostratigrapher to identify a paraholochronozone even in particular sections where the OKR and YKR are not present, by identifying the stratigraphic levels which are precisely the same age as those containing the OKR and YKR somewhere else in the world.

Equivalent units of time can also be recognized. Wash (1998) used the term *epizone-chron* for the time equivalent of an epizone, or the time which elapses between when the organism leaving the stratigraphically lowest fossil known to the biostratigrapher died and was buried, and when the organism leaving the stratigraphically highest fossil known to the biostratigrapher died and was buried. Walsh (1998) used the term *parateilchron* for an epizone-chron in a particular area, and the term *paraholochron* for the time equivalent of a paraholochronozone, or the total time interval for which an organism is known to exist anywhere. As these are events and units of time which can actually be identified (with sufficiently good dating techniques), they are epistemological.

To reiterate, a LO_k or HO_k is *not* the stratigraphic equivalent of an FHA_l or LHA_l. The former represent known, recognizable fossil datums. It is unlikely that the individual organisms representing these datums were actually the very first and last individuals of a taxon to enter an area, the remains of which were probably destroyed by scavenging, decomposition, or other natural processes. It is even unlikely that these highest and lowest known fossil datums even represent the first and last individuals of a taxon to be preserved as fossils (LO_a and HO_a of Walsh, 1998); those remains probably either remain buried and undiscovered or have eroded out and been destroyed. Even if, by some remarkable chance the remains of the first member of a taxon in an area was actually preserved as a fossil, and by an equally remarkable chance these remains have been discovered by a biostratigrapher (i.e. the stratigraphic equivalent of an FHA = the LO_a = the LO_k), *there is no way for the biostratigrapher to know it.* The biostratigrapher can identify the LO_k, but can never know with certainty if the LO_k is also the LO_a, much less whether the LO_a was the first individual of a taxon in an area. In a well sampled, densely fossiliferous section, the LO_k may approach the level of the LO_a, and the LO_a may approach the stratigraphic equivalent of the FHA_l, but the three stratigraphic levels will probably never be exactly equivalent. The LO_k and HO_k, and consequently the biozones based on them, can be empirically determined and are, therefore, epistemological in nature. The LO_a, HO_a, and the stratigraphic equivalents of the FHA_l and LHA_l, are strictly theoretical and consequently they and the units based on them (the “entozones” of Walsh, 1998, and all biochronozones) are ontological. *Biostratigraphic units that are actually identified are* always *epizones*.

Similarly, the OKR and YKR are not the stratigraphic equivalents of the FHA_o and FHA_{ce}. The OKR and YKR, the oldest and youngest known fossil datums for a taxon can be recognized (with the help of careful correlation between localities) and are therefore epistemological; consequently so are paraholochronozones. The OKR and YKR may conceivably be the stratigraphic equivalents of the FHA_o and FHA_{ce}, and consequently so might a paraholochronozone be equivalent to a holochronozone, but this unlikely and unknowable for the same reason that the LO_k and HO_k cannot be considered the stratigraphic equivalents of the FHA_l and LHA_l. A YKR and LHA_{ce} may not even occur in the same area (the first individual of a taxon to ever exist and the first individual of a taxon to be preserved as a fossil discovered by a biostratigrapher may have lived in completely different places).

The distinction between ontological and epistemological terms becomes even more striking when dealing with units of time. In spite of the critical distinction between temporal and stratigraphic units emphasized by many workers (e.g. Walsh, 1998), this distinction is somewhat artificial, and there are two vital and intimately related points that must be made: First, ontological “biochrons” (*sensu* Walsh, 1998) bounded by paleobiological events such as evolution, extinction, and immigration, have never, and *can* never, be recognized and used. In reality, no worker in vertebrate biochronology has *ever* identified a biochron in Walsh's usage of the term, because doing so would require omnipotence. Second, biochrons that are actually identified and used by paleontologists are, *and must be* based on empirically determined biostratigraphic datums and biozones (Woodburne, 1977; Emry, 1973). There is, literally, no other source of information on which to base biochronology (with the possible exception of stratocladistics). Biochrons are derived from known fossil occurrences, so teilchrons, holochrons, and even entozone-chrons are inherently unrecognizable. As acknowledged by Walsh (2000, p. 772) the boundaries of theoretical biochrons "can only be approached asymptotically with the collection of more and more data" from biostratigraphy; as the epizone grows to approximate a biochronozone, so the epizone-chron grows to approximate the "biochron" (*sensu* Walsh, 1998). However, there is no way to even be certain that they are precisely equivalent.

Just as the only unit recognizable to biostratigraphy is the epizone, the only unit of time recognizable to biochronology is the "epizone-chron" of Walsh (1998), although, if based on a sufficiently rich and well-sampled stratigraphic interval, epizone-chrons may be inferred to approximate "biochrons" sensu Walsh (1998). The biochrons identified and used by paleontologists *are therefore always epizone-chrons* (*sensu* Walsh, 1998), rather than "biochrons" (*sensu* Walsh, 1998). Consequently, I am loathe to use Walsh's (1998) definition of biochron as an ontological unit, as it is therefore unusable in practical biochronology. I instead retain the definition of "biochron" used Hedberg (1978) and Salvador (1994) as the stratigraphic equivalent of a biozone, or what Walsh (1998) referred to as an epizone-chron. If I refer to ontological units based on paleobiological events, I will use the terms teilchron and holochron, which Walsh (1998) used as categories of biochron.

This practical dependence on biostratigraphy is recognized in mammalian biochronology, even when not explicitly stated. As discussed in Woodburne (1987), both NALMAs and their subdivisions are often treated as true biostratigraphic units. The recognition of the "ages" is discussed in terms of the *stratigraphic* occurrence of fossils, even when the LO_ks and HO_ks if individual taxa aren't used in defining a NALMA boundary. Moreover, subdivisions of NALMAs are often treated as true biozones bounded by the first known occurrence of particular taxa (e.g. Woodburne, 1986; Archibald et al., 1986). Biostratigraphic and biochronologic terms will be used almost interchangeably.

To an omnipotent observer, the rock record is produced by unambiguous historical events. To the fallible real-life in biostratigrapher, inferred historical events are drawn from a flawed, incomplete, and sometimes misinterpreted rock record. Consequently, the following discussion will focus more on biostratigraphy and biostratigraphic datums than on biochronology.

Definition and Characterization of the North American Land Mammal Ages (NALMAs)

Biostratigraphic and Biochronologic Concepts in the NALMAs

Various authors (e.g. Tedford, 1970; Woodburne, 1977; Lucas, 1992) have noted that the North American Land Mammal "Ages" of Wood et al. (1941) are biochronological rather the biostratigraphic units, intended to represent intervals of time rather than stratigraphic intervals characterized by their fossil content. This attempted separation of the sequence of mammalian taxa from the stratigraphic record results from the rarity of vertebrate fossils. Vertebrates are generally very distributed very sporadically through the rock record, and concentrated into bone beds (e.g. Prothero, 1990, p. 240). Biochrons in the theoretical or ontological sense (*sensu* Walsh, 1998), often with vaguely defined limits, have therefore been deemed more useful by mammal workers then biozones. Berggren and VanCouvering (1974, p. 7) stated "mammalian biochrons (Land Mammal Ages, etc.) also originate as local zones tied to reference sections and 'type faunas', even though they are commonly liberated from such earthly bondage at birth, and in many instances are created with inferred or abstract limits not inferred in the type section itself". Vertebrate paleontologists are interested in the broad picture of vertebrate evolution and migration, and interpreting information gleaned from the rock record as reflecting unbiased paleobiological events independent of the rock record is therefore attractive. There is an apparent desire in mammalian biochronology to view the NALMAs as unbiased ontological units reflecting historical reality, even though they have been extracted from a flawed biostratigraphic record.

However, as discussed in the previous section, such extraction is impossible; any vertebrate biochron capable of being recognized *must* be an epizone-chron reflecting the imperfections of the fossil record. As discussed to a certain extent by Emry (1973) and Woodburne (1977), biochronologic units can only be inferred from biostratigraphic information, and are only of practical value to the field paleontologist converted back into biostratigraphic information. This practical dependence on biostratigraphy is recognized in mammalian biochronology, even when not explicitly stated. As discussed in Woodburne (1987), both NALMAs and their subdivisions are often treated as true biostratigraphic units. The recognition of "ages" is discussed in terms of the stratigraphic occurrence of fossils, even when the LO_ks and/or HO_ks of individual taxa aren't used in *defining* a NALMA boundary. Stratigraphic units are assigned to particular NALMAs based on known biostratigraphic occurrences, not hypothetical paleobiological events. Moreover, subdivisions of NALMAs are often treated as true biozones bounded by the first known occurrence of particular taxa (e.g. Woodburne, 1986b; Archibald et al., 1986). Recognizing the dependency of biochronology on biostratigraphy, the following discussion will treat the NALMAs as true biostratigraphic units rather than unit of time.

Quasibiostratigraphic Units in Mammalian Biostratigraphy

Both the NACSN (1983) and Salvador (1994) defined a biostratigraphic unit as a body of strata characterized by its fossil content. However, this definition does not specify how the unit is bounded. Walsh (2000) noted that a lithostratigraphic unit with lithologic boundaries (such as unconformities) characterized by its fossil content could therefore be considered a biostratigraphic unit. Walsh referred to such a quasibiostratigraphic unit as a "paleontologically distinct lithozone". This approach does not require that the biostratigraphic ranges of taxa be worked out in detail, only that it be known which broad lithostratigraphic unit they were derived from. This approach has therefore been historically convenient for mammalian paleontologists who often have to deal with low biostratigraphic resolution. However, Prothero and Emry (1996, p. 678) criticized this approach for "unacceptably mixing lithostratigraphy and biostratigraphy". One concern expressed by Prothero (1990, p. 240) is that "Too often an index fossil is equated with the formation, and no attempt is made to document the actual range of the fossil within the formation. This results in a loss of resolution of the data. The stratigraphic range of the fossil is often reported to be the same as the total thickness of the formation, which may artificially extend the range." Without plotting the precise known biostratigraphic ranges of taxa within a lithostratigraphic unit, it may be misleadingly implied that the entire unit is synonymous with the range of the defining taxon or taxa (e.g. Tedford, 1970, fig. 6).

Walsh (2000) also recognized the existence of quasibiostratigraphic units that have no concrete boundaries at all (even lithologic ones). He referred to these as "paleontologically distinct 'fuzzy' zones", and noted (Walsh, 2000, p. 767) that "…the concept of a 'fuzzy zone'…has an obvious temporal analog in the numerous mammal 'biochrons' whose boundaries are not rigorously defined by the evolution, immigration, and extinction of specified taxa, but whose contents are instead loosely characterized by a 'central core' of overall faunal aspect".

These concepts of quasibiostratigraphic units bear on those for "assemblage zones", which have been defined in a variety of ways in the literature, many of them vague. Salvador (1994, p. 62-63) defines an assemblage zone as "a stratum or body of strata characterized by a distinctive assemblage or association of three or more fossil taxa that, taken together, distinguishes it in biostratigraphic character from adjacent strata"; Hedberg's (1976, p. 50) and the NACSN's (1983, Article 51) definitions are similar, although Hedberg's does not specify a membership of three or more taxa. According to both Hedberg (1976, p. 52) and Salvador (1994, p. 63), the boundaries of an assemblage zone "are drawn at surfaces (biohorizons) marking the limits of occurrence of the assemblage characteristic of the unit". These biohorizons are most commonly LO_ks and HO_ks. However, Hedberg (1976) says that biohorizons are "*commonly* used as a biozone boundary" [italics mine], which implies that other means may be used. Additionally, both Hedberg (1976, fig. 4, p. 51) and NACSN (1983, fig. 5A) show explicitly that at least some assemblage zones may not bounded by the LO_ks and HO_ks of taxa at all (*contra* Walsh, 1998, p. 770), demonstrating that assemblage zones can be treated as quasibiostratigraphic units. Woodburne (2004, p. 6) preferred to treat assemblage zones as being imprecisely bounded, recognizing that as they are characterized by multiple taxa, it is unlikely that the LO_ks of these taxa will occur at precisely the same level.

Much of the pioneering work on mammalian biostratigraphy in the American west (e.g. Osborn, 1929) used such units (Tedford, 1970). Lithostratigraphic units were first recognized and bounded, and then characterized in terms of their fossil content, making them "paleontologically distinct lithozones" in the sense of Walsh (2000). The Wood Committee (Wood et al., 1941), in creating the first NALMAs, also sometimes employed them. For example, the Bridgerian age is "based on the Bridger formation of southwestern Wyoming…the time of deposition of Bridger A-D inclusive, with the enclosed faunas" (Wood et al., 1941, p. 10).

Quasibiostratigraphic units continue to be used. Cifelli et al. (2004) discuss pre-Campanian (Late Cretaceous) NALMAs as lithostratigraphic units characterized by their fossil content, but not given explicit taxon-based boundaries (e.g. "the Mussentuchit local fauna, collected from a restricted stratigraphic interval in the upper parts of the Cedar Mountain Formation"; Cifelli et al., 2004, p. 22). As another example, the Wasatchian through Duchesnean NALMAs have also been historically been treated as paleontologically distinct lithozones, lithostratigraphic units characterized by faunal content rather than bounded by specified LO_ks and/or HO_ks (see Krishtalka et al., 1987 for a review). Moreover, Krishtalka et al. (1987), Lucas (1992), and Robinson et al. (2004) have arguably continued to treat the Wasatchian through Duchesnean NALMAs as quasibiostratigraphic units. Although they may identify numerous first and last appearances for taxa within these biochrons, sometimes defining them based on the list of first appearances, they do not usually specify how to decide *which of the* LO_k*s are to be used to identify the base of the biozones.* This is an important consideration if the LO_ks for different taxa are at different stratigraphic levels. As such, the precise boundaries for these "ages" must be considered somewhat vaguely defined (Woodburne, 2004), and these units are paleontologically distinct 'fuzzy' zones (*sensu* Walsh, 2000).

The Definition and Characterization of Eubiostratigraphic NALMAs

Matthew (1924) may have been the first to define mammalian ranges independent of lithostratigraphy, although his concept was biochronologic rather than biostratigraphic; "Matthew did not directly state, but his usage indicates, that these 'faunal zones' are bounded by the temporal range of the horse genus in question, supplemented by the first appearance and limited occurrence of other mammalian genera within those time intervals" (Tedford, 1970). Although, Wood et al. (1941), as with most previous workers, did not use detailed biostratigraphic techniques in creating the NALMAs, which were often tied to particular lithostratigraphic units, in recent decades there has been an effort to incorporate detailed biostratigraphic information into mammalian biochronology (e.g. Repenning, 1967; Tedford, 1970; Woodburne, 1977, 1987, 2004; Lofgren et al., 2004).

Repenning (1967) made the suggestion that NALMAs should be defined based on the first occurrences of individual taxa, and this was supported by Woodburne (1977, 1987). Such boundaries are (at least hypothetically) less arbitrary then those defined based on multiple taxa, and also avoid the problem of potential gaps between biozones, as the top of each biozone is defined by the base of the next. Subdivisions of the NALMAs are often defined as biozones marked by the first occurrences in the stratigraphic record of single taxa (e.g. Woodburne, 1986; Archibald et al., 1986; Lofgren et al., 2004). Such biozones represent the "lowest occurrence interval zones" of Salvador (1994, p. 59), or the "LO-LO single-taxon interval fossilzones" of Walsh (2000, p. 760).

However, it is also possible for NALMAs defined by multiple taxa to represent eubiostratigraphic units. Although (as discussed above) assemblage zones have often been treated as quasibiostratigraphic units, others have used more explicit definitions based on the LO_ks and HO_ks of taxa. Salvador (1994, fig. 10, p. 62) and the NASC (1983, fig. 5B) show assemblage zones bounded by the LO_ks and HO_ks of *several* taxa, although which taxa varies regionally as best fits the assemblage. Walsh (2000) presented several assemblage zone concepts, all based on the LO_ks and HO_ks of multiple taxa, and these were also flexible as to which taxa formed to lower boundary of the biozone in a given region. Walsh (2000) also defined an "assemblage interval zone" as a biozone between the bases of two different eubiostratigraphic assemblage zones.

However, for either a single taxon or eubiostratigraphic multiple taxon assemblage zone definition to be applied, detailed biostratigraphic information is required. If the precise biostratigraphic ranges, and therefore the exact lowest and highest known stratigraphic positions of taxa are not known, it is meaningless to define a unit based on biostratigraphic first and last occurrences that are not recognizable. Establishing a biochronologic unit bounded by FHAs inferred from biostratigraphic information is likewise pointless. This problem was noted by Emry et al. (1986, p. 128) in discussing the Chadronian, Orellian, and Whitneyan NALMAs: "Although we advocate the development of mammalian biochronology based on biostratigraphic units…such a biochronology cannot yet be realized...much additional work is needed before detailed information on most of the taxa will be available. In any new definitions, the limits of the ages should be based…faunal breaks, and these cannot be recognized until we have detailed biostratigraphic information…" Eubiostratigraphic treatment of NALMAs is therefore often problematic unless detailed biostratigraphic data is available, and if such data is lacking, than there may be no alternative than to treat NALMAs as quasibiostratigraphic units.

What is a "Faunachron?"

The term "age" applied was intended by Wood et al. (1941) to reflect the NALMA's temporal intent, but the use of the term has been criticized. An age is a geochronologic unit, the temporal equivalent of a chronostratigraphic unit (a stage; NACSN, 1983, Article 74) rather than biostratigraphic unit (NACSN, 1983, Article 80). As discussed by Walsh (1998, pp. 169-170), formalizing biostratigraphic units as geochronologic units by establishing an immovable boundary stratotype is probably inadvisable, as it makes the unit inflexible to future fossil finds outside its defined boundaries.

Lucas (1993a) introduced the term "faunachron" as a biochronological term intended as a replacement for the misleading use of the term "age." Unfortunately, whether or not the term "faunachron" was intended as an empirically determined, epistemological "biochron" in the sense of Hedberg (1976; the temporal equivalents of a biozone), or a theoretical, ontological "biochron" in the sense of Walsh (1998; bounded by paleobiological events such as extinction and immigration), was not entirely clear.

Lucas (1992, p. 88) stated that a biochron represents "…the interval of geologic time that corresponds to the *duration of a taxon*" [italics mine], and also cited the above quote by Berggren and VanCouvering (1974, p. 74) claiming that biochrons are "created with inferred or abstract limits not inferred in the type section itself", which distinctly describes the NALMAs as theoretical units. Therefore, it seems that Lucas, at least initially, intended the term "faunachron" has having theoretical boundaries based on paleobiological events (FHAs and LHAs), and to therefore represent a teilchron or holochron (*sensu* Walsh, 1998, 2000). Walsh (2000) also stated that he considered a "faunachron" to be a type of "assemblage biochron", defined by paleobiological events. Confusingly, Lucas (1998) also referred to the Land Mammal "Age" as the time equivalent of an assemblage zone, which suggests they are the time equivalent of an empirically determined biozone.

Late Triassic Terrestrial Vertebrate Biostratigraphy and Biochronology in the Western United States

Systematic and Biostratigraphic Foundations for the Late Triassic Land Vertebrate Faunachrons

The Late Triassic Land Vertebrate Faunachrons (the Otischalkian, Adamanian, Revueltian, and Apachean) were first formally named by Lucas and Hunt (1993). However, the faunal associations forming the basis of the faunachrons, and recognition of the superpositional relationships of these faunas, had been largely worked out over proceeding decades, as was the clarification of the alpha taxonomy of various Upper Triassic vertebrates (especially phytosaurs and aetosaurs), which made characterizing these faunal successions possible. It is worth reviewing some of the more important studies which made formulation of the Late Triassic Land Vertebrae Faunachrons possible.

Except for basal forms such as *Paleorhinus* and *Promystriosuchus*, phytosaur alpha taxonomy through the middle of the 20th century tended to lump derived taxa into the genus *Machaeroprosopus* (Camp, 1930), and later *Rutiodon* (Gregory, 1962; Westphal, 1976). Camp (1930) established most of the important characters, especially in the posterior region of the skull, which are important in distinguishing phytosaur taxa, and was able to demonstrate that "*Machaeroprosopus*" *buceros* and "*Machaeroprosopus" tenuis* (now referred to *Pseudopalatus*; Ballew, 1989) were distinguished from other species by its extremely reduced and depressed supratemporal fenestrae and extremely broad and highly sculpted postorbitosquamosal bar. Unfortunately, there was also a common tendency in the years after Camp's monograph to unite taxa based on the presence or absence of a prenarial crest, with crested forms often being assigned to the German taxon *Nicrosaurus* or the *nomen dubium Phytosaurus* (see Hunt, 1994 and Hungerbühler, 1998 for reviews of the history of German phytosaur taxonomy) and the un-crested forms being placed in the eastern North American genus *Rutiodon* (e.g. Gregory, 1962; Westphal, 1976; Elder, 1978; Chatterjee, 1986a; Hunt, 1994). This tended to unite taxa which otherwise showed a degree of stratigraphic separation using Camp's criteria. This confusion was partly resolved by the assignment of the crested form *Brachysuchus* to *Angistorhinus* (Eaton, 1965; Westphal, 1976), a genus based on a non crested morphotype, and especially by Ballew's (1989) phylogenetic study which separated *Pseudopalatus* from the rest of "*Rutiodon*" (*Leptosuchus sensu* Long and Murry, 1995) and recognized that crested and un-crested forms were present in both genera. Colbert and Gregory (1957) also recognized that there was a highly derived phytosaur with completely closed supratemporal fenestrae in the uppermost strata of the Chinle Formation and Dockum Group, which Hunt and Lucas (1993a) later named *Redondasaurus*.

Aetosaur and metoposaur alpha taxonomy in western North America has lagged somewhat behind that of phytosaurs. Although Gregory (1953) recognized that species of the genus *Episcoposaurus* belonged in the valid genera *Desmatosuchus* and *Typothorax*, it wasn't until Long and Ballew's landmark 1985 study that aetosaur alpha taxonomy and the importance of osteoderm morphology to resolving it was clarified. Long and Ballew (1985) indentified two new genera (*Calyptosuchus* and *Paratypothorax*), and the recognized that "*Typothorax*" *meadei* (Sawin, 1945) belonged to a distinct genus from *Typothorax coccinarum* (also recognized by Small, 1985, 1989b), which Hunt and Lucas (1990) later named *Longosuchus*.

Metoposaur taxonomy in the western United States has tended to tended to recognize groups which vary geographically rather than stratigraphically, recognizing a morphological difference in metoposaur taxa between the Popo Agie Formation of Wyoming, and the Chinle Formation and Dockum Group of the Colorado Plateau and Llano Estacado. Branson and Mehl (1929) restricted the genera *Anaschisma*, *Koskinonodon*, and *Borborophagus* to the Popo Agie Formation of Wyoming, and recognized the genera *Buettneria* and *Kalamoiketor* from the Chinle Formation and Dockum Group, while Colbert and Imbrie (1956) and Roy-Chowdury (1967) assigned all western North American metoposaurs to the genus *Eupelor*, with the different species and subspecies also being divided geographically. Like Branson and Mehl (1929), they recognized the Chinle and Dockum metoposaurs as being more similar to each other than to the Popo Agie metoposaurs, rather than identifying *stratigraphic* variation in metoposaur taxa *within* these regions. As already discussed, Hunt's (1994) revision placed nearly all large metoposaurs in western North America into the taxon *Buettneria perfecta*, with only material from the Elkins' Place locality being assigned to *Metoposaurus bakeri* and interpreted as being biostratigraphically significant in helping diagnose the Otischalkian. Hunt (1994) named a third, small metoposaur *Apachesaurus*, which included material assigned to *Anaschisma* by Gregory (1980) and *Dictyocephalus* by Davidow-Henry (1987, 1989).

In spite of these sometimes confused and/or biostratigraphically unhelpful taxonomic histories, it has been appreciated for decades that there is stratigraphic separation between different vertebrate taxa in the Chinle Formation and Dockum Group. Huene (1926), Camp (1930), Colbert and Gregory (1957) Gregory (1962, 1972), Gregory and Westphal (1969), and Chatterjee (1978, 1986a) suggested that the primitive phytosaurs *Paleorhinus* (including to some, *Promystriosuchus*), *Angistorhinus*, and "*Brachysuchus"* occurred in strata older than those containing more derived taxa. These putatively older strata included both the Popo Agie Formation of Wyoming and the lower part of the Dockum Group in Texas: specifically the Otis Chalk quarries, Langston's (1949) *Paleorhinus scurriensis* locality in Scurry County, and localities low in the Tecovas Formation further north. It is important to note especially in the case of the Popo Agie Formation and Otis Chalk localities, that there are no known fossils of more derived phytosaurs occurring stratigraphically higher in the same area to confirm that the faunas form these localities are older. This was inferred entirely from the plesiomorphic characters of the basal phytosaurs. However, Murry (1986), Chatterjee (1986a), and Parrish (1989) recognized the co-occurrence of these taxa with more derived forms, at least in some areas. Gregory (1957, 1972) recognized that these basal phytosaurs co-occurred with *Trilophosaurus, Poposaurus, and Buettneria howardensis* (assigned to *Buettneria perfecta* by Hunt, 1994) at Otis Chalk, and that some of these taxa also occurred in the Popo Agie Formation, supporting a correlation between these regions.

Long and Ballew (1985) and Small (1985, 1989) also recognized the occurrence of an aetosaur, "*Typothorax*" *meadei* (Sawin, 1947; = *Longosuchus* of Hunt and Lucas 1990) from the Otis Chalk localities. This lower vertebrate fauna formed the basis of the Otischalkian (Lucas and Hunt, 1993).

Despite the historical problems with the alpha taxonomy of more derived phytosaurs, stratigraphic separation between species assigned to *Machaeroprosopus*, *Leptosuchus*, and/or *Rutiodon* has also long been recognized. Camp (1930) provided one of the few examples of correlated lithostratigraphic sections for the Chinle Formation near Adamana in eastern New Mexico, showing the exact relative superpositional placement of vertebrate localities, and demonstrated that "*Machaeroprosopus*" *tenuis* (referred to *Pseudopalatus* by Ballew, 1989) occurred stratigraphically higher than other species later assigned to *Rutiodon* and *Leptosuchus* by Ballew (1989) and Long and Murry (1995) respectively. Colbert and Gregory (1957, Table 3) identified different associations of phytosaurs in the lower and upper part of the Chinle Formation, with the species *Machaeroprosopus adamanensis, Phytosaurus doughtyi*, and *Leptosuchus crosbiensis* (all retained in *Rutiodon* by Ballew, 1989, and assigned to *Leptosuchus* by Long and Murry, 1995) occurring stratigraphically lower than *Machaeroprosopus tenuis* and *M. andersoni* (both referred to *Pseudopalatus* by Ballew, 1989 and in part by Long and Murry, 1995). Long and Ballew (1985) and Colbert (1985) also recognized that distinct forms of "*Rutiodon*" were present in the lower and upper parts of the Chinle Formation. Long and Ballew called the lower form "*Rutiodon* Group A" and the higher form "*Rutiodon* Group B", the latter of which was referred to as *Rutiodon tenuis* by Colbert (1985) and *Pseudopalatus* by Ballew (1989).

It has also long been noted that other vertebrates showed distinct biostratigraphic distributions in the lower and upper parts of the Chinle Formation in Petrified Forest National Park and the surrounding area of eastern Arizona. Camp (1930) identified *Stagonolepis* in the lower part of the Chinle Formation and noted that *Typothorax* (*coccinarum*) was restricted to the upper part, and Colbert (1985) identified *Desmatosuchus* in the lower part of the Chinle Formation as well. These observations were expanded upon by Long and Ballew (1985), who recognized a lower aetosaur fauna containing *Calyptosuchus* (=*Stagonolepis sensu* Heckert and Lucas, 2000), *Desmatosuchus*, and *Paratypothorax* (the latter two occurring slightly higher than *Calyptosuchus*), in association with "*Rutiodon* Group *A*" (=*Leptosuchus sensu* Long and Murry, 1995), and an upper fauna containing *Typothorax* in association with "*Rutiodon* Group B" (=*Pseudopalatus sensu* Ballew, 1989). These observations on aetosaur biostratigraphy in the park were corroborated by Colbert (1985) and Long and Padian (1986). Camp (1930), Colbert (1985) Long and Padian (1986) also recognized that metoposaurs were more common in the lower part of the Chinle Formation than the upper part, and that dicynodonts were only found in the lower part. These lower and upper faunal associations, which Long and Ballew (1985) referred to as the "C-D-RA assemblage" and the "T-RB assemblage" are equivalent to the Adamanian and Revueltian Land Vertebrate Faunachrons of Lucas and Hunt (1993).

Finally, Colbert and Gregory (1957, Table 3) and Gregory (1957, 1972) recognized an uppermost fauna in the Redonda Formation and Sloan Canyon Formation characterized by the highly derived phytosaur with fully concealed supratemporal fenestrae, which Hunt and Lucas (1993) named *Redondasaurus*. This upper phytosaur would form the basis for the Apachean land vertebrate faunachron of Lucas and Hunt (1993).

Definition and Characterization of the Late Triassic Land Vertebrate Faunachrons

Although the composition and relative superpositional order of these Late Triassic vertebrate faunas was recognized by 1990, they were not discussed as biozones or biochrons, but rather as faunal associations (e.g. Gregory, 1972; Long and Ballew, 1985). As these faunal associations were associated with particular lithostratigraphic units, they could arguably be considered to be quasibiostratigraphic units. Lucas' (1990) innovative suggestion was to formalize these faunal associations as a true system of vertebrate biochronology, following the lead of the North American Land Mammal Ages.

The Late Triassic Land Vertebrate Faunachrons as Quasibiostratigraphic Units Characterized by Multiple Taxa

The Late Triassic Land Vertebrate Faunachrons were originally numbered A, B, C, and D (Lucas, 1993b). Again, these were explicitly temporal units, representing "distinct intervals of Late Triassic time" (Lucas, 1993b, p. 31). Lucas did not provide type assemblages, although he did list those formations and members of the western United States that he included within the faunachrons (Lucas, 1993b, fig. 5). He also did not specify any defining taxa whose range limits *bounded* the faunachron, only a list of "characteristic" taxa (mostly phytosaurs and aetosaurs), which included taxa that were restricted to the faunachron, but also some that extended outside it.

Lucas and Hunt (1993) assigned formal names to the faunachrons; the Otischalkian ("A"), Adamanian ("B"), Revueltian ("C"), and Apachean ("D"), in which the suffix "-ian" appended to the end of the Late Triassic "faunachrons" was intended to emphasize their temporal intent. These faunachrons were still not formally bounded by the range limits of taxa, but were defined by a "type fossil assemblage" or "type fauna" from a particular area (Lucas and Hunt, 1993, p. 327). Lucas and Hunt (1993) again identified characteristic taxa, which included forms which were found within, but not necessarily restricted to, the faunachron; this list was slightly expanded from Lucas (1993b). However, they also listed *index* taxa, which Lucas (1992) had specifically used in the sense of Wood et al. (1941, p. 97) as being "known only from deposits of the age in question". These taxa were therefore supposed to be solely restricted to particular faunachrons.

In listing multiple taxa which characterize the assemblage, rather than providing a precise single taxon boundary definition, Lucas and his colleagues were apparently following the suggestion of Lucas (1992) that multiple taxon characterizations for NALMAs were preferable to single taxon definitions. In any case, as Lucas provided no detailed biostratigraphic range information for the taxa, defining precise boundaries based on taxon range limits would be meaningless, as they would be unrecognizable. As such, the faunachrons have boundaries which are not clearly identified, arguably making them the temporal equivalents of quasibiostratigraphic units.

What type of quasibiostratigraphic unit? Lucas (1993b, figs. 3, 5) showed the beginning and end of many of the ranges of individual taxa precisely corresponding to each other, and usually to faunachron boundaries. He also showed faunachron boundaries as precisely equating in many cases to those of lithostratigraphic units. This depiction of the boundaries of taxon ranges, faunachron boundaries, and/or the boundaries of lithostratigraphic units as all being synchronous would be repeated in future papers (e.g. Lucas and Hunt, 1993, fig. 1; Heckert and Lucas, 1996a, fig. 3; Lucas and Heckert, 1996b, fig 5; Lucas, 1997, figs. 23.5, 23.12).

It is highly unlikely that careful plotting of individual fossil occurrences for individual taxa on lithostratigraphic sections would produce such precise correspondence of the appearances and disappearances of multiple taxa with lithostratigraphic unit boundaries. It must be concluded therefore that the Late Triassic Land Vertebrate Faunachrons were originally the time equivalents of “paleontologically distinct lithozones” *sensu* Walsh (2000), with boundaries based on those of lithologic units *containing* the characteristic fossil assemblage rather than on the precisely plotted lowest and/or highest known occurrences of taxa. As discussed by Tedford (1970) and Prothero (1990), such units result when precise and detailed biostratigraphic information is lacking. In essence, Lucas is treating faunachrons as though they correspond to the duration of deposition of lithostratigraphic rather than biostratigraphic units, a practice disparaged by Tedford (1970).

In subsequent papers, Lucas and his colleagues began to apply more explicit definitions to the faunachrons similar to those applied in recent decades to the NALMAs. Lucas et al. (1997) defined the Otischalkian and Adamanian based on lists of first appearances and last appearances, and specifying (p. 35) that the purpose of this was to follow the procedure for defining and diagnosing the NALMAs used by many authors. Similar definitions have already been discussed for the Wasatchian through Duchesnean NALMAs (e.g. Krishtalka at al., 1987, Lucas, 1992; Robinson et al., 2004), and as a boundary-defining taxon is not specified, still makes the faunachrons the time equivalent of quasibiostratigraphic units, perhaps “paleontologically distinct ‘fuzzy’ zones” *sensu* Walsh (2000). Lucas et al. (1997) identified index taxa, and specified them as “fossils restricted to the time interval for which they provide an index and which are relatively common and readily identified” (p. 37). However (as in previous papers), this criterion was not met by all the index fossils they identified, as some (e.g. *Paleorhinus* and *Angistorhinus*) occurred in more than one biochron.

Eubiostratigraphic Units Using Single Taxon Phytosaur “FADs”

Lucas (1998, 1999) made yet another change to the definition of the Late Triassic faunachrons by presenting more explicit definitions based on the “FADs” of phytosaurs that had previously only been considered index taxa: *Paleorhinus* for the Otischalkian, *Rutiodon* (*Leptosuchus sensu* Long and Murry, 1995) for the Adamanian, *Pseudopalatus* for the Revueltian, and *Redondasuchus* for the Apachean. This method of defining the lower boundaries of the faunachrons is still in use (e.g. Lucas et al., 2007), and has been applied to proposed subdivisions of the faunachrons as well (e.g. Hunt, 2001; Hunt et al., 2005). Lucas had apparently revised his (1993, p. 89) opinion that multiple taxon definitions for faunachrons were preferable to single taxon definitions. The reason for this change of opinion is not made clear, although it may have been to divorce the faunachrons from lithostratigraphic units by bounding them explicitly with the appearances of particular taxa; reiterating the point made previously by Prothero (1990), Lucas (1998, p. 349) notes that it is a mistake to “imply that the LMA or LVA refers to the duration of deposition of the formation, not just to the duration of the vertebrate fossil assemblage, which is often much shorter”. As discussed previously, the term “FAD” has a confused history of usage. However, as Lucas apparently uses the term “faunachron” in the theoretical temporal sense (discussed above), it is assumed that “FAD” is intended in the sense of FHA *sensu* Walsh (1998), a theoretical paleobiological event.

However, as the stratigraphic equivalents of FHAs are ontological and inherently unrecognizable, it is best to treat Lucas’ (1998, 1999) “FADs” as the temporal equivalents of LO_ks instead. This makes the revised Land Vertebrate Faunachrons the temporal analogs of lowest occurrence interval zones (sensu Salvador, 1994), or "interval paraholochrons" (sensu Walsh, 1998, p. 158), which are the temporal analogs of "LO-LO single taxon interval fossilzones" (Walsh, 2000, p. 670). Defining such interval zones generally avoids the problem of potential gaps and overlaps posed to biozones and biochrons defined with both upper and lower boundaries, where the upper boundary of one biozone may not precisely coincide with the lower boundary of the next. However, Lucas (1998) referred to the newly defined units as "interval (assemblage) biochrons"[2]. This is an oddly ambiguous term; Lucas defined his faunachrons as interval biochrons based exclusively on the "FADs" of single taxa. However, he also refers to them also as "assemblage" biochrons, implying that multiple taxa are used in the *definition* of the biochron. However, if this is the case, there was no point in defining the biochron by the "FAD" of a single phytosaur taxon.

Papers published in recent years by Lucas and his colleagues seem to acknowledge the importance of recognizing that taxon ranges do not necessarily coincide perfectly either with each other or with faunachron boundaries (e.g. Heckert and Lucas, 2003, fig. 4; Heckert et al., 2007, fig. 4). However range charts showing the precise stratigraphic positions of vertebrate localities and taxa in stratigraphic sections are extremely rare except in a handful of papers for the Chinle Formation of eastern Arizona (Lucas and Heckert, 1996b, fig. 4; Heckert and Lucas, 1997, figs. 3-4; Heckert and Lucas, 2003, fig. 2; Parker, 2006, figs. 5-6). Without such raw biostratigraphic data, not only is a biochronological scheme nearly impossible to test, but there is no way to *apply* biozone or biochron boundaries in practice. This problem persists in the recent subdivision by Hunt (2001) of the Revueltian in the Bull Canyon Formation of New Mexico into the sub-faunachrons the ?Rainbowforestan (R0), Barrancan (R1) and Lucianoan (R2) based on vertebrate "FADs", which again presents no detailed range

[2] These are *not* analogous the the "assemblage interval fossilzones" of Walsh (2000), which are flexibly bounded by the LO_ks of *several* taxa.

charts[8]. Hunt et al. (2005) subdivided the Adamanian into the lower St. Johnsian and upper Lamyan based on vertebrate "FADs". Unfortunately, they presented a composite range chart combining data from the Chinle Formation of eastern Arizona with the Dockum Group of Santa Fe County in eastern New Mexico rather than individual range charts for each region, which makes it difficult to compare the two regions to test if they really show similar patterns of vertebrate biostratigraphy, or if the known ranges of the taxa which are shared are really equivalent. Without plotting the stratigraphic (and by inference, temporal) position of a phytosaur LO_k relative to other taxa, it can hardly be use to precisely *bound* a eubiostratigraphic unit containing those taxa.

If such detailed biostratigraphic data is available, I agree in principle with Lucas' (1998) formal definitions of the Late Triassic Land Vertebrate Faunachrons as interval biozones using the LO_ks of single taxa, as such exact boundaries serve as frames of reference for comparing faunas in different regions. However, there are several complications that must be considered in using such definitions, particularly using phytosaurs:

1. Lucas' (1998) ambiguous description of the faunachrons as "interval (assemblage) zones" needs to be clarified. If defined using LO_ks (or "FAD"s) of single taxa, they are interval biozones (or biochrons), and not assemblage biozones or biochrons *sensu* the NACSN (1984), Salvador (1994), Walsh (1998, 2000), or Woodburne (2004). These authors considered assemblage biozones to have either vaguely defined boundaries, or boundaries which may be variably based on the LO_ks of multiple taxa (Walsh, 1998, 2000). Then faunachrons as defined by Lucas (1998, 1999) using single-taxon FADs should simply be considered the biochronological equivalents of "lowest occurrence interval zones" *sensu* Salvador (1994, p. 59), or "LO-LO single-taxon interval fossilzones" *sensu* Walsh (2000, p. 760). Technically, it also means they are not truly "faunachrons" (Lucas, 1993a) if that term was intended to represent

[8] These sub-faunachrons were also noted by Heckert and Lucas (2002) to be based on the misidentification of a *Pseudopalatus* specimen as *Nicrosaurus*, and a tooth-based taxon (*Lucianosaurus*) which is not known beyond its type area

the time equivalent of an *assemblage* zone, although the term will continue to be used here out of convention.

2. As long as the single taxa used to define the boundaries occur in the proper stratigraphic sequence, no other taxon is required to remain confined to the interval zone for it to remain technically valid. However, this may allow the vertebrate content originally used to characterize the faunachrons to change considerably. This is not a problem if the goal of providing single taxon lowest occurrence definitions is to provide a consistent and non-arbitrary means of establishing faunachron boundaries. However, if an objective is to bound the faunachrons is to encompass the particular broad faunal associations identified by Lucas and Hunt (1993) and previous workers (e.g. Colbert and Gregory, 1957; Long and Ballew, 1985), than there is no way to know if phytosaurs are really best for this purpose before plotting detailed biostratigraphic range information. In other words, it is not guaranteed that the lowest occurrences of phytosaurs tend to consistently bracket those of other important taxa considered diagnostic of the faunachron when plotted on a detailed biostratigraphic range chart, or if another taxon might serve that purpose better.
3. There is some systematic ambiguity about phytosaur taxa used to define the faunachron boundaries. Axel Hungerbühler's (e.g. 2001a) questioning of the assignment of all basal phytosaur genera to *Paleorhinus* (Hunt and Lucas, 1991) and later *Parasuchus* (Lucas et al., 2007a) has already been discussed, as has Hungerbühler et al.'s (in prep) referral *Redondasaurus* to *Pseudopalatus*. If Hungerbühler's proposed alterations to the phytosaur taxonomy of Lucas and his colleagues does not necessarily invalidate these taxa as being useful for biostratigraphic/biochronologic correlation, although it does make the faunachron definitions messier as they are based on phylogenetic grades rather than easily distinguished genera based on particular character suites. Basal phytosaurs (*Parasuchus sensu* Lucas et al., 2007a) still occur stratigraphically low within the ranges of more derived phytosaur taxa (though not usually demonstrably *lower*, discussed in the next chapter) in rare cases where the superpositional relationship

between them can be demonstrated through lithostratigraphy (e.g. Colbert and Gregory, 1957; Hunt and Lucas, 1991a), highly derived specimens assigned to *Pseudopalatus* by Hungerbühler et al. (in prep) with fully concealed supratemporal fenestra (*Redondasaurus sensu* Lucas and Hunt, 1993) occur relatively high in the section compared to forms with slit-like supratemporal fenestrae. A further complication is Hungerbühler's (2001a) suggestion that the genus *Rutiodon*, the genoholotype of which comes from the Newark Supergroup of eastern North America, is cogeneric with the western North American taxon *Angistorhinus*, rather than *Leptosuchus* (*sensu* Long and Murry, 1995), as has long been advocated by other workers (Gregory, 1962; Westphal, 1976; Ballew, 1989; Lucas, 1998); this creates a potential complication to vertebrate correlation between western and eastern North America, as the ranges of *Angistorhinus* and *Leptosuchus* overlap but are not precisely stratigraphically equivalent.

4. Lucas and Heckert (1996a) and Lucas and Huber (2003, p. 147) suggested that aetosaurs are preferable Upper Triassic index fossils compared to phytosaurs and metoposaurs. Aetosaur armor is the extremely abundant in Upper Triassic deposits, with aetosaur material being locally even more common than that of phytosaurs, and identification of the armor at least to the generic level seems to be fairly unambiguous (e.g. Heckert and Lucas, 2000; Parker, 2007), providing it is sufficiently complete (Martz and Small, 2006). Phytosaurs are also extremely rare or absent in Upper Triassic deposition many parts of the world (e.g. Benton 1983a). Although aetosaur-based definitions can applied no better than phytosaur-based definitions without detailed regional biostratigraphic range charts, the LVFs all contain characteristic aetosaur taxa which might hypothetically serve as well as the phytosaur taxa. The choice of Lucas (1998, 1999) in using phytosaurs to define the Late Triassic LVFs in light of the arguments used by Lucas and Heckert (1996a) and Lucas and Huber (2003) is puzzling. However, this study focuses on provincial biochronology in western North America, where phytosaurs are geographically and stratigraphically

ubiquitous and have featured heavily in Upper Triassic biostratigraphy for decades, so the globally sporadic distribution of phytosaurs is not an issue.

CHAPTER 6

VERTEBRATE BIOSTRATIGRAPHY AND BIOCHRONOLOGY OF THE DOCKUM GROUP (UPPER TRIASSIC) OF SOUTHERN GARZA COUNTY, WEST TEXAS

Introduction

Goals of this study

A testable and useful vertebrate biochronology depends on accurate a detailed biostratigraphic range charts, which can be compared from region to region to determine if postulated patterns of vertebrate appearances and disappearances really hold true. Detailed and accurate biostratigraphic range charts depend on detailed and accurate lithostratigraphy in which the precise superpositional order of vertebrate occurrences has been determined. This in turn depends on careful field work tracing, and preferably mapping, individual lithologic units such as sandstones and mudstones, and measuring the stratigraphic distance between these lithologic units and individual vertebrate localities.

Unfortunately, there are few areas where the biostratigraphic ranges of Upper Triassic vertebrates have been established with this type of detail. An important exception is the Chinle Formation of eastern Arizona, especially within Petrified Forest National Park (PEFO). The lithostratigraphy of the Chinle Formation in this region has been subjected to several detailed studies (e.g. Stewart et al., 1972; Billingsly, 1985; Murry, 1990; Lucas et al., 1997b; Heckert and Lucas, 2002; Woody, 2006), some of which present not only correlated sections, but trace and map sandstone and mudstone-dominated units throughout the park. The Upper Triassic vertebrate fauna of the park and its biostratigraphic distribution has also been described by numerous workers (e.g. Camp, 1930; Long and Ballew, 1985; Long and Padian, 1986; Long and Murry, 1995; Heckert and Lucas, 2002). Ongoing work by Bill Parker and his colleagues (Parker and Clements, 2004; Irmis, 2005; Parker et al., 2004; Parker and Irmis, 2005; Parker, 2006) is carefully placing vertebrate localities geographically and stratigraphically, discovering new ones, re-evaluating the taxonomic status of vertebrate specimens from the park, and using this information to construct a detailed biostratigraphic framework with which to test biochronologic hypotheses.

After establishing the placement of boundaries for the Late Triassic Land Vertebrate “Faunachrons” in southern Garza County using the single taxon lowest occurrence interval zone definitions provided by Lucas (1998), I will compare the biostratigraphy of southern Garza County primarily with eastern Arizona. Petrified Forest National Park (hereafter, PEFO) will be the main region used for comparisons, but I will also discuss material from other localities in eastern Arizona, namely the *Placerias* Quarry, which lies low in strata possibly correlative to the base of the section in PEFO (e.g. Lucas, 1993; Lucas and Heckert, 1996b; Heckert and Lucas, 1997), and from the Navajo Indian Reservation north of PEFO (e.g. Kirby, 1989, 1991; Parker, 2003; Spielmann et al., 2007b). In keeping with the theme of the previous chapter, the “faunachrons” will be discussed as true biostratigraphic rather than biochronologic units.

Upper Triassic Stratigraphy of Eastern Arizona

In eastern Arizona, pedogenically modified “mottled strata” are present below the base of Chinle Formation (e.g. Stewart et al., 1972). The base of the Chinle Formation is sometimes formed by the Shinarump Formation or Shinarump Member, a siliceous sandstone probably correlative with the Santa Rosa Sandstone (e.g. Cooley, 1957; Stewart et al., 1972; Lucas, 1993; Riggs et al., 1993; Heckert and Lucas, 1996b). Where the Shinarump is locally absent, the overlying reddish sandstones, siltstones, and mudstones variously referred to as the Mesa Redondo Member or Formation (Cooley, 1958; Stewart et al., 1972; Lucas, 1993; Parker, 2006), or the Bluewater Creek Formation (Heckert and Lucas, 2002) may rest directly on the “mottled strata.” The top of this unit may be exposed in Petrified Forest National Park (Heckert and Lucas, 2002; Woody, 2006; Parker, 2006).

Above the Mesa Redondo Member is a sequence of mostly drab-colored bentonitic mudstones with some interbedded sandstones (including the prominent

"Newspaper Rock Bed"), showing extensive pedogenic development in the form of mottling and carbonate nodules. This unit was traditionally referred to as the lower Petrified Forest Formation or Member (e.g. Cooley, 1957; Stewart et al., 1972; Murry, 1990), but is now usually called the Blue Mesa Member or Blue Mesa Formation (Lucas, 1993; Heckert and Lucas, 2002; Woody, 2006). The term Sonsela Member refers to a complex but generally coarse-grained unit above the Blue Mesa Member. The base of this unit is now considered to be a pale-colored siliceous conglomeritic sandstone called the "Rainbow Forest bed(s)," followed by a sequence of complexly interbedded mudstone, sandstone, and conglomerate called the "Jim Camp Wash bed(s)," and capped by a unit of interbedded sandstone and conglomerate called the "Agate Bridge Bed" or "Flattops One Bed" (Heckert and Lucas, 2002; Woody, 2003, 2006).

Above the Sonsela Member is a section dominated by reddish mudstones with some interbedded sandstone beds (including those referred to as the Flattops beds 2-4 and the Black Forest bed) which has been referred to as the Upper Petrified Forest Member (e.g. Cooley, 1957; Stewart et al., 1972), Painted Desert Member (Lucas, 1993; Heckert and Lucas, 2002), or simply the Petrified Forest Member (Woody, 2003, 2006). The Painted Desert Member is capped by a sequence of complexly interbedded limestone, sandstone, siltstone, and mudstone called the Owl Rock Member or Formation (Tanner, 2000; Heckert and Lucas, 2002).

Preservational and Collecting Biases in the Dockum Group

Several factors influencing the biostratigraphic ranges of vertebrates from the Dockum Group of southern Garza County need to be considered, several of which become apparent by examining the biostratigraphic range chart (Fig. 6.1):

1. The number of stratigraphic levels at which individual taxa have been identified is not very high. Many taxa are only known from a single locality, and even most of the rest are only known from a very few stratigraphic levels, usually two to four. Most of the longest ranges are actually composed of specimens assignable only to

higher taxa (e.g. Indeterminate large metoposaurs; Rauisuchidae *incertae sedis*, Shuvosauridae *incertae sedis*; Theropoda *incertae sedis*). Therefore, the known ranges of most alpha taxa are based on incomplete information, and often the LO_k and HO_k may be the only specimens. In fact, if only a single specimen is known, the LO_k and HO_k are the same!

2. Most localities produce at most only a few specimens of a few taxa, while some, especially the Boren Quarry (MOTT 3869) and the Post Quarry (MOTT 3624), and to a lesser extent the Headquarters localities (mainly MOTT 3892 and MOTT 3898) and the Patricia Site localities (mainly MOTT 3870 and MOTT 3880), produce extremely abundant and diverse material. These localities are marked with an asterisk in Fig. 6.1, and stand out in the biostratigraphic range chart due to the high number of occurrences at those levels.
3. These highly diverse localities show variable preferences toward large and small vertebrates. Macrovertebrates and microvertebrates mostly occur at slightly different stratigraphic levels (a few meters apart) in the case of the Boren Quarry (Edler, 1999; Lehman and Chatterjee, 2005). The bulk of the specimens from the Headquarters localities (especially Headquarters South) are microvertebrates, whereas the Patricia Site produces primarily large vertebrates (Cunningham et al., 2002; Hungerbühler et al., 2003; Lehman and Chatterjee, 2005). At the Post Quarry microvertebrates and macrovertebrates mostly occur together in the main bone bed (Chatterjee, 1986a; Small, 1989a; Lehman and Chatterjee, 2005)

Depositional biases play an important part in the biostratigraphic patterns observed. Microvertebrates from the Boren (Neyland) Quarry and Simpson Ranch locality (Fig. 2.27c) are recovered small “low order” conglomeritic sandstone beds with clasts composed of reworked floodplain sediments and pedogenic carbonate nodules (Frehlier, 1987; Lehman and Chatterjee, 2005), while the Headquarters microvertebrates are recovered from a sheetflood deposit (Fig. 2.25), all high energy environments associated with small channels. Conversely, the best large vertebrate localities are low energy depositional systems. The Boren Quarry macrovertebrates are recovered from small lacustrine basins (Edler, 1999; Lehman and Chatterjee, 2005), while the Post Quarry was deposited in overbank deposits (Chatterjee, 1985; Small, 1989a; Lehman and Chatterjee, 2005), and the Patricia Site vertebrates were preserved in abandoned channel facies of a meandering river (Lehman and Chatterjee, 2005).

4. Collecting biases are also important to consider. The Boren Quarry and Post Quarry in the lower unit of the Cooper Canyon Formation have been collected for twenty years, while the Headquarters and Patricia Site localities are fortunate recent discoveries which have helped fill in our knowledge of vertebrates from the middle and upper unit of the Cooper Canyon Formation. Consequently, the biostratigraphic data for southern Garza County may be a little "bottom heavy," especially for microvertebrates, reflecting not only a preservational bias favoring microvertebrates in the best fossil localities in the lower part of the Cooper Canyon Formation, but more long term collection for those localities.

To summarize, the biostratigraphic record from southern Garza County is not uniform, but sporadic and heavily influenced by local depositional patterns and probably collecting biases. It is important to keep these biases in mind when drawing even tentative conclusions from the available biostratigraphic data. Apparent stratigraphic ranges of taxa are heavily influenced by available sample sizes (e.g. Marshall, 1998), and the extension of apparent stratigraphic ranges as more specimens are discovered is almost inevitable, as continued collection in the Upper Triassic of Petrified Forest National Park and eastern New Mexico (Parker and Irmis, 2005; Hunt et al., 2005) has demonstrated. It is important to treat observed stratigraphic ranges for taxa (range epizones *sensu* Walsh, 1998) with caution, especially when based on a small number of specimens, as they likely to expand with future collection. Or, to reiterate the points made in the last chapter, a range epizone is probably not a range entozone, much less a range biochronozone (Fig. 5.1). This also means that "faunachron" boundaries defined by LO_ks are likely to drop stratigraphically with future collection, an especially important consideration in the case of base of the Adamanian (discussed below).

It is also important to keep in mind that such a detailed biostratigraphy depends on the relative superpositional position of vertebrate localities being placed with accuracy, and therefore on the accuracy of lithostratigraphic correlation between localities. As discussed in Chapter 4, this is an issue particularly in the case of localities in the middle unit of the Cooper Canyon Formation. This creates some measure of uncertainty about which localities fall within the uppermost Adamanian, and which in the lower Revueltian (discussed below). In summary, although using detailed biostratigraphic data to determine the exact stratigraphic placement of vertebrate LO_ks to bound "faunachrons" gives a measure of precision and testability to vertebrate biostratigraphy, it also paradoxically places us at greater mercy of an imperfect fossil record and questions about lithostratigraphic correlation.

Phytosaurs, Aetosaurs, and the Faunachron Boundaries

In defining the Late Triassic Land Vertebrate Faunachrons, I prefer to apply the single taxon lowest occurrence interval zone definitions applied by Lucas (1998) using the lowest occurrences of *Paleorhinus*, *Leptosuchus*, *Pseudopalatus*, and *Redondasaurus* to define the bases of the Otischalkian, Adamanian, Revueltian, and Apachean respectively, rather than the emended definitions of Hunt et al. (2005). In this I follow Parker (2006), although for slightly different reasons discussed at the end of this section.

Phytosaurs

The lowest occurrence of the three critical phytosaur genera, *Paleorhinus*, *Leptosuchus*, and *Pseudopalatus*, occur in the expected stratigraphic order predicted by previous workers (e.g. Camp, 1930; Colbert and Gregory, 1957; Long and Ballew, 1985; Lucas and Hunt, 1993), and allow precise placement of the "faunachron" boundaries using Lucas' (1998) definitions. *Paleorhinus* occurs lowest in the section, and over a short stratigraphic interval. The lowest specimen, defining the base of the Otischalkian, is *Paleorhinus* sp. (TTU P-11706) from the Boren Ranch beds at the OS Ranch localities, occurring about 15-18 meters above the contact between the Boren Ranch beds and the Santa Rosa Sandstone. The highest known occurrence, the excellent skull and skeleton from the Boren Quarry referable to *Paleorhinus* cf. *P. sawini* (TTU P-9423) occurs just a few meters above the top of the Boren Ranch sandstone, at the base of the lower unit of the Cooper Canyon Formation.

Leptosuchus is known only from a skull and lower jaws (TTU P-9234) from the Post Quarry, about eight meters below the base of the Cooper Creek beds (which is stratigraphically equivalent to the Dalby Ranch sandstone), near the top of the lower unit. This specimen technically defines the base of the Adamanian, although it must be considered extremely tentative given that it is only based on a single specimen, and future occurrences are likely to occur lower in the section. The unrecovered phytosaur specimen at the OS Ranch Giants locality, which may lie in the Boren Ranch beds or at the base of the lower unit, may belong to this genus. The true base of the Adamanian may therefore lie close to the level of the Boren Quarry, or lower. This would make the Post Quarry upper Adamanian.

Pseudopalatus occurs over a fairly broad stratigraphic interval. The lowest *Pseudopalatus* specimen, defining the base of the Revueltian, is an isolated squamosal (TTU P-11880) from the Headquarters Site, a few meters below the Miller Ranch sandstone along Middle Creek. Material referable to *Pseudopalatus buceros/pristinus* occurs at the Lott-Kirkpatrick localities just below the Kirkpatrick Ranch sandstone, and at the top of the Macy Ranch sandstone at the Patricia Site. The lowest specimen of *Pseudopalatus* ("*Macysuchus*") sp. (McQuilkin, 1998; Christina Chavez, in prep) is from the Macy Ranch locality, about 9 meters below the base of the Macy Ranch sandstone, and this form is also from within the Macy Ranch sandstone at the Patricia Site.

Determining if the Apachean is present in southern Garza County is more problematic, given that "*Redondasaurus*" *sensu* Hunt and Lucas (1993b) may be a considered a derived grade of *Pseudopalatus* (Hungerbühler et al., 2003; *contra* Hunt and Lucas, 1993b; Parker and Irmis, 2006), with *P*. nov. sp. and *P*. ("*Macysuchus*") sp. showing a mosaic of features present in *Redondasaurus gregorii* and *Pseudopalatus buceros/pristinus*. However, Hunt and Lucas (1993b) specified that they considered *Redondasaurus* to be distinguished from *Pseudopalatus* by one particular character: supratemporal fenestrae which are completely concealed in dorsal view. This is also what Colbert and Gregory (1957) and Gregory (1957, 1972) used to distinguish this form from other phytosaurs, and by this criterion, *Pseudopalatus* nov. sp. is "*Redondasaurus*" *sensu* Hunt and Lucas (1993b). *Pseudopalatus* nov. sp. is known only from two specimens (TTU P-10076 and TTU P-10077), both from high in the Macy Ranch sandstone at the Patricia Site, and is tentatively used to identify the base of the Apachean. Taken at face value, the evidence suggests that *Pseudopalatus* become more diverse during the course of deposition of the upper unit Cooper Canyon Formation, with *P. buceros* and/or *P. pristinus* being known from the lower part of the unit, and a greater diversity of forms bearing characters of "*Redondasaurus*" occurring higher in the section.

The *Placerias* Quarry, low in the Mesa Redondo Member, contains the only known basal phytosaur from eastern Arizona (Hunt and Lucas, 1991a; Padian, 1994; Long and Murry, 1995; Lucas et al., 1997, 2007a; Irmis, 2005), co-occurring with *Leptosuchus* (Long and Murry, 1995). This makes the known lower boundaries of the Otischalkian and Adamanian confluent, and very near the TR-3 unconformity (Lucas et al., 1997). These strata are therefore technically Adamanian (Lucas and Heckert, 1996b; Lucas et al., 1997). *Leptosuchus* is very well known from the Blue Mesa Member (Camp, 1930; Long and Murry, 1995; Heckert and Lucas, 2002; Parker and Irmis, 2005), and the highest specimens of *Leptosuchus* come from just above the Rainbow Forest bed near the top of the Sonsela Member, creating a broad overlap between *Leptosuchus* and *Pseudopalatus* within the Sonsela Member (Hunt et al., 2005; Parker, 2006) and making the upper end of the range of *Leptosuchus* lower Revueltian. *Redondasaurus* is not known from PEFO, so base of the Apachean is unrecognized there.

These distinct range overlaps in Arizona differ from southern Garza County, where the known occurrences of *Paleorhinus*, *Leptosuchus*, and *Pseudopalatus* are stratigraphically distinct. As the number of specimens of *Leptosuchus* and *Pseudopalatus* recovered from Petrified Forest National Park is considerably higher than known from southern Garza County, it is therefore probable that these shorter, non-overlapping ranges is Garza County are an artifact of small sample size, supporting the previous suggestion that the *Leptosuchus*, and the base of the Adamanian, may eventually extend much further down section than currently recognized.

Aetosaurs

A single specimen (TTU P-11750) consisting of an almost complete anterior caudal paramedian osteoderm and associated lateral osteoderm from the Boren Quarry near the base of the Lower unit (Otischalkian or early Adamanian?), referred to Aetosaurinae *incertae sedis*, may belong to *Stagonolepis* or a closely related taxon. Without more complete material this must be considered very tentative identification, and the presence of non-typothoracisine aetosaurines (*sensu* Parker, 2007) in southern Garza County is not yet certain. If this osteoderm does belong to *Stagonolepis* (*sensu* Heckert and Lucas, 2000; = *Calyptosuchus sensu* Long and Ballew, 1985), it is consistent with the range of the taxon in eastern Arizona, which spans from the lowermost to uppermost Adamanian, being known from the *Placerias* Quarry, throughout the Blue Mesa Member, and having the known highest occurrence just above the Rainbow Forest Bed (Long and Ballew, 1985; Long and Murry, 1995; Heckert and Lucas, 2002; Parker, 2006).

Typothorax is another problematic taxon. Specimens referable with confidence to *Typothorax coccinarum*, for which exact stratigraphic information is available, are so far restricted to the middle and upper units of the Cooper Canyon Formation, with a stratigraphic range identical to *Pseudopalatus*. The lowest specimen is an incomplete dorsal paramedian osteoderm (TTU P-12108) from the Headquarters Site, found near the *Pseudopalatus* squamosal mentioned previously (TTU P-11880). The highest are several specimens (the best are TTU P-10070 and TTU P-11591) from within the Macy Ranch sandstone at the Patricia Site, and partial paramedians (TTU P-1156) from the Bauchier-Crenshaw locality at the top of the Macy Ranch sandstone, all considered here lowermost Apachean.

However, two other specimens pose biostratigraphic problems. As discussed previously, two partial paramedian osteoderms (TTU P-9209) referable to *Typothorax coccinarum* from “Rocker A Oil Field” have uncertain stratigraphic and geographic provenance. They were probably recovered from near the base of a mesa capped by the Dalby Ranch sandstone, east of the Post Quarry. This would place them in the lower unit, probably several meters lower than the Post Quarry, unless they were recovered as float which weathered out of the Dalby Ranch sandstone. Either way, they would at least double the stratigraphic range of *Typothorax coccinarum* from the Headquarters specimen, extending it well below the lowest known occurrence of *Pseudopalatus* into the Adamanian, and possibly even the Otischalkian.

The other problematic specimen is TTU P-9214, the excellent partial skeleton identified by Small (1985, 1989b) and Martz (2002) as a juvenile of *Typothorax coccinarum*. If this identification is correct, the lowest occurrence of the species would again be Adamanian, at the same level as the lowest known occurrence of *Leptosuchus*. However, as already discussed, this specimen may also be referable to the species *Typothorax antiquum* (Lucas et al., 2002c).

Oddly, the situation in PEFO regarding uncertainties about the stratigraphic distribution of *Typothorax coccinarum* and *T. antiquum* is similar to that in southern Garza County. Hunt (1998) identified a possible *Typothorax antiquum* specimen from the uppermost Blue Mesa Member (Adamanian), while Parker and Irmis (2005) and identified it and a slightly higher specimen as *T. coccinarum*. However, Parker (2006) expressed reservations about the identification of these specimens as *T. coccinarum,* and noted that all unequivocal *T. coccinarum* specimens are Revueltian. In both southern Garza County and PEFO therefore, there is a possible Adamanian occurrence of *T. antiquum*, and possible but uncertain Adamanian occurrences of *T. coccinarum*, with the latter being known with certainty only from the Revueltian (*sensu* Lucas, 1998).

The stratigraphic range of *Paratypothorax* is interesting. The best and lowest known specimens are from the Post Quarry (the most important specimens are DMNH 9942, TTU P-9169, and TTU P-12540). Fragmentary paratypothoracisine osteoderms, a the lateral end of a paramedian (TTU P-12546) from Headquarters NW and an incomplete lateral osteoderm (TTU P-11885) from Problematic Hill, may belong to *Paratypothorax*, and the specimen from Macy Ranch Debbie represented by partial paramedian and lateral osteoderms and a gigantic femur (TTU P-12547) from about 24 meters below the Macy Ranch sandstone, is the stratigraphically highest specimen comfortably referable to the genus. These specimens give *Paratypothorax* a range from the Adamanian into the lower part of the Revueltian. This is roughly the same in PEFO, with the lowest specimen occurring in the Rainbow Forest Bed in the uppermost Adamanian (Parker, 2006), and all other definite material occurring higher in the Sonsela Member or in the lowermost Painted Desert Member (Hunt and Lucas, 1992; Lucas et al., 2006a; Parker, 2006; *contra* Long and Ballew, 1985), making all occurrences uppermost Adamanian and lower Revueltian.

The specimen of cf. *Rioarribasuchus* (TTU P-10449) from UU Sand Creek is from high in the middle unit of the Cooper Canyon Formation. Although this is considered here to lie very high in the Adamanian, even a slight downward range extension for *Pseudopalatus*, or revised correlation between localities in the middle unit, would place it in the lower Revueltian. *Rioarribasuchus chamaensis* is known in PEFO from a single occurrence just above Flattops Sandstone #2 in the Petrified Forest Member, in the lower Revueltian (Parker, 2006). The type material for the genus from the Snyder Quarry in the Chinle Formation of North-Central New Mexico occurs with *Pseudopalatus* and *Typothorax coccinarum*, and is therefore also (lower?) Revueltian (Ziegler et al., 2003a).

The only definite occurrence of *Desmatosuchus* in southern Garza County is the type material of the species *D. smalli*, known from excellent material at the Post Quarry described by Small (1985, 2002) and Parker (2005), an Adamanian record which co-occurs with the only putative *Typothorax antiquum* and *Leptosuchus* specimens. Other species of *Desmatosuchus*, *D. haplocerus* and *D. spuriensis* (Parker will discuss the taxonomic status of these taxa), are unknown from southern Garza County. In eastern Arizona, *Desmatosuchus spuriensis* (*sensu* Parker, in prep; = *D. haplocerus* of most workers) spans almost the entire Adamanian, from the *Placerias* Quarry to the top of the Blue Mesa Member (Long and Ballew, 1985; Long and Murry, 1995; Heckert and Lucas, 2002; Parker, 2003), but *D. smalli* is known from a single occurrence just above the Flattops #2 Sandstone, somewhat low in the Revueltian (Parker, 2006). It may be therefore that *Desmatosuchus spuriensis* and *D. smalli* had partially overlapping ranges in the Adamanian, with *D. smalli* also occurring somewhat higher than yet known in southern Garza County.

Choosing definitions for the Revueltian

Hunt et al. (2005) reported a specimen of *Pseudopalatus* from surprisingly low in the Dockum Group near Lamy in Santa Fe County in eastern New Mexico, in strata that they identified as the Tres Lagunas Member of the Santa Rosa Formation. This would place the lowest occurrence of *Pseudopalatus* well below known occurrences of the distinctively Revueltian index fossil *Typothorax coccinarum* they identified in this region, but also co-occurring at Lamy with the aetosaur *Stagonolepis*, which they considered to characterize Adamanian time. On the basis of this specimen, Hunt et al. (2005) decided to change the faunachron definitions of Lucas (1998), redefining the Revueltian as the lowest occurrence of *Typothorax coccinarum* rather than *Pseudopalatus*, and also to divide the Adamanian into two sub-faunachrons, the Lamyan (higher) and St. Johnsian (lower). The base of the St. Johnsian, which is also the base of the Adamanian, was still defined by the lowest occurrence of *Leptosuchus*, but the base of the Lamyan was defined by the lowest occurrence of *Typothorax antiquum*. Parker (2006) did not apply Hunt et al.'s (2005) revised definitions, as he did not consider *Typothorax antiquum* to be distinct from *T. coccinarum*.

In southern Garza County, the lowest well-established occurrence of *Typothorax coccinarum* is at the Headquarters Site low in middle unit of the Cooper Canyon Formation. As this is also the lowest known occurrence of *Pseudopalatus*, the base of the Revueltian is placed here regardless of whether Lucas' (1998) or Hunt et al.'s (2005) definition is applied. However, the paramedians of uncertain provenance from the "Rocker A Oil Field" locality may fall lower in the section, possibly below the Post Quarry, creating potential uncertainty about a boundary based on *Typothorax coccinarum*. As the Post Quarry contains the only known specimen of *Leptosuchus* in the area, accepting the stratigraphic placement of the Rocker A specimens as being from lower in the lower unit would place the base of the Revueltian (*sensu* Hunt et al., 2005) *below* the known base of the Adamanian. Moreover, even if *Typothorax antiquum* is a valid taxon, the only known specimen in the study area is the Post Quarry specimen co-occurring with the *Leptosuchus* skull, making the bases of the Lamyan and St. Johnsian equivalent. For these reasons, it was decided to simply apply the original definitions of Lucas (1998) and ignore the St. Johnsian and Lamyan altogether, following Parker (2006). However, if *Leptosuchus* is discovered lower in the section than the St. Johnsian and Lamyan may be recognizable as distinct subdivisions of the Adamanian in southern Garza County.

Can the Otischalkian and Adamanian be distinguished in western North America?

Although Lucas and his colleagues (e.g. Lucas et al., 2007b) continue to recognize and use all four of the original Late Triassic Land Vertebrate Faunachrons presented by Lucas and Hunt (1993b), various issues have been raised as to their stratigraphic and temporal distinctiveness. The issue of lithostratigraphy of the Dockum Group in West Texas was discussed in Chapter 2. To briefly summarize, Lehman (1994) and Lehman and Chatterjee (2005) considered the "Colorado City Member" of southern Howard County (Lucas et al., 1994), which contains the Otischalkian type assemblage of Lucas and Hunt (1993b), to be lithostratigraphically correlative and equivalent in age with the type Cooper Canyon Formation in southern Garza County on the basis of lithologic similarities, while Lucas et al. (1994) insisted that the Colorado City Member must be older. Both were working under the assumption that the Cooper Canyon Formation was lithostratigraphically correlative with the Bull Canyon Formation of eastern New Mexico (Hunt and Lucas, 1989a), which contains a distinctly Revueltian fauna (e.g. Lucas and Hunt, 1993b; Hunt, 2001). However, as discussed in Chapter 2, the Bull Canyon Formation and Trujillo Sandstone are probably lithostratigraphically correlative only with the upper unit of the Cooper Canyon Formation. The "Garita Creek Formation" and Tecovas Formation, which contain faunas of Adamanian character (e.g. Lucas, 1998; Lucas et al., 2001), are correlative with the lower unit of the Cooper Canyon Formation, and probably so is most of the "Colorado City Member" of Howard County. Although this suggests that the Otis Chalk type fauna is not correlative with Revueltian faunas further north as suggested by Lehman and Chatterjee (2005), it is still probably correlative with slightly younger strata than indicated by Lucas et al. (1994).

This brings up a second issue previously raised by Rayfield et al. (2005): are the faunas of the Otischalkian and Adamanian really distinct? As has long been acknowledged, including by Lucas and Hunt (1993b), the plesiomorphic phytosaurs *Paleorhinus* and *Angistorhinus* co-occur with *Leptosuchus* at some localities, so the mere *presence* of these taxa cannot identify the Otischalkian. Other taxa are also unhelpful in determining if the faunas are truly distinct. In western North America, *Longosuchus* is still only known from the Otis Chalk quarries, so its stratigraphic distribution in other units considered to be Otischalkian or Adamanian cannot be assessed, and a similar problems exist for "*Metoposaurus*" *bakeri* and *Doswellia* (discussed below), taxa which were considered by Lucas (1998) to be Otischalkian index taxa. Moreover, Lucas et al. (2007b) recently claimed that *Stagonolepis*, long considered to an Adamanian index fossil (Lucas and Hunt, 1993b; Lucas, 1998), also occurs in the Otischalkian. Therefore, the *only* index taxon of either the Adamanian or Otischalkian which does not, according to Lucas et al. (2007b) occur in both, and which *also* occurs in western North America outside of its type area, is *Leptosuchus* ("*Rutiodon*" in their usage).

The first thing that needs to be recognized is that the Otischalkian and Adamanian are no longer defined (according to Lucas, 1998, and accepted by Parker, 2006, and here) by overall faunal content. They are defined by the lowest occurrences of two taxa: *Paleorhinus* (or *Parasuchus*), and *Leptosuchus*. Therefore, *whether or not the Adamanian and Otischalkian are distinct depends entirely on whether the lowest occurrence of* Paleorhinus *is lower than that of* Leptosuchus, *and not on the geographic or stratigraphic occurrence of* any *other taxon*.

For the sake of argument, let us take all phytosaurs retaining the pleisiomorphic characters of external nares anterior to the antorbital fenestra, and a supratemporal fenestra that is entirely level with the skull roof, and unite them following Hunt and Lucas (1991a) and Lucas et al. (2007a) into a single entity, which we will call "basal phytosaurs" or "*Paleorhinus*-grade phytosaurs." The lowest occurrence of this "taxon" forms the base of the Otischalkian. That the characters that separate basal phytosaurs from other taxa are pleisiomorphic for Parasuchia has long been recognized (e.g. Camp, 1930; Colbert and Gregory, 1957), and borne out by phylogenetic analysis (Ballew, 1989; Hungerbühler, 2002b), so phytosaurs bearing these characters probably occurred before *Leptosuchus*. If we use these plesiomorphic characters in a phytosaur to define the base of the Otischalkian, than the base of the Otischalkian *must* be older than the base of the Adamanian. Are the Otischalkian and Adamanian distinct and sequential? Technically, yes.

However, *this does not guarantee that the Otischalkian exists anywhere in western North America*. The *presence* of basal phytosaurs is not enough identify strata as Otischalkian, because they have been noted to occur in places with *Leptosuchus*, which technically makes the *highest* occurrences of basal phytosaurs Adamanian (e.g. Lucas, 1998). It may be that the first occurrences of *Leptosuchus* in western North America coincided with, or even predated, the initiation of Upper Triassic sedimentation. This would mean that (with a sufficiently complete fossil record) the lowest Upper Triassic strata in western North America are Adamanian. What we need therefore are areas where basal phytosaurs and *Leptosuchus* are both known, and found in close enough proximity, and with sufficiently rigorous local lithostratigraphic control, that their relative lowest occurrences can be worked out *solely on the basis of superposition*. Is there anywhere in western North America where the lowest occurrence of a basal phytosaur can be demonstrated to occur lower than the lowest occurrence of *Leptosuchus*?

Unfortunately, there are only a few areas where *Leptosuchus* and basal phytosaurs specimens were recovered in close geographic proximity, or more distantly but in strata with good lithostratigraphic correlation: the *Placerias* Quarry in Arizona, southern Crosby County in the vicinity of Home Creek, Palo Duro Canyon, and southern Garza County. In southern Garza County, as already discussed, the available specimens of *Paleorhinus* and *Leptosuchus* are distinctly separated by a considerable thickness of strata, with *Paleorhinus* being confined to the Boren Ranch sandstone/beds and the base of the Cooper Canyon Formation, and *Leptosuchus* occurring considerably higher. However, *Leptosuchus* is only represented by a single specimen at the Post Quarry, and with such a pitiful sample, not much can be said about how low in the section it actually occurs. The Otischalkian in southern Garza County gets a question mark.

The case of the *Placerias* Quarry has also already been discussed. As noted by previous workers (e.g. Hunt and Lucas, 1991a; Long and Murry, 1995; Lucas et al., 1997), a partial basal phytosaur skull recovered from the quarry co-occurs in the bone bed with *Leptosuchus*, and is therefore Adamanian. Moreover, the probable base of the Upper Triassic section occurs only 1-3 meters below this horizon (Lucas et al., 1997). This extremely low occurrence of *Leptosuchus* almost immediately above the TR-3 unconformity makes the existence of the Otischalkian in eastern Arizona highly dubious.

In southern Crosby County, fossiliferous exposures of the Dockum Group lie in the Tecovas Formation, below cliffs capped by the Trujillo Sandstone, and above the sandstone exposed around White River Reservoir which is various referred to the Santa Rosa Sandstone or Camp Springs Member (e.g. Lehman, 1994, fig. 3; Lucas et al., 1994, fig. 3, section 7). Case (1922) described the holotypes of *Buettneria perfecta, Desmatosuchus spuriensis*, *Promystriosuchus ehlersi*, *Leptosuchus crosbiensis*, and *L. imperfecta*, as well as abundant postcranial material, from this area. In cases where he described the locality in detail, it is clear that material was recovered from the Tecovas Formation (e.g. Long and Murry, 1995). He unfortunately did not give precise locality data for either of the *Leptosuchus* specimens. However, Long and Murry (1995) suggests that this may have been Home (or Holmes) Creek, just southwest of where White River Reservoir is today, and Gregory (1972) indicates that subsequent to Case's work in the area, only "advanced phytosaurs" (=*Leptosuchus*?) were found along Home Creek.

Case (1922, p. 49) described the type locality of the basal phytosaur *Promystriosuchus ehlersi* as being "a bed of yellowish sandy clay near the head of Holmes Creek, Crosby County." Hunt and Lucas (1991a) suggested that the specimen may have been recovered from the Camp Springs Member, which outcrops along Home Creek downstream from the Tecovas Formation exposures (e.g. Lehman, 1994, fig. 3). However, Case (1922, p. 49) noted that the "the patch of sandy clay is but a minor phase of the larger deposit in which the remains if so many remains of reptiles and amphibians occur in this locality." This seems to suggest that the specimen was recovered from the same unit as the other material, i.e. the Tecovas Formation. To say the least, the superpositional relationship of *Promystriosuchus* and *Leptosuchus* in southern Crosby County is ambiguous, but Case's comment indicate that they probably at least occurred in the same unit, and possibly in equivalent stratigraphic levels (Murry, 1986).

However, a basal phytosaur skull is known from the Santa Rosa Sandstone/Camp Springs Member in Palo Duro Canyon (Hunt and Lucas, 1991a). This is stratigraphically below the Tecovas Formation, and therefore lower than the multiple specimens of *Leptosuchus* known from Crosby County (Hunt and Lucas, 1991a; Long and Murry, 1995). However, it would take only a slight range extension for *Leptosuchus* to make the LO_ks of these taxa equivalent, and as already noted, *Leptosuchus* indeed occurs in eastern Arizona almost on the TR-3 unconformity. Will the base of the Dockum Group in the Texas Panhandle eventually turn out to be Adamanian with stratigraphically lower discoveries of *Leptosuchus*? Or, alternately, is either the TR-3 unconformity, or the first occurrence of *Leptosuchus*, diachronous between the Panhandle and eastern Arizona so that the Otischalkian is present in the Panhandle? It is not yet clear.

What about the two regions considered the exemplar of the Otischalkian: the Otis Chalk type fauna in southern Howard County, and the Popo Agie Formation of Wyoming (Camp, 1930; Colbert and Gregory, 1957; Lucas and Hunt, 1993b; Lucas, 1993, 1998)? *Leptosuchus* is not known from either area. In the case of southern Howard County, *Leptosuchus* is not known from either the Otis Chalk Quarries in the "Colorado City Member" of Lucas et al. (1994; ="Iatan Member" of Lucas and Anderson, 1993a), or from overlying strata suggested to be correlative with the Tecovas Formation by Lucas et al. (1994). Technically, the placement of the base of the Adamanian in southern Howard County is therefore unclear. As the alleged index taxa *Longosuchus* and *Doswellia* are not known to occur stratigraphically lower than *Leptosuchus* anywhere else, and the other alleged Otischalkian index taxon "*Metoposaurus" bakeri* does not occur at Otis Chalk at all, they cannot be used to establish an Otischalkian age for the Otis Chalk localities. The fact that a rich phytosaur fauna including multiple specimens of the basal phytosaur *Paleorhinus* and almost somewhat plesiomorphic form *Angistorhinus* (=*Brachysuchus*) is known from Otis Chalk, but does not include *Leptosuchus* (Case, 1929; Hunt and Lucas, 1991a; Long and Murry, 1995), has been taken as circumstantial evidence that the locality predates derived phytosaurs (e.g. Camp, 1930; Colbert and Gregory, 1957; Gregory, 1957, 1972; Hunt and Lucas, 1991a).

However, as already discussed, the extremely thick "Colorado City Member" is probably correlative with the Cooper Canyon Formation in southern Garza County as postulated previously by Lehman (1994), at least with the lower unit. The Otis Chalk quarries, which even by the most conservative estimate of Lucas and Anderson (1993a, fig. 3) occur over 40 meters above the TR-3 unconformity, are probably lithostratigraphically correlative with the lower unit, and may therefore actually fall within the stratigraphic range of *Leptosuchus*. The Otis Chalk quarries may therefore, ironically, be Adamanian (*sensu* Lucas, 1998) rather than Otischalkian, and the apparent absence of *Leptosuchus* an artifact of preservation or collection in southern Howard County.

The same problem potentially exists for the Popo Agie Formation of Wyoming, where all the taxa identified as occurring there by Lucas (1998, p. 364) either also co-occur with *Leptosuchus* (*Paleorhinus, Angistorhinus, Desmatosuchus, "Buettneria perfecta"*, *Poposaurus*, *Placerias*) or are unknown outside the Popo Agie Formation (*Heptasuchus*) (e.g. Long and Murry, 1995; Lucas, 1998). Again, as with Otis Chalk, the fact that *Leptosuchus* is not known from the Popo Agie Formation may be taken as evidence that the fauna is older, but this is somewhat circumstantial.

In summary, occurrences of *Leptosuchus* and *Paleorhinus* in western North America are either too geographically disparate to make a firm judgment about their superpositional relationships, co-occur stratigraphically low in the Upper Triassic section, or are based on sample sizes for *Leptosuchus* too small to give an informative picture of stratigraphic range. Moreover, the Otischalkian and lower Adamanian faunas of western North America originally identified by Lucas and Hunt (1993b) and Lucas (1998) have become increasingly homogenized by discoveries over the past decade, and it is not clear that any significant faunal differences really exist between them. Lucas et al.'s (2007b, p. 232) claim that "Otischalkian and Adamanian tetrapod assemblages are stratigraphically superposed and readily distinguished in the Chinle Group of the American Southwest" cannot currently be substantiated.

The biostratigraphic distribution of other vertebrates

Osteicthyes

The only fish fossil in the Dockum Group of southern Garza County identifiable to an alpha taxon is *Turseodus dolorensis* (TTU P-10361) from the un-relocated OS Fish locality, which probably lies low in the lower unit or in the Boren Ranch beds. These localities are Otischalkian, or possibly lower Adamanian?). Unfortunately, the biostratigraphic significance of *Turseodus* in western North America is unclear. Schaeffer (1967) named *Turseodus dolorensis* for a specimen from high in the Chinle

Formation in southwestern Colorado (Schaeffer, 1967; Dubiel et al., 1989), and Huber et al. (1993) identified *T. dolorensis* as being diagnostic of the Apachean, in which case TTU P-10361 represents a considerable range extension. However, Murry (1989) and Heckert (2004) reported *Turseodus*-like scales through most of the section of the Chinle Formation in eastern Arizona and the Dockum Group in West Texas, including the Tecovas Formation and at Otis Chalk. Heckert (2004) noted that other palaeoniscid fish have similar scale patterns, and considered these specimens to be palaeoniscids with possible affinities to *Turseodus*. The biostratigraphic significance of TTU P-10361 is therefore unclear.

Temnospondyls

The only large metoposaurs in southern Garza County identifiable to an alpha taxon are the two skulls (TTU P-11046, TTU P-10530) from the Otischalkian (or early Adamanian?) Boren Quarry referable to "*Metoposaurus" bakeri* (based on the lacrimal character *sensu* Hunt, 1994). Fragmentary large metoposaur material is fairly common in the Boren Ranch beds, and is known sparsely from as high as the Macy Ranch sandstone. However, as cranial material showing the position of the lacrimal relative to the orbit is unknown in southern Garza County outside the Boren Quarry, this material must be considered Metoposauridae *incertae sedis*.

Aside from the Boren Quarry occurrence, "*Metoposaurus" bakeri* is known in western North America only from the Elkins Place type locality in adjacent Kent County (Hunt, 1994; Houle and Mueller, 2004), from very low in the "Shinarump sandstone" (Case, 1931; pp. 1-4), which is probably the Santa Rosa Sandstone. Although the Boren Quarry occurrence supports Hunt's (1994; Hunt and Lucas, 1993) claim that the taxon is limited to the Otischalkian (*sensu* Lucas, 1998), the restricted geographic range of the taxon to two localities in western North America in adjacent counties in West Texas raises questions about the biostratigraphic utility of the taxon.

All other large metoposaurs in western North America assigned by Hunt (1994) to *Buettneria perfecta*, a name emended by Mueller (2007) to *Koskinondon perfectum*, were distinguished by Hunt (1994) from "*Metoposaurus" bakeri* based on the lacrimal contacting the orbit. In the western United States, cranial material sufficiently complete to assign to *Koskinonodon perfectum* based on the lacrimal character is known only from the Popo Agie Formation, Mesa Redondo Member, Blue Mesa Member, Garita Creek Formation/Tecovas Formation, and Otis Chalk localities (e.g. Case, 1922; Colbert and Imbrie, 1956; Hunt, 1994; Long and Murry, 1995; Zanno et al., 2002).

However, the remains of large metoposaurs are not restricted to the lower strata of the Chinle Formation and Dockum Group. Although, as with southern Garza County, large metoposaur material is extremely common in the lower part of the section in the Chinle Formation in eastern Arizona, especially in the Mesa Redondo Member and Blue Mesa Member (e.g. Camp, 1930; Colbert, 1985; Long and Padian, 1986; Hunt, 1994; Heckert and Lucas, 1997; Irmis, 2005), large metoposaur material is also known from the Sonsela Member, Painted Desert Member (e.g. Parker, 2006), and as high as the Owl Rock Formation/Member (Kirby, 1989), and also from the Bull Canyon Formation of New Mexico (Hunt, 2001). However, these authors do not make the state of the lacrimal character clear for these stratigraphically high specimens. As noted by Irmis (2005) here is tendency to assign all large metoposaur material from western North America to "*Buettneria*" (*Koskinonodon*), even based on postcranial material and cranial material for which the lacrimal character cannot be assessed, apparently based on the assumption that "*Metoposaurus" bakeri* is restricted to Otischalkian strata.

This makes the biostratigraphic range of *Koskinonodon perfectum* somewhat uncertain. Although Lucas and Hunt (1993b) Hunt et al. (2005) restricted "*Buettneria*" to the Otischalkian and Adamanian, Heckert and Lucas (2003, fig. 3) show it extending into the Apachean. The conservative approach of restricting the identification of material to *Koskinondon* to material where the lacrimal character can be assessed is preferred here. In the Chinle Formation of eastern Arizona, this probably restricts the highest occurrences of the taxon to the Adamanian Blue Mesa Member. In fact, for reasons already discussed, all occurrences of *Koskinonodon* which can be placed relative to the lowest occurrences of both basal phytosaurs and *Leptosuchus* are Adamanian, and it is unclear if the specimens from Otis Chalk (*Buettneria howardensis* of Sawin, 1945) and the Popo Agie Formation (*Anaschisma*, *Kalamoiketor*, and *Borborophagus sensu* Branson and Mehl, 1929) are Otischalkian or Adamanian.

The only specimen in southern Garza County referable with certainty to *Apachesaurus* is the Post Quarry specimen (TTU P-9216) described by Davidow-Henry (1989). This is an Adamanian occurrence. The taxon is considered to extend from the oldest to the youngest Upper Triassic units in western North America (Otischalkian?-Adamanian to Apachean), and be of little biostratigraphic significance (e.g. Heckert and Lucas, 2003, fig. 3). In eastern Arizona, the taxon is known from as low as the *Placerias* Quarry (Long and Murry, 1995; Lucas et al., 1997), through the Blue Mesa Member, Sonsela Member, and Painted Desert Member (Hunt and Lucas, 1993b; Parker, 2006), and as high as the Owl Rock Member (Hunt, 1993), giving it a range of at least Adamanian through Revueltian. Hunt and Lucas (1993) and Heckert and Lucas (1997) indicated that *Apachesaurus* was more abundant in the upper part of the Chinle Formation in eastern Arizona than in the lower part, but this cannot be assessed in southern Garza County, where only a single specimen is known.

The small temnospondyl *Rileymillerus cosgriffi* (Bolt and Chatterjee, 2000) from the Post Quarry (Adamanian) the only definite non-metoposaur temnospondyl in the Upper Triassic of western North America with the exception of *Latiscopus disjunctus* (Wilson, 1948) from the Otis Chalk Quarry. Small non-metoposaurs temnospondyls are therefore known in western North America only in the lower part of the Dockum Group, and possibly restricted to the Otischalkian?-Adamanian.

In summary, temnospondyls are of little value in comparing the Chinle Formation of eastern Arizona with the Dockum Group of southern Garza County aside from the broad observation that large metoposaurs are common in the lower part of the section (Otischalkian-Adamanian) and rare in the upper part (Revueltian-Apachean). No alpha taxa are yet known to be shared; “*Metoposaurus*” *bakeri* and *Rileymillerus cosgriffi* are known only from southern Garza County and Kent County, and *Koskinonodon perfectum* has not been identified in either county. *Apachesaurus* is of no biostratigraphic utility except for its greater abundance in the Revueltian, which cannot be assessed for southern Garza County as only a single specimen is known there from the Adamanian.

Dicynodonts and trithelodontids

Dicynodonts are restricted to the lower part of the Dockum Group, and range from the Boren Ranch beds and to high in the Lower unit, from the Otischalkian to the Adamanian, and are not known for some distance below the base of the Revueltian. None of these specimens are referable to *Placerias*, and the only material diagnostic to an alpha taxon is the taxon being described by Bill Mueller and Sankar Chatterjee (2007, in prep) from the Otischalkian (or early Adamanian) Boren Quarry. The Boren Quarry taxon is the first definite non-*Placerias* dicynodont in western North American represented by good cranial material, but there have been indications for some time of Upper Triassic dicynodonts in the United States that are not referable to *Placerias* (Lucas and Hunt, 1993a; Long and Murry, 1995; Green et al., 2005).

The only Upper Triassic taxon yet named from North America is *Placerias* (Lucas, 1904), which is known from excellent cranial and postcranial material, most of it collected from (obviously) the *Placerias* Quarry (Camp and Welles, 1956; Cox, 1965) in the Mesa Redondo Member. In Petrified Forest National Park, material is known from the Crocodile Hill, Blue Forest Quarry, and Blue Mesa Northwest localities (Camp and Welles, 1956; Murry and Long, 1989; Long and Murry, 1995), which are near the top of the Blue Mesa Member, in the upper Adamanian. Material has also been collected from the Blue Mesa Member along Ward's Terrace near Cameron (Camp and Welles, 1956; Lucas and Hunt, 1993a). The range of the taxon in eastern Arizona therefore spans most of the Adamanian.

The indeterminate trithelodontid material from the Post Quarry referred to "*Pachygenelus milleri*" by Chatterjee (1983) is Adamanian. Heckert (2004) reported possible trithelodontid material from low in the Tecovas Formation (the Lower Kalgary and Upper Kalgary localities), in the same interval which produced other possible cynodont material (Hunt, 2004), and the mammal *Adelobasilius cromptoni* (Lucas and Hunt, 1990). These records are also Adamanian, and probably older than the Post Quarry specimen.

Procolophonids

All diagnostic procolophonid material in the Dockum group of southern Garza County is referable to *Libognathus sheddi* (Small, 1997; Mueller and Chatterjee, 2004, in press). The holotype and stratigraphically lowest specimen from the UU Sand Creek locality (DMNS 20491) in the middle unit of the Cooper Canyon Formation is upper Adamanian (or possibly lower Revueltian), and the remaining specimens, from the Simpson Ranch several meters below the Macy Ranch sandstone, are high in the Revueltian. At Simpson Ranch, several procolophonid specimens are known, but no other microvertebrates have been collected.

Procolophonids are not common in the Upper Triassic of western North America. In eastern North America, Jacobs and Murry (1980) and Murry and Long (1989) identified procolophonid material from the *Placerias* Quarry, and Polcyn et al. (2002) identified material from the Blue Mesa Member in the Stinking Springs area of eastern Arizona. None of these putative Adamanian procolophonids have been described or illustrated in detail. Long and Murry (1995) reported the enigmatic taxon *Colognathus* (Case, 1928), which Heckert (2004) identified as a possible procolophonid, from the Crocodile Hill locality near the top of the Blue Mesa Member. Murry (1982, 1986, 1989) and Heckert (2004) also described *Colognathus* material from the Tecovas Formation of Crosby County, and Heckert (2004) and Heckert and Lucas (2006) suggested *Colognathus* was an index fossil for the Adamanian. The taxon has not been identified from southern Garza County.

Sues et al. (2000) briefly mentioned procolophonid material from the Owl Rock Formation of Arizona, and Fraser et al. (2005) described procolophonids from the Owl

Rock Formation/Member of Utah. Both papers noted the affinities of their material to *Hypsognathus*, and to Ivakhnenko's (1979) family Leptopleurinae, to which *Libognathus* also belongs (Small, 1997; Mueller and Chatterjee, 2004, in review). There is the possibility therefore that procolophonids show faunal change in western North America, with the enigmatic form *Colognathus* being confined to the Adamanian, and the leptopleurines occurring only in the Revueltian.

Sphenodontids

In southern Garza County, sphenodontids are known from the Otischalkian or early Adamanian Boren Quarry, and the Adamanian Post Quarry, with the latter material possibly belonging to *Clevosaurus* (Nick Fraser, personal communication). Murry (1987) and Kaye and Padian (1994) described sphenodontid material from the *Placerias* Quarry, with Fraser (1994) noting similarities between the *Placerias* Quarry material and *Clevosaurus.* Heckert (2004) and Nick Fraser (personal communication) have also identified sphenodontids from localities in the Tecovas Formation (Adamanian) of southern Crosby County, including some material referable to *Planocephalosaurus*. Consequently, although Heckert and Lucas (2007) suggested that sphenodontids are not very useful biostratigraphically, Heckert's (2004) observation that the *Placerias* Quarry and Tecovas Formation sphenodontid faunas are similar may have merit. In western North America sphenodontids appear to be restricted to the Adamanian (Heckert, 2004) and possibly the Otischalkian.

Basal archosauromorphs and *Doswellia*

The enigmatic putative protorosaur *Malerisaurus* (Chatterjee, 1980, 1986b), if valid, is known from abundant material at the Otischalkian or early Adamanian Boren Quarry at the base of the lower unit of the Cooper Canyon Formation, with single elements known from the Adamanian Post Quarry and lower Revueltian Headquarters locality. If *Malerisaurus* is valid and distinct from *Trilophosaurus* (*contra* Spielmann et al., 2006a), than both taxa are more abundant in the Boren Quarry than in other localities higher in the section. If the two taxa are synonymous, than Headquarters specimen represents a slight range extension for *Trilophosaurus* into the lower Revueltian (see below). The only other occurrence of *Malerisaurus* in western North America is the (Otischalkian or Adamanian) Otis Chalk type locality for *Malerisaurus langstoni* (Chatterjee, 1986b).

In southern Garza County, drepanosaur material is rare in the Adamanian. A few elements are known from the Boren Quarry and Post Quarry, but abundant material is known from the lower Revueltian Headquarters localities (Mueller and Chatterjee, in prep). The abundance of drepanosaur material at the Headquarters localities is conspicuous, as is the rarity of it in the micro vertebrate-rich Boren Quarry. The relative abundance of drepanosaurs in the lower Revueltian compared to in the Otischalkian/Adamanian in southern Garza County is therefore probably real.

No drepanosaur material has been identified in eastern Arizona, but *Dolabrosaurus aquilatus* (Berman and Reisz, 1992) is known from middle of the Upper Petrified Forest Formation (or Painted Desert Formation) of north-central New Mexico, which contains *Pseudopalatus* and *Typothorax coccinarum* and is therefore Revueltian (e.g. Zeigler et al., 2003a), and Harris and Downs (2001) reported a complete drepanosaur pectoral girdle from the Ghost Ranch *Coelophysis* (Whittaker) Quarry in the overlying Rock Point Formation of the same area, which contains *Redondasaurus* and is therefore Apachean (Hunt and Lucas, 1993a). Although these specimens confirm the presence of post-Adamanian drepanosaurs outside southern Garza County, it is hard to say if drepanosaurs in New Mexico were more abundant in the Revueltian and Apachean than in the Adamanian based on such a small sample size.

In southern Garza County, *Trilophosaurus* is extremely common in the Otischalkian-Adamanian, with a diverse fauna of three named species (*Trilophosaurus buettneri, T. jacobsi, and T. dornorum*) co-existing in the Boren Quarry (Mueller and Parker, 2006; Spielmann et al., 2007a), although only *T. dornorum* is present in the Post

Quarry and Lott Hill localities higher in the Adamanian (Mueller and Parker, 2006). As noted above, if *Malerisaurus* is referable to *Trilophosaurus* as suggested by Spielmann et al. (2007a), the genus extends at least into the lower Revueltian.

In eastern Arizona, *Trilophosaurus jacobsi* is known from the *Placerias* Quarry (Murry, 1987) in the lowermost Adamanian, and *T. buettneri* is known from the Dying Grounds higher in the Adamanian near the top of the Blue Mesa Member (Murry and Long, 1989; Murry, 1989). Spielmann et al. (2007) also referred a tooth from the Blue Mesa Member at the North Stinking Springs locality southwest of PEFO, which Polcyn et al. (2002) had previously referred to *Trilophosaurus jacobsi*, to *T. buettneri*. The type specimen of *T. dornorum* is known from the Jim Camp Wash beds of the Sonsela Member, in the lower Revueltian (Mueller and Parker, 2006). Kirby (1989, 1991) reported a *Trilophosaurus* tooth from the Owl Rock Formation along Ward's Terrace, which Heckert et al. (2006) allowed might be referable to *T. buettneri*, although they questioned whether the tooth was really from that locality. In eastern Arizona therefore, *Trilophosaurus jacobsi* is known from low in the Adamanian, consistent with southern Garza County, and *T. dornorum* ranges much higher in the section. However, *Trilophosaurus buettneri* is also known from higher in the Adamanian than *T. jacobsi* (Heckert et al., 2006), particularly if Kirby's specimen really came from the Owl Rock Member.

In southern Crosby County, *Trilophosaurus buettneri* and *T. jacobsi* are both known from the lower part of the Tecovas Formation (Heckert, 2004). South of Garza County, *Trilophosaurus buettneri* is well known from the Otis Chalk localities (Gregory, 1945), and Heckert et al. (2006) and Spielmann et al. (2007a) described abundant *Trilophosaurus* material from the Kahle Quarry locality in central Boren County. They identified this material as *T. jacobsi*, although Spielmann et al. (2007a) described some specimens from this site as having all the characters ascribed to *T. dornorum* by Mueller and Parker (2006). The material was recovered from a unit they identify as the Trujillo Formation, which I suspect based on the information they provide may be the Route 669 Sandstone. If this is the case, than their identification of the approximate stratigraphic position of the locality in the Dockum Group is probably correct, and *T. jacobsi* and *T. dornorum* may co-occur together somewhat higher in the section than seen at the Boren Quarry.

In summary, the biostratigraphy of different species of *Trilophosaurus* in either southern Garza County or eastern Arizona is hard to establish. As noted by Spielmann et al. (2007a), the taxon mostly occurs in the Adamanian, although their claim that *T. jacobsi* occurs higher than *T. buettneri* cannot be substantiated. This claim was largely based on their identification of the Jim Camp Wash beds and all southern Garza County specimens referred to *T. dornorum* by Mueller and Parker (2006) as *T. jacobsi*, a claim for which, as discussed in Chapter 4, they did not make a convincing argument, and also of their correlation of the Cooper Canyon Formation in southern Garza County with the Bull Canyon Formation following Lehman (1994) and Lucas et al. (1994). With the exception of the Jim Camp Wash beds *Trilophosaurus dornorum* specimen (Mueller and Parker, 2006) and Kirby's (1989, 1991) alleged Owl Rock Member specimen, all known *Trilophosaurus* specimens known are probably Otischalkian?/Adamanian.

The only possible occurrence of the enigmatic archosauriform *Doswellia* in southern Garza County in the single partial osteoderm from the Boren Ranch Quarry, an Otischalkian or early Adamanian occurrence. In western North America *Doswellia* is otherwise only known from Otis Chalk (Long and Murry, 1995), and therefore considered by Lucas (1998) to be an Otischalkian index fossil. Although the taxon may be restricted to the Otischalkian and/or Adamanian, its limited occurrence, as with *Longosuchus* and *"Metoposaurus" bakeri*, limits its current value as an index fossil.

Suchian archosaurs (exclusive of aetosaurs)

The biostratigraphic utility of most rauisuchians is not entirely clear, and in southern Garza County, material for which I am comfortable using alpha taxonomy is restricted to single localities. The rauisuchid *Postosuchus kirkpatricki* and the shuvosaurid *Shuvosaurus inexpectus* are both known from abundant material in the Adamanian Post Quarry, but rauisuchids and shuvosaurids are both known from scrappy material lower in the section. Possible rauisuchid teeth are known from the Boren Quarry at the bottom of the lower unit, and shuvosaurid material is known from the Boren Ranch beds (including the extremely large maxilla from the OS Flat Road locality), although the referral of any of this material to the particular genera *Postosuchus* or *Shuvosaurus* is uncertain. However, a calcaneum from Lott Hill, high in the Adamanian, is identical to *Shuvosaurus* material from the Post Quarry, and exquisitely preserved isolated elements (a rauisuchid ectopterygoid and a shuvosaurid femur) are known from the lowermost Apachean Patricia Site locality in the Macy Ranch sandstone. These elements seem to also be identical to the Post Quarry material of *Postosuchus* and *Shuvosaurus*, so these taxa may extend to the Apachean. The poposaurid *Poposaurus* is known only from the OS Ranch Brazos locality in the Dalby Ranch sandstone, which is high in the Adamanian.

In eastern Arizona, *Postosuchus kirkpatricki* is known from abundant material from the *Placerias* Quarry, but material referred to the taxon occurs throughout the Blue Mesa Member, Sonsela Member, and Painted Desert Member, (Murry and Long, 1989; Long and Murry, 1995; Weinbaum, 2002; Parker and Irmis, 2005), and Long and Murry (1995) reported a specimen from the Owl Rock Member, giving *Postosuchus* a range of Adamanian through upper Revueltian in eastern Arizona. The Apachean occurrence of the taxon is confirmed by a juvenile skeleton co-occurring with *Redondasaurus* in the Ghost Ranch *Coelophysis* Quarry in the "Siltstone Member" (Long and Murry, 1995; Weinbaum, 2002). *Postosuchus kirkpatricki* (or at least a closely related rauisuchian) is therefore known from the Adamanian through the Apachean and probably not very useful for biostratigraphy. The specimen from the Blue Mesa Member referred to *Saurosuchus* by Heckert et al. (2002) is probably an indeterminate rauisuchian (Irmis, 2005).

In eastern Arizona, Long and Murry (1995) identified mostly isolated elements of *Shuvosaurus* ("*Chatterjeea*") from the *Placerias* Quarry, and isolated and fragmentary material is also known from the Blue Mesa Member, Painted Desert Member, and Owl Rock Member (Long and Murry, 1995; Parker and Irmis, 2005), giving *Shuvosaurus* (or at least, shuvosaurids), a range of at least Adamanian through the upper Revueltian in eastern Arizona. The shuvosaurid *Effigea okeeffae* (Nesbitt and Norell, 2005; Nesbit, 2007), which is very similar to *Shuvosaurus inexpectus*, is known from the Apachean Ghost Ranch *Coelophysis* Quarry. *Shuvosaurus* or very similar shuvosaurids therefore extend from the Otischalkian?-Adamanian to the Apachean, and their biostratigraphic value is dubious.

Murry and Long (1989) reported *Poposaurus* from *Placerias* Quarry, and Long and Murry (1995), Polcyn et al. (2002), and Irmis (2005) reported a few additional specimens from the Blue Mesa Member. Long and Murry (1995) also reported a specimen from the Battleship NW locality, which lies in the lowermost Sonsela Member (Parker, 2006). *Poposaurus* therefore occurs throughout the Adamanian in eastern Arizona. It is also known from Otis Chalk, the Popo Agie Formation, and the Tecovas Formation (Long and Murry, 1995; Lucas, 1998; Weinbaum and Hungerbühler, 2006), and unlike other rauisuchids may therefore be restricted to the Otischalkian?-Adamanian (Long and Murry, 1995; Lucas, 1998).

Sphenosuchian material is known from the Adamanian and lowermost Revueltian in southern Garza County, although its biostratigraphic utility is unclear. The femora known from the Adamanian Post Quarry can probably only be identified as sphenosuchian (Jonathan Weinbaum, personal communication). The superb skull and skeleton from the lowest Revueltian Headquarters locality is one of the best sphenosuchian specimens known from in western North America, but it has not yet been described. In eastern Arizona, sphenosuchians are known from the *Placerias* Quarry and Blue Mesa Member and seem to be restricted therefore to the Adamanian, with most of the diagnostic material usually being referred to *Hesperosuchus* (e.g. Colbert, 1952; Parrish, 1991; Long and Murry, 1995; Parker and Irmis, 2005).

In southern Garza County, a single tooth of the small pseudosuchian archosaur *Revueltosaurus callenderi* is known from the Boren Quarry in the Otischalkian (or lower Adamanian). This is a significant occurrence, as the taxon is considered to be a Revueltian index fossil (Hunt, 2001; Heckert, 2004; Heckert and Lucas, 2007), and indicates a considerable range extension.

"*Pteromimus*" and "*Procoelosaurus*"

The two enigmatic taxa "*Pteromimus*" and "*Procoelosaurus*", which are recognized mostly by their distinctive procoelous vertebrae (Atanassov, 2002), are known mainly from the Boren Quarry (Otischalkian or early Adamanian) and Post Quarry (Adamanian), both in the lower unit of the Cooper Canyon Formation, where they are extremely abundant. Isolated and badly preserved vertebrae possibly referable to "*Procoelosaurus*" are known from the middle unit of the Cooper Canyon Formation UU Sand Creek and Headquarters localities, which are respectively in upper Adamanian and lowermost Revueltian. "*Procoelosaurus*" and "*Pteromimus*" have a range therefore which is Otischalkian or earliest Adamanian to earliest Revueltian. They are both also known from the Adamanian Tecovas Formation of southern Crosby County (Atanassov, 2002), but have not been described from elsewhere.

Dinosauromorphs

Dinosauromorphs of various grades, from basal dinosauromorphs to coelophysoid theropods, are known from southern Garza County, and show a hint of a stratigraphic trend with respect to how derived they are within Dinosauromorpha. The basal dinosauromorph *Dromomeron* (Irmis et al., 2007) is the lowest, being known from the Boren Quarry in the Otischalkian (or earliest Adamanian?) to the Headquarters locality in the lowermost Revueltian (Bill Parker and Sterling Nesbitt, personal communication). The Adamanian Post Quarry has the most diverse dinosauromorph assemblage. *Dromomeron* is not known from there, but basal dinosauriform material, including the possible *Silesaurus*-like form *Technosaurus* (Chatterjee, 1984; Nesbitt et al., 2007), a basal saurischian, and theropod material, including at least some which is coelophysoid (Nesbitt et al., 2007; Nesbitt and Chatterjee, in prep), and the braincase of *Protoavis* may belong to a derived theropod, though how derived is a matter of contention (e.g. Paul, 1988; Chatterjee, 1991; Witmer, 2002). Basal saurischian material is also known from the Headquarters NW locality in the lowest Revueltian, and theropod material is known from the Lott-Kirkpatrick locality in the Revueltian, and the Patricia Site in the lowermost Apachean (Nesbitt and Chatterjee, in prep; Nesbitt et al., 2007).

In summary, taken at face value the biostratigraphic evidence indicates that in southern Garza County basal dinosauromophs appear in the Otischalkian (or lowermost Adamanian), and that a diverse assemblage of basal dinosauromorphs, basal dinosauriforms, basal saurischians, and theropods was present higher in the Adamanian. In the lowest Revueltian only basal dinosauromorphs, crown-clade dinosaurs (basal saurischians and theropods) were left, with the less derived forms dropping out until only theropods survive to the Apachean.

This scenario must be taken with caution given the scrappy nature of the material, but is given very weak support by other dinosauromorph material from western North America. The coelophysoid theropod "*Camposaurus arizonensis*" (Hunt et al., 1998), as well as indeterminate dinosauriform and saurischian material, is known from the lower Adamanian *Placerias* Quarry (Long and Murry, 1995; Hunt et al., 1998; Nesbitt et al., 2007), a *Silesaurus*-like basal dinosauriform is known from high in the Adamanian Blue Mesa Member (Parker et al., 2006), and *Coelophysis* material and the basal saurischian *Chindesaurus* are known from high in the Petrified Forest Member (Painted Desert Member) at PEFO, well within the Revueltian (Padian, 1986; Long and Murry, 1995; Langer, 2004; Stocker et al., 2004; Parker and Irmis, 2005; Parker et al., 2006; Nesbitt et al., 2007). In eastern Arizona therefore, basal saurischians and coelophysoids are known from the lower Adamanian to well into the Revueltian, and basal dinosauriforms are known from at least from the upper Adamanian.

The Petrified Forest Member (or Painted Desert Member) in North-Central New Mexico also shows a roughly similar pattern to what is seen in southern Garza County. The diverse dinosauromorph assemblage from the Hayden Quarry described by Irmis et al. (2007) includes the basal dinosauromorph *Dromomeron,* a *Silesaurus*-like basal dinosauriform, basal saurischians, and coelophysoid theropods. Although similar in diversity to the Post Quarry, the Hayden Quarry assemblage includes both *Pseudopalatus* and *Typothorax coccinarum*, and is therefore (lower?) Revueltian. Basal dinosauromorphs and coelophysoids are also known from the Snyder Quarry (Heckert et al., 2000; Zeigler et al., 2003b; Nesbitt et al., 2007), which is slightly higher in the section (Irmis et al., 2007, fig. 1). However, only the coelophysoid theropod *Coelophysis* is known from the Ghost Ranch *Coelophysis* (Whittaker) Quarry, which is located in the "Siltsone Member" (=Rock Point Member?) near the very top of the Chinle Formation (e.g. Stewart et al., 1972; Dubiel, 1989; Lucas and Hunt, 1992).

This recent work on dinosauromophs assemblages in western North America (Parker et al., 2006; Nesbitt et al., 2007; Irmis et al., 2007; Nesbitt and Chatterjee, in prep) all suggest that in the southern Garza County, eastern Arizona, and North-Central New Mexico dinosauromorph faunas, *Silesaurus*-like basal dinosauriforms co-existed with saurischian dinosaurs (including true theropods) in the Adamanian and at least part of the Revueltian, although the saurischians outlasted the *Silesaurus*-like forms well into the Revueltian. At least in southern Garza County and North-Central New Mexico, the basal dinosauromorph *Dromomeron* also co-existed with these more derived forms and may also have slightly outlasted the *Silesaurus*-like forms in the Revueltian. In the uppermost Revueltian and Apachean, only true theropods are known, and nearly all are probably coelophysoids, although coelurosaurs of some kind may have been present from the Adamanian onward (Chatterjee, 1991; Witmer, 2002). Dinosauromorph diversity therefore shows a general decline during the Revueltian and Apachean.

The Age of the Dockum Group

Introduction

When reading through the literature on Upper Triassic vertebrate biostratigraphy/biochronology, it is easy to lose sight of the fact that stages and substages of the Upper Triassic are not biostratigraphic units based on terrestrial vertebrate fossils. They are chronostratigraphic units, (hypothetically) independent of and free to cross lithostratigraphic and biostratigraphic boundaries, and are tied to Upper Triassic marine strata correlated using marine invertebrates. Any allegations that terrestrial redbeds in the western United States belong to the Carnian, Norian, or Rhaetian stages or their constituent substages must therefore be able to demonstrate direct or indirect correlation of these strata to marine rocks whose stages and substages have been established based on invertebrate (particularly ammonoid) biostratigraphy. These correlations from the marine to the terrestrial come in a variety of forms, especially through palynology and magnetostratigraphy, with the occasional vertebrate or invertebrate fossil occurring in both marine and terrestrial strata taking subordinate roles. Between terrestrial strata, particularly between the Chinle Group, Dockum Group, and Newark Supergroup of North America, correlation is primarily through pollen and vertebrate fossils, with plant megafossils, invertebrates, and magnetostratigraphy taking subordinate roles.

These correlations are rarely laid out in detail in the literature on the vertebrate fauna of the Dockum Group, and the validity of age determinations for these strata is therefore difficult for the casual reader to evaluate. What sorts of fossils are used in these correlations? How reliable are these fossils as age indicators? What are the sample sizes? How many correlations link a particular set of terrestrial strata to marine strata? Are these correlations ever circular? When conflicts occur between proposed ages for strata, why should one method or type of fossil be given over another? These questions become especially relevant given the recent reevaluation of the Carnian-Norian boundary in terrestrial Upper Triassic strata in North America. Although a detailed critique of the various dating methods is beyond the scope of this dissertation (and would probably be a dissertation in itself), it is worth briefly reviewing the proposed correlations.

Pollen and Vertebrate Correlations for Western North America

Traditionally, correlation of the Dockum Group and Chinle Formation to marine strata which can be tied using ammonoids and conodonts to the Carnian, Norian, and Rhaetian stages, has been based primarily on pollen (Dunay, 1972, Dunay and Fisher, 1974; Litwin et al., 1991; Cornet, 1993), which have generally yielded a late Carnian age for the lower part of the Chinle Formation and Dockum Group (including the Blue Mesa Member and Tecovas Formation), and a Norian age for the upper part (including the Painted Desert Member). These have been used to assign late Carnian and Norian ages to the Adamanian and Revueltian respectively (Lucas and Hunt, 1993b; Lucas, 1998).

The pollen correlations have received weak corroboration from vertebrate fossils occurring both in the Upper Triassic of the western United States and in marine strata in Europe (particularly Hunt and Lucas, 1991a; Lucas 1993, 1998; Lucas and Heckert, 2000). A basal phytosaur is known from Tuvalian (late Carnian) marine strata in Austria (Hunt and Lucas, 1991a), and *Aetosaurus*, which occurs in the Bull Canyon Formation of New Mexico, and is considered to be Revueltian (Heckert and Lucas, 1998) is also known Norian marine strata in Italy (Wild, 1989). Lucas (1998) also used the close relationship between *Pseudopalatus* and the pseudopalatine *Nicrosaurus* from the Norian Stubensandstein of Germany, which contains the type material of *Aetosaurus* (Schoch, 2007), to advocate a Norian age for the Revueltian.

Pollen, Vertebrates, and Magnetostratigraphic Correlations for the Newark Supergroup

The Newark Supergroup is an important Upper Triassic correlative of the Chinle Formation and Dockum Group, for both pollen and vertebrate fossils. The Newark Basin contains, in ascending order, the Stockton Formation, Lockatong Formation, and Passaic Formation. Cornet (1993) recognized distinct pollen floras in the Lockatong and lower Passaic Formation. He identified the former as being correlative with Carnian and also with the palynoflora of the Blue Mesa Member in eastern Arizona (Litwin et al.'s, 1991 Zone II) and with the Tecovas Formation in the lower Dockum Group (Dunay, 1972; Dunay and Fisher, 1979). This pollen zone is therefore roughly equivalent to the Adamanian (Lucas, 1993, 1998). Cornet (1993) considered the overlying Passaic palynoflora to correlate with the Norian, and to with the palynoflora of the Painted Desert

Member (Litwin et al.'s 1991 Zone III). This palynoflora is therefore roughly equivalent with the Revueltian (Lucas, 1993, 1998).

Huber et al. (1993) and Lucas and Huber (1993) identified *Rutiodon* (Huene, 1913; co-generic with *Leptosuchus* according to Lucas et al. 2007b, or *Angistorhinus* according to Hungerbühler, 2001b, both of which occur in the Otischalkian?-Adamanian in western North America) from the upper part of the Stockton Formation, and *Stegomus arcuatus* (Baird, 1986; referred to *Aetosaurus* by Lucas et al., 1998, and possibly indicating correlation with the Revueltian) from the lower Passaic Formation. They also interpreted the Carnian-Norian boundary as falling between the Lockatong Formation and Passaic Formations, which would suggest it also falls between the Adamanian and Revueltian.

However, in recent years Krystyn et al. (2002) and Channel et al. (2003) used magnetostratigraphic correlation of the Newark Supergoup in the Newark Basin of eastern North America to marine strata in Europe and Asia. They placed the Carnian-Norian boundary well within the Stockton Formation, indicating that the upper Stockton Formation, Lockatong Formation, and the lower part of the Passaic Formation were all Norian. If these revised magnetostratigraphic correlations between the Upper Triassic marine and the Newark Basin are accepted, and the pollen and (somewhat weaker) vertebrate correlations between the Stockton, Lockatong, and Passaic Formations with the Chinle Formation and Dockum Group of western North America are also accepted, this gives a Lacian (Early Norian) age for the Adamanian, and a probable Alaunian and/or Sevatian (Late Norian) for the Revueltian.

Lithostratigraphic correlation of the continental and marine in the Upper Triassic of western North America

Lithostratigraphic correlation has been attempted in various ways between the Dockum Group with the Chinle Formation of the Colorado Plateau region (Chinle Group *sensu* Lucas, 1993). The presence of siliceous conglomeritic sandstones at the base of the Upper Triassic strata throughout the western United States and have received numerous names (e.g. Shinarump, Agua Zarca, Gartra, Santa Rosa, Camp Springs) (e.g. Stewart et al., 1972; Lucas et al., 1985; Lucas, 1993). Paleocurrent, petrologic, and provenance studies (particularly of detrietal zircons) indicate that these basal conglomerates were part of a single extensive braided river system flowing northwest from West Texas through the Four Corners states into Nevada, deposited in paleovalleys incised into the broad regional "TR-3" unconformity (e.g. Stewart et al., 1972; Pipiringos and O'Sullivan, 1979; Blakey and Gubitosa, 1984; Lucas, 1993; Riggs et al., 1993; Dubiel, 1994). These basal siliceous conglomerates are important not only because they provide lithostratigraphic correlation for the base of the Upper Triassic sequence through the western United States, but because they have been correlated with Upper Triassic marine strata in Nevada. However, there has been some disagreement as to exactly how these strata correlate, and these conflicts have received curiously little attention even though they have important implications for dating the base of the Upper Triassic continental strata of the western United States.

The Star Peak Group and overlying Auld Lang Syne are transitional, shallow marine, and deep marine Upper Triassic strata being deposited in western Nevada (Nicholls and Silberling, 1977; Lupe and Silberling, 1985), in the direction that the basal Chinle-Dockum fluvial system was flowing (e.g. Stewart et al., 1972; Riggs et al., 1993). The Star Peak Group is composed primarily of platform carbonates, which contain numerous intraformational unconformities and occasional influxes of clastic material, indicating a complex tectonic history (Nichols and Silberling, 1977). The Auld Lang Syne Group is composed primarily of sandstones and mudstones interpreted as being deposited in a deltaic environment, and the basal, relatively sandy strata of the Auld Lang Syne Group including the Grass Valley and Osobb Formations (Silberling and Wallace, 1969; Lupe and Silberling, 1985). This dramatic shift from predominantly carbonate deposition in the Star Peak Group to clastic deposition in the Auld Lang Syne Group has been interpreted as being under both tectonic (Lupe and Silberling, 1985) or eustatic control (Lucas, 1991). Well-constrained ammonite biostratigraphy places the Carnian-Norian boundary at the beginning of Auld Lang Syne clastic deposition, with the Osobb

Formation falling within the Lacian (Early Norian) *Stikinoceros kerri* zone (e.g. Lupe and Silberling, 1985).

Which Chinle Formation (and by extension, Dockum Group) strata correlate with the Early Norian base of the Auld Lang Syne Group is therefore of vital importance. Lupe and Silberling (1985) correlated the basal Auld Lang Syne Group with the Moss Back Member of the Chinle Formation in Utah, a sandstone positioned well up within the Chinle Formation, and the uppermost Star Peak Group with the lowermost Chinle Formation, including the Shinarump Member. This correlation was based on their interpretation that the base of the Chinle Formation, being composed largely of mottled strata, was deposited under a "passive, stagnant depositional regime" (p. 264) in which there was "little or no sediment transport" (p. 269). If sediments were not being actively transported into western Nevada, this would be consistent with their relative absence in the carbonate dominated strata in the Star Peak Group. On the other hand, the sudden influx of clastic sediments in the Moss Back Member was interpreted as coinciding with the development of the northwesterly flowing fluvial system of Moss Back Member (e.g. Stewart et al., 1972), which they interpreted as the first "regionally integrated drainage system" in the Late Triassic of western North America (Lupe and Silberling, 1985, p. 268). However, as already discussed, the first such Upper Triassic drainage system flowing toward western Nevada was actually the Santa Rosa-Shinarump river system, which transported sediment from Texas to Nevada. This makes it a makes a more likely initiator of Auld Lang Syne clastic deposition. Lucas (1991) made essentially the same correlations between the Chinle Formation, Star Peak Group, and Auld Lang Syne Group as Lupe and Silberling (1985), although he apparently based his correlation on existing vertebrate and pollen biochronology (already discussed), which placed the base of the Chinle Formation in the upper Carnian, and therefore correlative with the upper Star Peak Group.

However, the work of Gehrels and Dickinson (1995) and Riggs et al. (1996) correlated the siliceous conglomeratic sandstones of the Santa Rosa-Shinarump system with the Osobb Formation at the base of the Auld Lang Syne Group. They based this correlation on the presence of very similar detrietal zircon populations (especially of Cambrian age) found in the Santa Rosa Sandstone, Shinarump Member, the base of the Chinle Formation in eastern Nevada, and the Osobb Formation. Given that that Lupe and Silberling (1985) probably based their correlation on an erroneous depositional model for the Shinarump Member and Lucas (1991) was basing his dating for the Chinle Formation on other biostratigraphic methods, the direct lithologic evidence of Gehrels and Dickinson (1995) and Riggs et al. (1993) correlating the Santa Rosa Sandstone with the base of the Auld Lang Syne Group seems more compelling. If correct, this correlation suggests that the bases of the Dockum Group and Chinle Formation are Lacian (early Norian), as suggested by the revised magnetostratigraphic correlations for the Newark Supergroup already discussed.

Summary and Discussion

This study corroborates the basic patterns of faunal change recognized in western North America during the Late Triassic (Camp, 1930; Colbert and Gregory, 1957; Long and Padian, 1986; Long and Ballew, 1985; Lucas and Hunt, 1993; Lucas, 1993; Parker, 2006). Lucas' (1998) definition of the Late Triassic land-vertebrate faunachron boundaries base on the lowest occurrences of phytosaur taxa provides useful reference points for discussing faunal change for other vertebrates, providing of course that the biostratigraphic range information is plotted so that the boundaries can actually be applied. I use his definitions for the Otischalkian, Adamanian, Revueltian, and Apachean, even though there are issues with the alpha taxonomy for the phytosaur taxa used to define the base of the Otischalkian and Apachean. Given that it is not entirely clear how the Carnian, Norian, and Rhaetian stages correlate to western North America, and most of these correlations are fairly broad, I prefer to discuss vertebrate faunal change primarily in reference to the "faunachron" boundaries rather than to the Carnian, Norian, and Rhaetian stages/ages.

Although the Otischalkian and Adamanian can be distinguished in southern Garza County using the strict phytosaur-based boundary definitions, this may be an artifact of a very limited sample size for *Leptosuchus*, and I agree with Rayfield et al. (2006) that the distinctiveness of the Otischalkian and Adamanian in western North America is not well-supported based on either clear faunal differences or a well-supported superpositional distinction for the defining phytosaur taxa in most areas. Even if all of the identifications by Lucas and his colleagues (e.g. Lucas, 1993, 1998; Lucas et al., 2007b) of *Longosuchus*, *Metoposaurus bakeri*, and *Doswellia* as Otischalkian index fossils is correct, their extreme rarity outside their type areas, and their recent claim that *Stagonolepis* occurs in both the Otischalkian and Adamanian (Lucas et al., 2007c), makes distinguishing Adamanian and Otischalkian faunas dependant almost entirely on the presence of absence of *Leptosuchus*.

The Adamanian and Revueltian are easier to distinguish, based on the lowest occurrence of *Pseudopalatus* and faunal differences, although how reliable these apparent faunal changes really are, or how gradually or abruptly they occurred, is hard to assess given the sporadic and scanty nature of the vertebrate fossil record. Most likely, little can be said with confidence about the nature of this faunal transition, either in favor of a mass extinction or against it (Lucas and Tanner, 2004). The importance of dense stratigraphic fossil sampling in identifying mass extinctions, demonstrated by investigations of the K-T boundary (e.g. Hulbert and Archibald, 1995; Sheehan et al., 2000) emphasizes that care should be taken about making any strong statements about the nature of faunal change in the Chinle Formation or Dockum Group based on such modest sample sizes. Moreover, given the contentious nature of the placement of the Carnian-Norian boundary in western North America, even if such an event did occur, it is not clear if it would have occurred at the Carnian-Norian boundary (Benton 1991, 1993, 1994) or within the Norian, and it would therefore not be clear whether it corresponded to a global faunal overturn impacting both marine and terrestrial life.

The following patterns in faunal change seen in southern Garza County (at least some of which seem to be reflected elsewhere), must therefore be treated with caution.

However, the establishment of a detailed lithostratigraphic and biostratigraphic framework at least makes them *testable* hypotheses which may be supported or weakened with the ongoing collection of additional fossils, and the clarification of taxonomic assignment for this material.

A decline in diversity?

One of the more striking patterns observed in southern Garza County is the evidence of a possible turnover in the microvertebrate fauna between the Adamanian and Revueltian, a possibility suggested primarily by comparing the microvertebrate faunas of the Boren Quarry, Post Quarry, Headquarters localities, and Simpson Ranch locality. This possible turnover is characterized by a general decrease in diversity, and some appearances and disappearances. The Otischalkian?-Adamanian microvertebrate fauna contains rare specimens of non-metoposaur temnospondyls, trithelodontids, sphenodontids, drepanosaurs, cf. *Doswellia*, and *Revueltosaurus callenderi*, rare but diverse dinosauromorphs, and common specimens of *Malerisaurus*, *Trilophosaurus*, "*Procoelosaurus*" and "*Pteromimus*." The Revueltian faunas are lower diversity, containing more abundant drepanosaurs and (higher up) leptopleurine procolophonids, and dinosauromorphs are represented almost exclusively by theropods (probably coelophysoids). Adamanian taxa are rare or absent. Again, given the sample size, it is difficult to say how gradual or abrupt this change may have been.

This drop in diversity also is reflective of faunal change in other Upper Triassic vertebrates. At least in some areas of western North America, phytosaurs are diverse in the Otischalkian?-Adamanian, where *Leptosuchus* co-occurs both with basal phytosaurs and *Angistorhinus* (=*Rutiodon* sensu Hungerbühler, 2002b) (Chatterjee, 1986a; Long and Murry, 1995; Lucas, 1998), but only pseudopalatines remain by the upper Revueltian and Apachean (e.g. Lucas, 1998). In the upper Revueltian-Apachean in southern Garza County, *Pseudopalatus* seems to have undergone a minor radiation which included forms of *Redondasaurus*-grade. Although large metoposaurs persist from Adamanian to the

Apachean, their remains become less common in the Revueltian and Apachean, and the poposauroid rauisuchian *Poposaurus* is altogether absent. Aetosaur diversity also seems to show a decline, although it is more subtle; the genera *Paratypothorax*, *Typothorax*, and *Desmatosuchus* are all present in the Adamanian Post Quarry, the only the latter two persist into the uppermost Adamanian-lower Revueltian?, where cf. *Rioarribasuchus* also occurs, and only *Typothorax coccinarum* is known from the Apachean Patricia Site. Dicynodonts occur in the Adamanian, but are unknown in the Revueltian.

The rise of dinosaurs in western North America

Of all the faunal changes to occur in the Late Triassic, the rise of dinosaurs from predominantly small-bodied and rare components of the terrestrial vertebrate fauna to the dominant land animals on the surface of the Earth is arguably of the most interest. The nature and mechanism for this transition has been highly contentious. Benton (e.g. 1986; 2004) divided models for the dinosaur takeover into two categories: “competitive replacement,” in which dinosaurs were able to actively out-compete other archosauromorphs and therapsids through locomotor or metabolic advantages (e.g. Charig, 1984; Bakker, 1972, 1980), and “opportunistic replacement”, in which dinosaurs became abundant and diverse only after extinctions of other therapsids and archosauromorphs due to other factors such as changes in the climate and flora, and that dinosaurs were not directly responsible for the extinction of these other groups (e.g. Tucker and Benton, 1982; Benton, 1983; 1986; 1994; 2004).

The pattern seen in western North America corroborates the “opportunistic replacement” model to some extent, as least in that the apparent decline in diversity of large non-dinosaurian herbivores and carnivores cannot be linked to an increase in diversity and body size in dinosaurs. However, it differs slightly from Benton’s model, which was based largely on the pattern observed in Germany and South America, in that dinosaurs remain relatively rare and small-bodied for the duration of the Late Triassic, while pseudosuchian archosaurs remain the most abundant large vertebrates, and both the pseudosuchians *and* dinosauromorphs may experience a broad decline in diversity.

Dicynodonts are present in the lower part of both the Chinle Formation and the Dockum Group (Otischalkian?-upper Adamanian), where they are locally abundant, but absent in upper strata (Revueltian-Apachean). However, unlike Germany and South America, where the decline in non-dinosaurian herbivores is followed by the herbivore fauna becoming dominated by sauropodomorph dinosaurs (Benton, 1986), putative evidence of prosauropods in western North America is based almost exclusively on rare teeth (Harris et al., 2002; Hunt et al., 1998) and ichnotaxa, the latter of which are confined to strata high in the Chinle Formation and Dockum Group (e.g. Hunt et al., 1998; Lockley et al., 2001). Recently Nesbitt et al. (2007) questioned the assignment of any of this material to prosauropods. Moreover, the recent work of Irmis et al. (2006) and Nesbitt et al. (2007) has cast doubt on the presence of ornithischians outside of Gondwana until the Jurassic. In summary, the absence of dicynodonts in western North America *cannot* be tied to competition with herbivorous dinosaurs, as both prosauropods and ornithischians were either extremely rare or absent in North America until long after the last record of dicynodonts in the Adamanian. This provides at least circumstantial support for the suggestion (Benton, 1986; Crompton and Attridge, 1986) that competition with prosauropods was *not* responsible for the extinction of other herbivorous amniotes.[9]

The nature of faunal turnover among carnivorous terrestrial archosaurs is difficult to assess. Carnivorous rauisuchians such as *Poposaurus* and *Postosuchus* are best known from the Adamanian, but at least *Postosuchus* persisted into the Apachean. Given the

[9] This also raises the puzzling question of what animals occupied the large herbivore niches during the Revueltian, if dicynodonts were extinct and herbivorous dinosaurs were not yet present. Aetosaurs were abundant, but Small (2002) has noted that dentition and other aspects of aetosaur anatomy may indicate an omnivorous or insectivorous diet rather than herbivory. The ornithischian or ornithischian tooth-based taxa known from the Revueltian have a tooth morphology consistent with a herbivorous diet (e.g. Heckert, 2004), but most are small, rare, or both, as are basal dinosauromorphs allied to *Silesaurus* (Nesbitt et al., 2007; Irmis et al., 2007). Were large carnivores like rauisuchids and theropods relying primarily on large, heavily armored omnivores and a variety of small herbivores?

scanty fossil record for these predators, it is hard to determine how, or even if, large rauisuchians diversity and abundance changed throughout the Late Triassic. Carnivorous dinosauromorphs experienced a (gradual?) decline in diversity during the Revueltian, but this does not tell us how abundant the surviving groups were. The fantastic abundance of *Coelophysis* (at least locally at the Ghost Ranch *Coelophysis* Quarry) suggests that coelophysoids may have been quite successful in the Apachean, and it is entirely possible that they were replacing rauisuchians as the most common large carnivores.

The decline in dinosauromorph diversity in both southern Garza County and the Chinle Formation of eastern Arizona and north-central New Mexico therefore seems to be a reflection of a general pattern seen across the spectrum of Upper Triassic tetrapods in western North America, in which the majority of groups declined and lost alpha taxa but (with a few notable exceptions, such as the dicynodonts) did not disappear entirely, during the Revueltian. This is not fully consistent with the "opportunistic" model of the rise of dinosaurs, in which dinosaurs radiated following a mass extinction near the Carnian-Norian boundary which eliminated most of the other large vertebrates (particularly pseudosuchian archosaurs). It is also not entirely consistent with "competitive" models favoring replacement of pseudosuchians by steadily diversifying dinosaurs over an extended period. Rather, it seems to mix aspects of both models: an extended period of decline in diversity for all Late Triassic vertebrates in western North America, in which dinosauromorphs remained generally rare members of the terrestrial vertebrate faunas, and theropod dinosaurs simply outlasted not only other dinosauromorphs but most of the pseudosuchians (phytosaurs, rauisuchians, and phytosaurs) which had previously dominated terrestrial faunas. This may, perhaps, best described as a "last man standing" model, though its evaluation depends on further work detailing Upper Triassic vertebrate biostratigraphy in western North America.

APPENDIX 1

MEASURED SECTIONS

These measured sections, which include nearly all mapped units across Garza County, comprise most of the sections used in Fig. 2.3 with the exception of the exception of a few taken from Frehlier (1987) and Lehman and Chatterjee (2005). Vertebrate localities are listed first, followed by unfossiliferous localities where lithostratigraphic sections were measured. Each section heading includes what was collected there (vertebrate fossils, mudstone samples for major and trace element analysis, and/or petrographic samples), coordinates in latitude and longitude (except for especially significant and productive vertebrate localities), the quadrangle which contains the locality, the total thickness of the unit, and figures which show the locality (including the measured section). The mapped lithostratigraphic unit in which each section unit is contained is identified, with the broad identifications “lower unit,” “middle unit,” and “upper unit” being used for those parts of the Cooper Canyon Formation dominated by overbank deposits or un-mapped channel deposits.

In the unit descriptions and figures, mudstone samples which were used in major and trace element analysis are in boldface, while petrographic thin sections are underlined. The latter are not discussed by detail in this dissertation, but it is important to note their stratigraphic position for future petrologic studies. There is also some attempt made to identify the depositional system which formed each unit (e.g. overbank deposits, channel deposits), although these must be taken with a grain of salt until a more detailed examination and description of units is conducted. The colors of individual units were identified using the Geological Society of America Rock-Color Chart, which is based on the Munsell system, and mostly applied to mudstones (claystones and siltstones), although in some cases the color of coarser-grained units is also identified. Comments on sandstone petrology (e.g. claystone, siltstone, siliceous clasts, and reworked sedimentary rock clasts) are based almost entirely on field identification. Figure A1.1 gives the symbols used in measured sections.

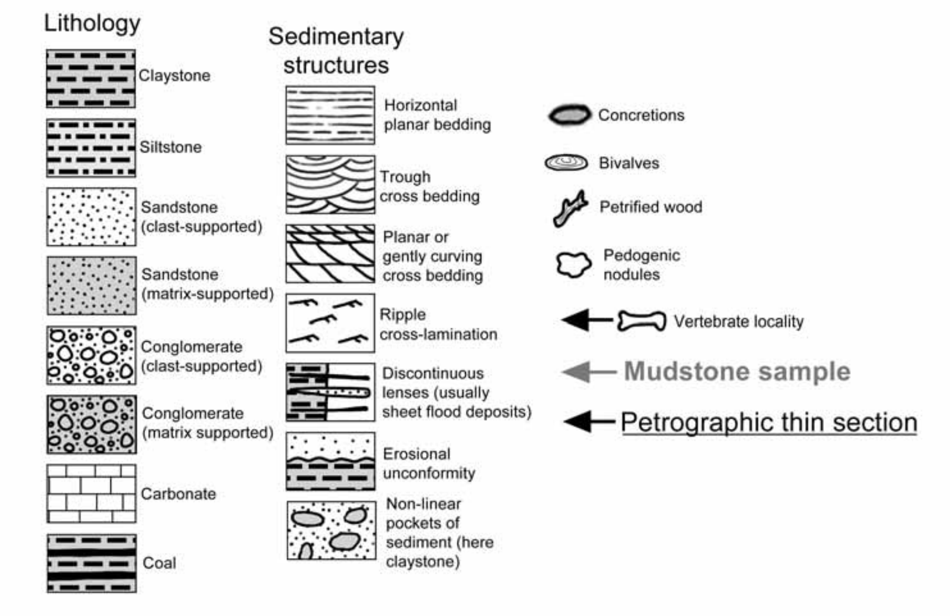

Fig. A1.1. Key to symbols used in the measured sections

MOTT 3634 (LOTT-KIRKPATRICK)

N33°05’02” W101°25’02”

Mudstone samples

Miller Creek Quadrangle

Total thickness: 40.64 m

Figs. 2.19a, A1.2

This hill is clearly visible from Highway 84, and is important not only in being one of the first vertebrate localities worked by Sankar Chatterjee in West Texas, but in including good exposures of both the Macy Ranch sandstone and Kirkpatrick Ranch sandstone, although the latter is fairly thin here. The section was only measured part of the way through the Macy Ranch sandstone.

1) 0 m → 0.15 m (thickness: 0.15 m) u**pper unit of the Cooper Canyon Formation**

Medium reddish brown (10R 4/6) coarse to very coarse-grained matrix supported sandstone with light greenish-gray (5G 8/1) mottling. Proximal overbank deposits?

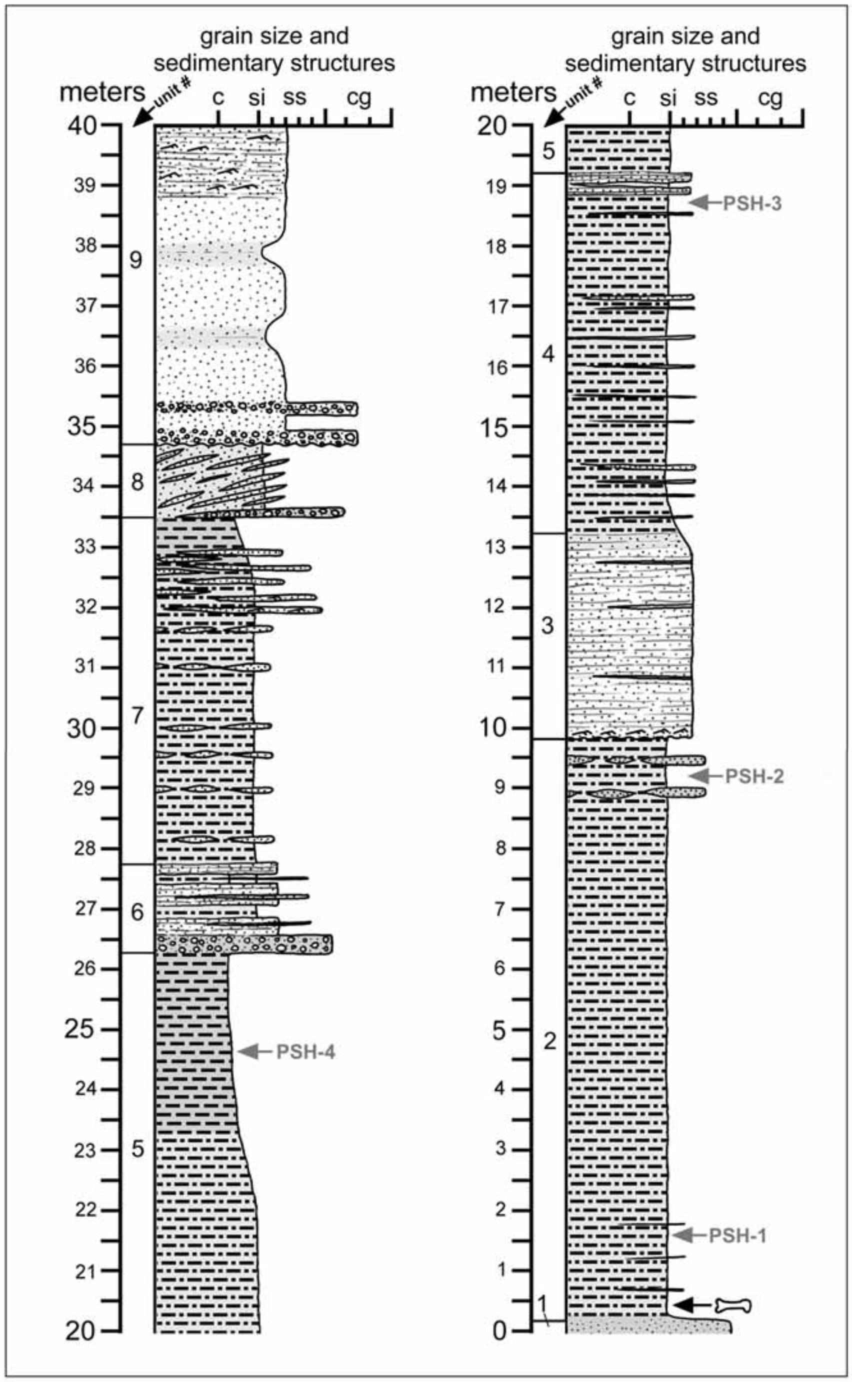

Fig.A1.2. MOTT 3634 (Lott-Kirkpatrick) measured section.

2) 0.15 m → 9.8 m (thickness: 9.65 m) **upper unit of the Cooper Canyon Formation**
Light brown (5YR 5/6) siltstone with light greenish gray (5G 8/1), mostly random reduction mottles associated with very thin (less than 1 cm thick) lenses of very fine-grained, horizontal planar bedded sandstone in the lower 2 m of the section, very irregular reduced greenish gray (5G 6/1) pockets of medium to fine-grained matrix supported sandstone containing large mud clasts in the top meter. Overbank deposits and sheet sands. Mudstone sample **PSH-1** was taken from just over 2 m above the base of the unit, sample **PSH-2** was taken 50 cm from the top.

3) 9.8 m → 13.2 m (thickness: 3.4 m) **Kirkpatrick Ranch sandstone**
Medium reddish brown (10R 4/6) very fine-grained to fine-grained, mostly clast-supported sandstone. The lower 10 cm is well-cemented horizontal planar and ripple cross bedded sandstone with some interbedded mudstone, and the rest of the unit is mostly friable, faintly horizontal planar bedded sandstone interbedded with thin (less than 1 cm thick up to 10 cm thick) layers of more resistant lenses of fine to very fine-grained sandstone similar to the base of the unit. Channel sandstone. Although given as 3.4 meters here, the thickness of this unit is somewhat variable at this hill. Contact with next unit is gradational.

4) 13.2 m → 19.2 m (thickness: 6 m) **upper unit of the Cooper Canyon Formation**
Medium reddish brown (10R 4/6) siltstone with very fine reduction mottling, interbedded with thin (less than 1 cm to almost 10 cm thick) layers of fine to very fine-grained sandstone as in the previous unit. The unit is capped with a thicker (about 30 cm thick) layer of the same sandstone with some inter-bedded siltstone. Overbank deposits. Mudstone sample **PSH-3** comes from immediately below this sandstone.

5) 19.2 → 26.35 m (thickness: 7.15 m) **upper unit of the Cooper Canyon Formation**
Medium reddish brown (10R 4/6) siltstone grading into slightly silty claystone with greenish gray (5G 6/1) reduction mottling showing both random and layered patterns. A very thick mottled patch about 40 cm thick in present near the top. Mudstone sample **PSH-4** comes from immediately below it, about 6 m from the base of the unit.

6) 26.35 m → 27.75 m (thickness: 1.4 m) **upper unit of the Cooper Canyon Formation**
Coarse grained unit. 30 cm of greenish gray (5G 6/1) matrix-supported very coarse-grained sand to granule conglomerate followed by 1.1 m of medium brown (5YR 3/4) inter-bedded silt and very fine to fine- grained, mostly horizontal planar bedded sand, with some thin lenses of coarse sand. Channel deposits.

7) 27.75 m → 33.75 m (thickness: 5.1 m) **upper unit of the Cooper Canyon Formation**
Medium brown (5YR 3/4) siltstone with a few sparse pockets of very fine-grained sandstone in the lower few meters, and densely interbedded fine to very coarse-grained sandstone lenses with horizontal planar bedding and ripple cross bedding in the next couple meters, grading in the very top meter or so into silty claystone with irregular and sometimes linear greenish grey (5G 6/1) reduction mottling.

8) 33.75 m → 34.65 m (thickness: 0.9 m) **Macy Ranch sandstone**
Mostly reduced greenish gray (5G 6/1) friable fine-grained sand and silt, complexly interbedded with more well-cemented and often tilted lenses of planar bedded fine-grained sandstone. The base of the unit is a discontinuous lens of matrix-supported, cross bedded granule conglomerate.

9) 34.65 → 40.64 m + (thickness: over 6 m) **Macy Ranch sandstone**
Well-cemented fine-grained, mostly structureless sandstone interbedded with friable fine-grained sand and silt similar to the previous unit, except that the well-cemented sandstone dominates, mostly structureless near the base, but becomes planar and (to a lesser extent) ripple cross-bedded higher up about 4 m above the base. Two thick granule and pebble conglomerate layers are present near the base.

MOTT (3867 & 3868) OS RANCH SITE 1 AND PETRIFIED GROVE

Vertebrate fossils

Justiceburg Quadrangle

Total thickness: 18.65 m

Figs. 2.16, 2.17a, A1.3

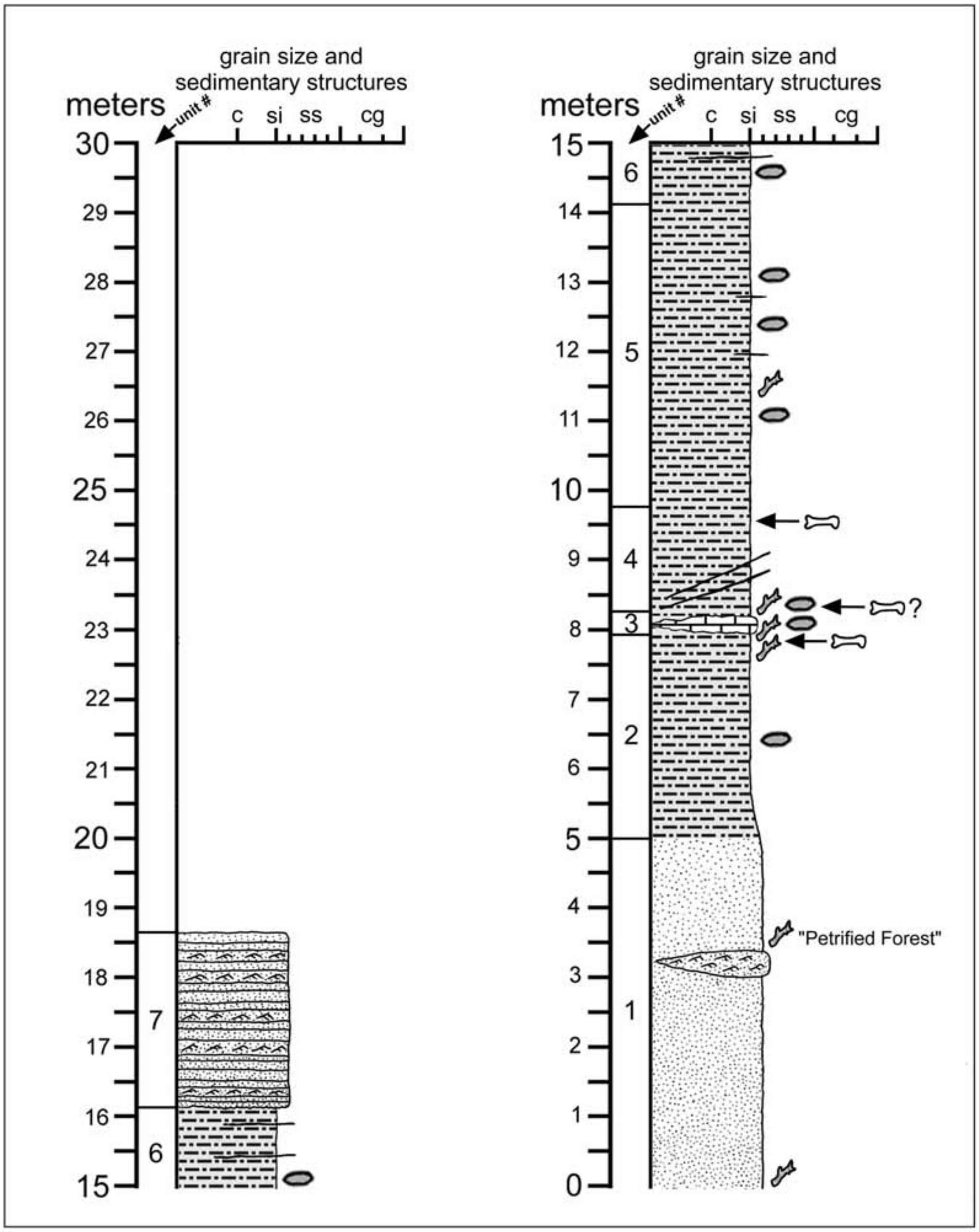

Fig. A1.3. MOTT 3867 & 3868 OS Ranch Site 1 and Petrified Forest measured section.

The OS Ranch section was measured up the south side of the hill at OS Ranch Site 1, informally referred to as "Dicynodont Hill", which produced material from two different stratigraphic levels. This section is shown in Fig. 2.16a with the lower grayish beds representing unit 2, and the upper reddish beds representing units 4-6. OS Ranch Sites 2 and 3, and the OS Ranch East locality (MOTT 3873) are correlated to this section using in particular the distinctive yellowish carbonate bed (unit 3) and the upper Boren Ranch sandstone (unit 7) capping the hill. However, all units, including the carbonate bed(s) and sandstone cap, show considerable lateral variation, and the stratigraphic placement of all sites except for Site 1 must be considered approximate. The base of the section was extended on the north side of the hill, where several petrified logs are preserved (the "Petrified Grove", MOTT 3869), stratigraphically below the fossils localities, some in upright position.

1) 0 m → 5 m (thickness: 5 m) **lower Boren Ranch sandstone**

Very fine-grained greenish gray (5G 6/1) sandstone, fairly structureless. At about three meters there is a very fine to fine-grained ripple-bedded sandstone about 40 centimeters thick, well cemented and resistant. Petrified logs are found at least two levels; a horizontal log was found at the base of the section, and most of the upright stumps making up the "petrified grove" (MOTT 3869) are just above the discontinuous resistant sandstone. Channel sandstone and lacustrine deposits?

2) 5 m → 7.9 m (thickness: 2.9 m) **Boren Ranch beds**

Greenish gray (5G 6/1) siltstone containing massive siltstone concretions, with thick splotches of dark yellowish orange (10YR 6/6) in the top 20 centimeters. The uppermost part of this unit produced dicynodont material (TTU P-10404) and petrified wood at OS Ranch (MOTT 3867) Site 1. The carbonate bed above it can be roughly traced to Site 2, where it also occurs as a thin bed immediately above the *Paleorhinus* skull (TTU P-11706), which therefore occurs at roughly the same stratigraphic level as the material Site 1. At Site 2, the color of the upper part of the unit is grayish red (5YR 4/2) rather than greenish gray, and contains abundant coprolites. There is a remarkable strongly dipping black layer composed almost entirely of charcoal present near Site 3, also probably just below the carbonate unit; I have never seen anything like this. Lacustrine deposits?

3) 7.9 m → 8.25 m (thickness: .35 m) **Boren Ranch beds**

Moderate yellowish brown (10YR 5/4) carbonate bed. The calcite forms impressive crystal aggregations in geode-like voids, suggesting that the bed is composed almost entirely of calcium carbonate rather than being a calcified soil horizon. This unit is highly irregular in form, sometimes being ripple bedded and strongly dipping as though deposited over an inclined surface, sometimes forming rounded concretionary beds, sometimes being absent and represented only by dark yellowish orange (10YR 6/6) mottled silt as seen at the top of unit 2. Contains some petrified wood. Lacustrine carbonate?

4) 8.25 m → 9.75 m (thickness: 1.5 m) **Boren Ranch beds**

Siltstone with mottling of greenish gray (5G 6/1), grayish red (5R 4/2), and dark yellowish orange (10YR 6/6), in places arranged in dipping bands containing thin (couple centimeter thick) lenses of very fine to fine-grained sandstone. Abundant petrified wood. OS Ranch (MOTT 3867) Site 3 is located near the top of this unit, and OS Ranch East (MOTT 3873) is tentatively placed near its base, as it sits directly above a yellowish carbonate bed possibly correlative with unit 3.

5) 9.75 m → 14.15 m (thickness: 4.4 m) **Boren Ranch beds**

Dusky red (5R 3/4) siltstone with large mottles of dark yellowish orange (10YR 6/6). Contains occasional concretions, very thin (few centimeter thick) pockets of very fine to fine-grained sandstone, and petrified wood. A bone was recovered near the base of the unit.

6) 14.15 m → 16.15 m (thickness: 2 m) **Boren Ranch beds**

Moderate reddish brown (10R 4/6) siltstone with locally dense packages of thin (few centimeter thick) very fine to fine-grained sandstone lenses, and occasional concretions.

7) 16.15 m → 18.65 m (thickness: 2.5 m) **upper Boren Ranch sandstone**

Greenish gray (5G 6/1), very fine-grained, horizontal planar bedded and ripple cross laminated sandstone.

MOTT 3869 (BOREN QUARRY) SITE 1

Vertebrate fossils, mudstone samples

Fluvanna Quadrangle

Total thickness: 20+ m

Fig. A1.4

1) 0→.35 m (thickness: .35 m) **lower unit of the Cooper Canyon Formation**

Very muddy, moderate brown (5YR 4/4) fine-grained sandstone (really just mud with some sand in it), grading up into silty mudstone of the same color in its upper third. Contains a discontinuous lens of well-cemented siltstone to very fine-grained sandstone with no obvious bedding. Overbank deposits. Most of the large vertebrate fossils from the Boren Quarry locality are from stratigraphically a short distance below this level.

2) .35→1.17 m (thickness: .82 m) **lower unit of the Cooper Canyon Formation**

Well cemented, moderate brown (5YR 4/4) siltstone to very fine-grained sandstone, with extremely sparse light greenish gray (5G 8/1) reduction mottling. Overbank deposits.

3) 1.17→3.0 m (thickness: .33 m) **lower unit of the Cooper Canyon Formation**

Moderate reddish-brown (5YR 3/4) siltstone, with greenish gray (5G 6/1) reduced mottled bands at the base and at about 1.5 m, but almost no mottling above that. At about 1.65 m are isolated pockets of grayish red purple (5RP 4/2) pebble conglomerate, and pockets of very fine sand with greenish gray reduction mottling are present near the top. Overbank deposits.

4) 3.0→7.0 (thickness: 4 m) **lower unit of the Cooper Canyon Formation**

Dark reddish brown (10R 3/4) siltstone without mottling, grading up into claystone at about 4 m which contains a couple large greenish gray (5G 6/1) reduction mottles at 5.5 m, with the color becoming moderate brown (5YR 3/4) around 6.5 m. Overbank deposits. Mudstone sample **Neyland-1** was taken at 5.5. m.

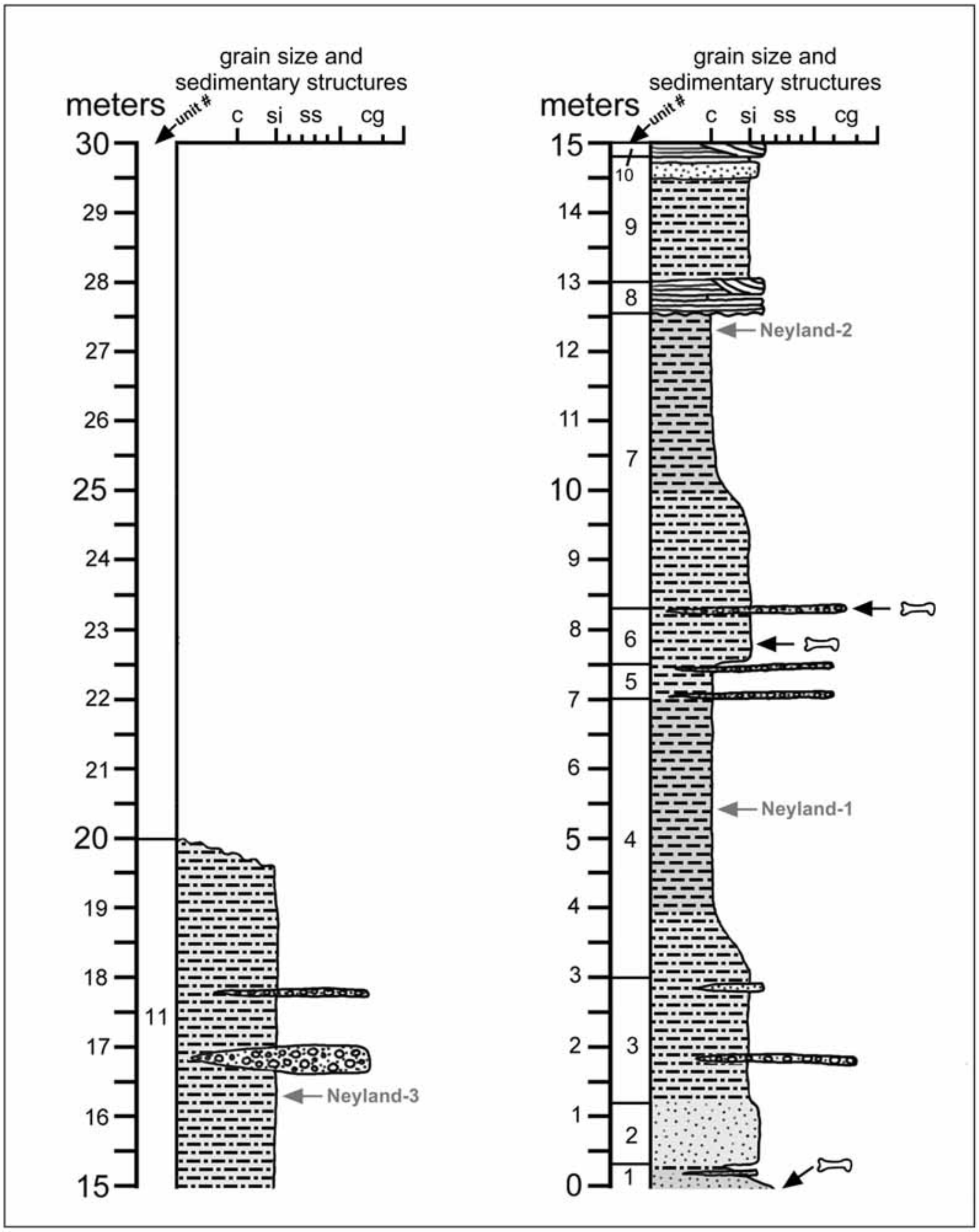

Fig. A1.4. MOTT 3869 (Boren/Neyland Quarry) Site 1 measured section.

5) 7.0→7.5 m (thickness: 1.35 m) **lower unit of the Cooper Canyon Formation**
More moderate brown (5YR 3/4) mudstone containing two lenses of very muddy sedimentary rock clast granule conglomerate about 10 cm thick each at the top and bottom. Overbank deposits.

6) 7.5→8.35 m (thickness: .85 m) **lower unit of the Cooper Canyon Formation**
Dark reddish brown (10R 3/4) siltstone, topped by a muddy sedimentary rock clast granule-pebble conglomerate about 15 cm thick. The conglomerate is the main Site 1 vertebrate horizon, although bone is found in the lower .7 m of silty mud as well. Overbank deposits.

7) 8.35→12.55 m (thickness: 4.2 m) **lower unit of the Cooper Canyon Formation**
More dark reddish brown (10R 3/4) silty mud, grades into mudstone without silt at about 10 m, extremely sparse greenish gray (5G 6/1) reduction mottling also present at about 10 m. Mudstone sample **Neyland-2** was taken directly below the “Neyland sandstone”. Overbank deposits.

8) 12.55→13.0 m (thickness: .45 m) **lower unit of the Cooper Canyon Formation**
Well cemented very fine grained sandstone with both planar bedded and planar cross-bedded layers complexly interbedded with lesser amount of mudstone. The color of the whole unit is mostly dark reddish brown (10 3/4), but the top and bottom 15 cm or so of the sandstone is mottled greenish gray (5G 6/1). Channel sandstone. This sandstone is referred to informally as the “Neyland sandstone”, and is one of the more prominent sandstones in the lower part of the lower unit. It is mapped as “stream channel facies” in Lehman and Chatterjee (2005, fig. 10) map of the “Neyland Quarry.”

9) 13.0→14.8 m (thickness: 1.8 m) **lower unit of the Cooper Canyon Formation**
Dark reddish brown (10R 3/4) siltstone. At 14.5 m begins an extremely well-cementer layer of greenish gray (5G 6/1) silt to very fine sand about 20 cm thick. Overbank deposits.

10) 14.8→15.0 m (thickness: .2 m) **lower unit of the Cooper Canyon Formation**
Well cemented, complexly interbedded horizontal planar and planar cross-bedded very fine-grained sandstone as in unit 8, though probably not as laterally continuous. Channel sandstone.

11) 15.0→20.0 m (thickness: 1.6 m) **lower unit of the Cooper Canyon Formation**
Dark reddish brown (10R 3/4) mudstone with some sand, grading into dark reddish brown (10R3/4), moderate reddish brown (10R 4/6) and grayish red (5R 4/2) silty claystone. Contains lenses of granule to pebble sedimentary rock clast conglomerate, capped unconformably by Quaternary deposits. Overbank deposits and channel gravels. Mudstone sample **Neyland-3** was taken at about 16.3 m.

MOTT 3870 (PATRICIA SITE, SITE 1)

Vertebrate fossils, Mudstone samples

Miller Creek Quadrangle

Total thickness: 28.65 m

Fig. A1.4

This section was measured as a transect from the base of the Kirkpatrick Ranch sandstone some distance from the Patricia Site, up the creek to Site 1. Consequently, the section is a composite of beds and sedimentary structures that show considerable lateral variation. The upper part of this section corresponding to the Macy Ranch sandstone was measured previously by Lehman and Chatterjee (2005, fig. 6A), who interpreted it as oxbow lake facies.

1) 0→1.3 m (thickness: 1.3 m) **upper unit of the Cooper Canyon Formation**
Pale reddish brown (10R 5/4), muddy fine to very fine-grained sandstone with no visible bedding and greenish-gray (5GY 6/1) reduction mottling in a random pattern. Contains a discontinuous granule-pebble conglomeratic sandstone layer (sand-sized grains mostly very-coarse grained, at least some gravel is re-worked fine-grained clastics) about 30 cm thick, with weakly expressed cross beds, and greenish-gray (5GY 6/1) reduction near the bottom. The lens is bounded above and below by 10 cm thick planar beds of fine sand.

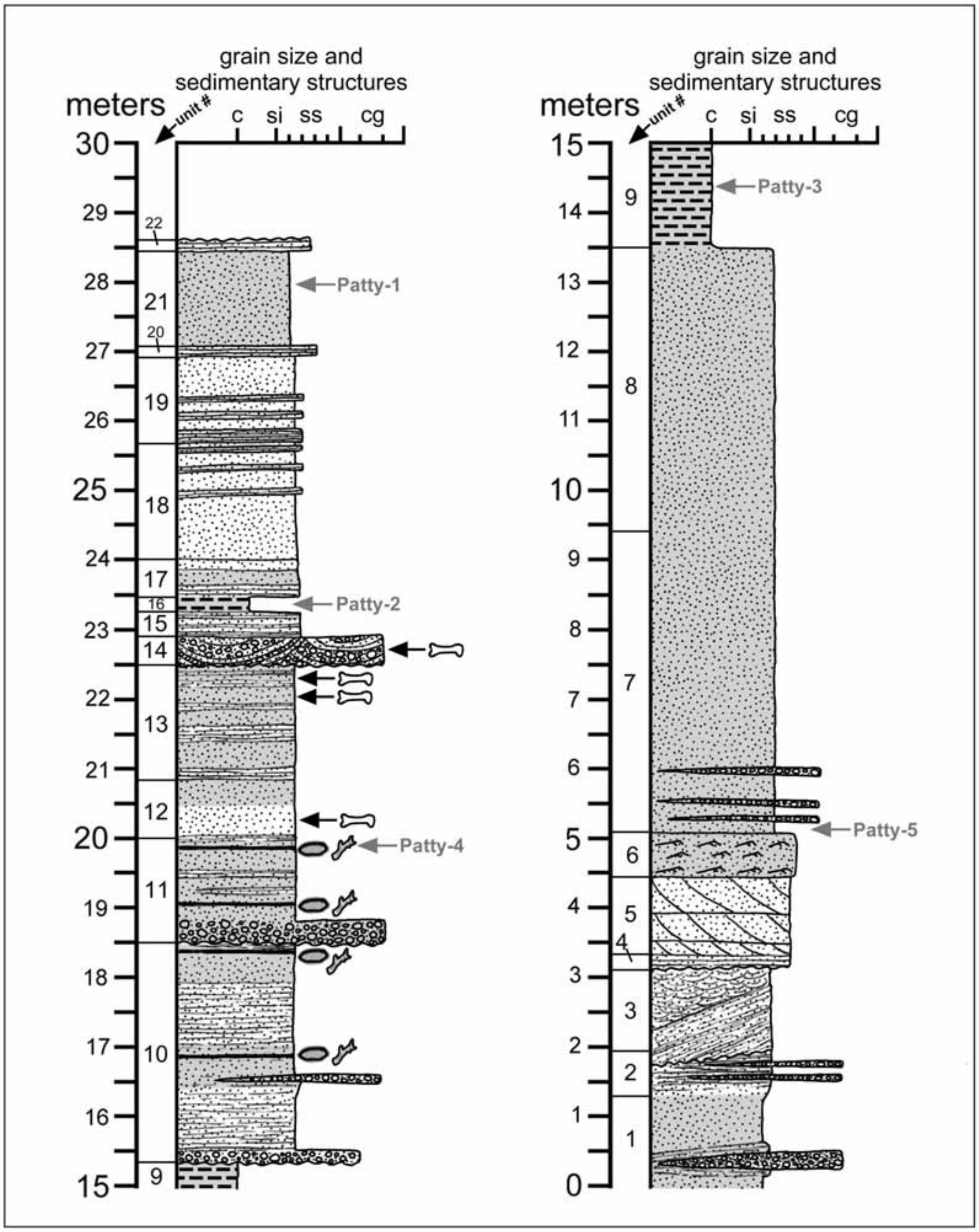

Fig. A1.5. MOTT 3870 (Patricia Site, Site 1) measured section.

The upper part of unit 1 grades laterally into the lower part of unit 2. Overbank deposits with channel gravels.

2) 1.3→1.9 m (thickness: 0.6 m) **upper unit of the Cooper Canyon Formation**

Moderate brown (5YR 5/4), clast supported fine-grained sandstone with horizontal planar bedding and greenish gray (5GY 6/1) reduction spots in a random pattern. A reduced layer of the same color is at the base of the unit. There are thick lenses of cross-bedded granule-pebble conglomeritic sandstone composed of reworked sedimentary rock clasts similar to that in unit one, only thinner (about 10 cm thick). The lenses are bounded above and below by moderate reddish brown (10R 4/6), horizontal planar bedded, clast supported, fine-grained sandstone. The unit varies somewhat in thickness due to truncation from above by unit 3. Overbank deposits with channel gravels.

3) 1.9→3.1 m (thickness: 1.2 m) **Kirkpatrick Ranch sandstone**

Moderate brown (10R 5/4), clast supported, fine-grained sandstone with greenish gray (5GY 6/1) reduction spots in a random pattern, similar to the bulk of unit 2 except that it is dominated locally by large scale cross beds (lateral accretion beds?) and small trough cross beds. Channel deposits.

4) 3.1→3.3 m (thickness: 0.2 m) **Kirkpatrick Ranch sandstone**

Pale reddish brown (10R 5/4) medium grained sandstone with planar bedding. Channel deposits.

5) 3.3→4.4 m (thickness: 1.1 m) **Kirkpatrick Ranch sandstone**

Moderate reddish brown (10R 4/6) medium-grained sandstone with large cross-beds (possibly lateral accretion beds), band of greenish gray (5GY 6/1) reduction at the base. Channel deposits.

6) 4.4→5.1 m (thickness: 0.7 m) **Kirkpatrick Ranch sandstone**

Moderate brown (5YR 4/4), matrix supported, medium to coarse-grained ripple cross-laminated sandstone. Channel deposits.

7) 5.1→9.4 m (thickness: 4.3 m) **upper unit of the Cooper Canyon Formation**

Moderate red orange (10R 6/6), fine-grained, friable, matrix-supported micaceous sandstone with no visible bedding structures, reduction mottles in a random pattern. In the lower half, there are a few lenses of resistant clast-supported cross-bedded granule conglomerate (sand-sized grains mostly medium-coarse sand) generally less than 10 cm thick, moderate brown (5YR 4/4) with greenish gray (5GY 6/1). Mudstone sample **Patty-5** was taken at about 5.4 m. Proximal overbank deposits and small channel gravels.

8) 9.4→13.5 m (thickness: 4.1 m) **upper unit of the Cooper Canyon Formation**

Pale reddish brown (10R 5/4), fine-grained, friable muddy sandstone, no visible bedding structures and very few reduction mottles. Overbank deposits.

9) 13.5→15.4 m (thickness: 1.9 m) **upper unit of the Cooper Canyon Formation**

Grayish red (10R 4/2) claystone with mud clasts and some very fine-fine grained sand, no visible bedding structures, large greenish-gray (5GY 6/1) reduction mottles. There is a solid reduced band of the same color directly below unit 10. Oxbow lake lacustrine deposits. Mudstone sample **Patty-3** was taken from about 14.4 m. Overbank deposits.

10) 15.4→18.5 m (thickness: 3.1 m) **Macy Ranch sandstone**

Greenish gray (5GY 6/1) sandstone and conglomerate. The section mostly consists of interbedded clast-supported horizontal planar bedded very fine to fine-grained sandstone and matrix supported (very muddy) very fine to fine-grained sandstone lacking any visible bedding and often fining up into sandy claystone, with less common lenses of claystone and granule to pebble conglomerate composed of reworked sedimentary rock clasts. Such conglomerate forms the base of the unit, resting on the unconformity with the previous unit. The muddy sandstone and claystone often contain coal, recognizable carbonized plant material, and dark yellowish orange (10YR 6/6) concretions. Oxbow lake lacustrine deposits

11) 18.5→20 m (thickness: 1.5 m) **Macy Ranch sandstone**

Greenish gray (5GY 6/1) sandstone and conglomerate, as in previous unit. The section mostly consists of interbedded clast-supported horizontal planar bedded very fine to fine-grained sandstone and matrix supported (very muddy) very fine to fine-grained sandstone lacking any visible bedding and often fining up into sandy claystone, with less common lenses of claystone and granule to pebble conglomerate composed of reworked sedimentary rock clasts. Such conglomerate forms the base of the unit, resting on the unconformity with the previous unit. The muddy sandstone and claystone often contain coal, recognizable carbonized plant material, and dark yellowish orange (10YR 6/6) concretions. Mudstone sample **Patty-4** was taken from the sandy claystone at about 19.9 m. Oxbow lake lacustrine deposits

12) 20→20.8 m (thickness: 0.8 m) **Macy Ranch sandstone**

Moderate yellow (5Y 7/6) very fine to fine-grained sandstone lacking any visible bedding structure, grading up into greenish gray (5GY 6/1) matrix supported very fine to grained sandstone also lacking any apparent bedding structure. An un-numbered TTUP articulated phytosaur skeleton lacking a skull comes from the yellowish part of the unit, and Site 1b which produced the crested *Pseudopalatus* sp. nov. skull (TTU P-10077, "Andy") comes from approximately the same level, and so does the isolated theropod tibia (TTU P-10534) found at Patty East on the other side of the ridge. Although generally similar to the previous two units, neither this unit nor any higher within the Macy Ranch sandstone are as muddy or rich in coal, plant material, and concretions. Oxbow lake lacustrine deposits

13) 20.8→22.5 m (thickness: 1.7 m) **Macy Ranch sandstone**

Interbedded greenish gray (5GY 6/1) horizontal planar bedded fine to very fine-grained clast supported sandstone, and greenish gray (5GY 6/1), matrix-supported very fine to fine-grained sandstone lacking any visible bedding structure. Most of the Patricia Site (Site 1) vertebrate material comes from this unit. A *Pseudopalatus* sp. skull (TTU P-10074, "Patty") came from one of the muddy levels at about 1 m above the base of the unit, a phytosaur pelvis and femur came from the next and last muddy level at 1.2 m above the base of the unit, and a *Pseudopalatus* ("*Macysuchus*") sp. skull (TTU P-11423, "Spike") came from approximately the same level. Oxbow lake lacustrine deposits

14) 22.5→22.9 m (thickness: 0.4 m) **Macy Ranch sandstone**

Light brown (5YR 6/4) horizontal planar bedded fine to very fine-grained clast supported sandstone as in previous units, complexly interbedded with pebble conglomerate with rip up clasts of fine grained sedimentary rocks. The whole unit is broadly trough cross bedded, and becomes dominated by the conglomerate higher up. A fragmentary

Pseudopalatus buceros or *P. pristinus* skull (TTU P-10075) and a fragmentary *Typothorax coccinarum* osteoderm come from this level, as well as unidentified fish material (TUU P-10721). Channel deposits.

15) 22.9→23.25 m (thickness: 0.35 m) **uppermost beds**

Light gray (N7) fine grained, clast-supported horizontal planar-bedded sandstone with some interbedded layers lacking planar bedding. The top and bottom 10 cm or so are more resistant, though there is no obvious difference in lithology. Proximal overbank deposits?

16) 23.25→23.45 m (thickness: 0.2 m) **uppermost beds**

Reddish brown (5YR 4/4) silty claystone. Proximal overbank deposits?

17) 23.45→24 m (thickness: .55 m) **uppermost beds**

Pale olive (10Y 6/2) very fine to fine-grained sandstone, clast supported with faint horizontal planar bedding near the base, a matrix-supported section in the middle with biotite flakes , and capped by clast-supported sandstone lacking any visible bedding. Mudstone sample **Patty-2** was taken from the middle of the unit. Proximal overbank deposits?

18) 24→25.65 m (thickness: 1.65 m) **uppermost beds**

Moderate reddish brown (5YR 4/4), very fine to fine-grained, resistant sandstone containing perhaps three layers of slightly more resistant fine-grained very faintly horizontal planar bedded sandstone of the same color. High in the unit are a few very thin pale olive (10Y 6/2) reduction bands in a layered pattern. There is also a reduced band of the same color at the top of the unit. Proximal overbank deposits?

19) 25.65→26.9 m (thickness: 1.25 m) **uppermost beds**

Yellowish gray (5Y 8/1) horizontal planar bedded fine-grained sandstone, grading up into more faintly bedded very fine-grained sandstone. Proximal overbank deposits?

20) 26.9→27.05 m (thickness: 0.15 m) **uppermost beds**

Light olive gray (5Y 6/1) speckled with black horizontal planar bedded clast-supported medium-grained sand. Proximal overbank deposits?

21) 27.05→28.45 m (thickness: 1.4 m) **uppermost beds**

Pale olive (10Y 6/2) grading into moderate reddish brown (10R 4/6) friable matrix-supported very fine grained micaceous sandstone lacking any visible bedding structures. Mudstone sample **Patty-1** was taken at about 28 m. Proximal overbank deposits?

22) 28.45→28.65 m (thickness: 0.2 m) **uppermost beds**

Pale red (10R 6/2) well-cemented horizontal planar bedded fine to medium-grained sandstone. Capped unconformably by the Ogallala Sandstone. Proximal overbank deposits?

MOTT 3870 (PATRICIA SITE, SITE 2)

Vertebrate fossils

Miller Creek Quadrangle

Total thickness: 15.24

Fig. A1.6

1) 0 → 0.6 m (thickness: 0.6 m) **upper unit of the Cooper Canyon Formation**

Moderate brown (5YR 4/4) very fine-grained sandstone with greenish gray (5GY 6/1) reduction mottling, grading upwards into very fine-grained muddy sandstone in the upper 30 cm.

2) 0.6 → 1.1 m (thickness: 0.5 m) **Macy Ranch sandstone**

Generally greenish gray (5GY 6/1) resistant matrix-supported granule to pebble conglomerate lacking any visible bedding features, clasts of reworked sedimentary rocks. The unconformable base of this unit is equivalent to the base of the Macy Ranch sandstone at Site 1.

3) 1.1 → 2.7 m (thickness: 1.6 m) **Macy Ranch sandstone**

Pale yellowish brown (10YR 6/2) resistant clast-supported very fine-grained sandstone with some horizontal planar bedding, grading into moderate brown (5YR 4/4) matrix-supported very fine-grained sandstone, containing a discontinuous lens of the fine grained clast supported sandstone.

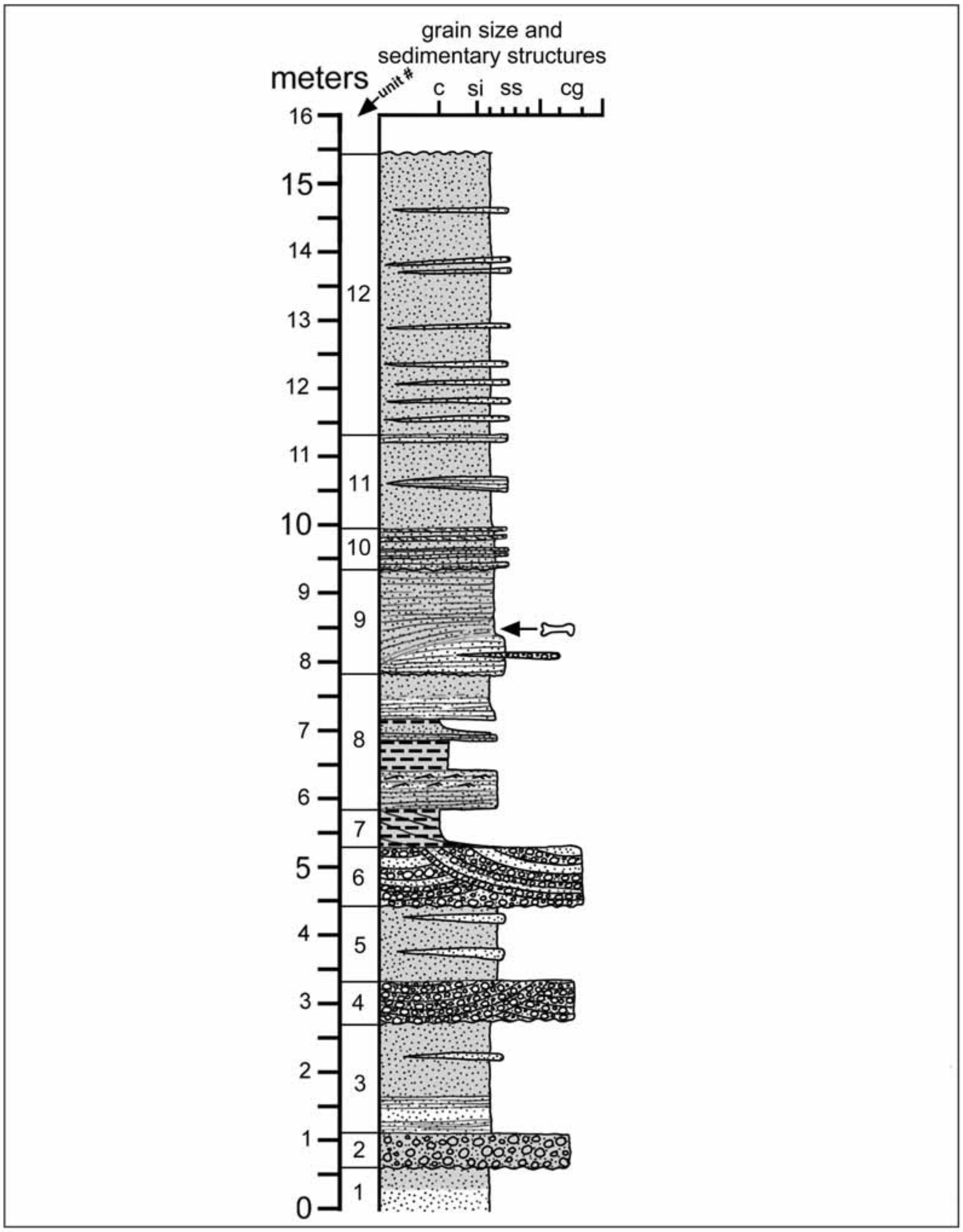

Fig. A1.6. MOTT 3870 (Patricia Site, Site 2) measured section.

4) 2.7 → 3.3 m (thickness: 0.6 m) **Macy Ranch sandstone**

Generally moderate brown (5YR 4/4) laterally discontinuous resistant clast supported granule-pebble conglomerate with very distinct trough cross bedding. The top is reduced greenish gray (5G 6/1).

5) 3.3 → 4.4 m (thickness: 1.1 m) **Macy Ranch sandstone**

Moderate reddish brown (10R 4/6) horizontal planar bedded very fine-fine grained matrix supported sandstone, containing a couple lenses of resistant pale reddish brown (10R 5/4) clast-supported fine-grained sandstone.

6) 4.4 → 5.3 m (thickness: 0.9 m) **Macy Ranch sandstone**

Complexly interbedded section of clast-supported pebble conglomerate and discontinuous lenses of well cemented, trough cross bedded, light brown (5YR 6/4) fine grained sandstone, with the sandstone gradually becoming more prominent, and the upper conglomeratic beds becoming mudstone with very coarse gravel sized clasts, grading into next unit. The base of the unit is heavily reduced greenish gray (5G 6/1).

7) 5.3 → 5.8 m (thickness: 0.5 m) **Macy Ranch sandstone**

Light brown (5YR 6/4) mudstone with some very coarse gravel sized mud clasts with weak large scale planar cross beds (possibly lateral accretion bedding), containing a few very thin (a couple centimeters thick) reduced greenish gray (5G 6/1) resistant fine-grained clast-supported sandstone lenses.

8) 5.8 → 7.8 m (thickness: 2 m) **Macy Ranch sandstone**

Light brown (5YR 6/4) and moderate brown (5YR 3/4) matrix-supported very fine to fine grained matrix-supported sandstone with weak horizontal planar bedding, interbedded with some pale reddish brown (10R 5/4) resistant clast-supported very fine to fine-grained sandstone with horizontal planar bedding and ripple cross lamination, and moderate brown (5YR 4/4) silty mudstone with greenish gray (5G 6/1) reduction.

9) 7.8 → 9.35 m (thickness: 1.55 m) **Macy Ranch sandstone**

Moderate brown (5YR 3/4) clast-supported fine-grained sandstone with large scale cross beds, containing at least one lens of gravel conglomerate with clasts of reworked siltstone, grading up into moderate brown (5YR 3/4) matrix supported very fine to fine-grained sandstone with weak horizontal planar bedding., with a reduced greenish gray (5GY 6/1) layer at the top. The Site 2 bone bed is in the lower part of the unit, in and just above the cross-bedded base of the unit, and is approximately equivalent to the main Site 1 bone-producing unit (unit 13) at Site 1. The holotype of *Pseudopalatus* nov. sp. (TTU P-10076, "Poppa John") came from the same stratigraphic level at Site 3 a short distance away.

10) 9.35 → 9.95 m (thickness: 0.6 m) **Macy Ranch sandstone**

Greenish gray (5GY 6/1) matrix supported very fine to fine-grained sandstone, interbedded with clast supported fine to medium grained sandstone with horizontal planar bedding and large cross bedding. This unit is correlative with the conglomeritic unit capping the main bone bed at Site 1 (unit 14).

11) 9.95 → 11.35 m (thickness: 1.4 m) **uppermost beds**

Greenish gray (5GY 6/1) matrix supported very fine-grained sandstone with some interbedded clast-supported fine to medium-grained sandstone with horizontal planar bedding.

12) 11.35 → 15.45 m (thickness: 4.1 m) **uppermost beds**

Moderate brown (5YR 3/4) matrix supported very fine-grained sandstone, containing about a half dozen discontinuous very thin (a few centimeters thick) lenses of pale reddish brown (10R 5/4) fine to medium grained horizontal planar bedded sandstone, and a few randomly spaced greenish gray (5GY 6/1) reduction spots. Unconformable upper contact with the Ogallala Formation.

MOTT 3879 (LOTT HILL)

N33°01'12" W101°25'56"

Vertebrate fossils

Middle Creek Quadrangle

Total thickness: 6.45 m

Fig. A1.7

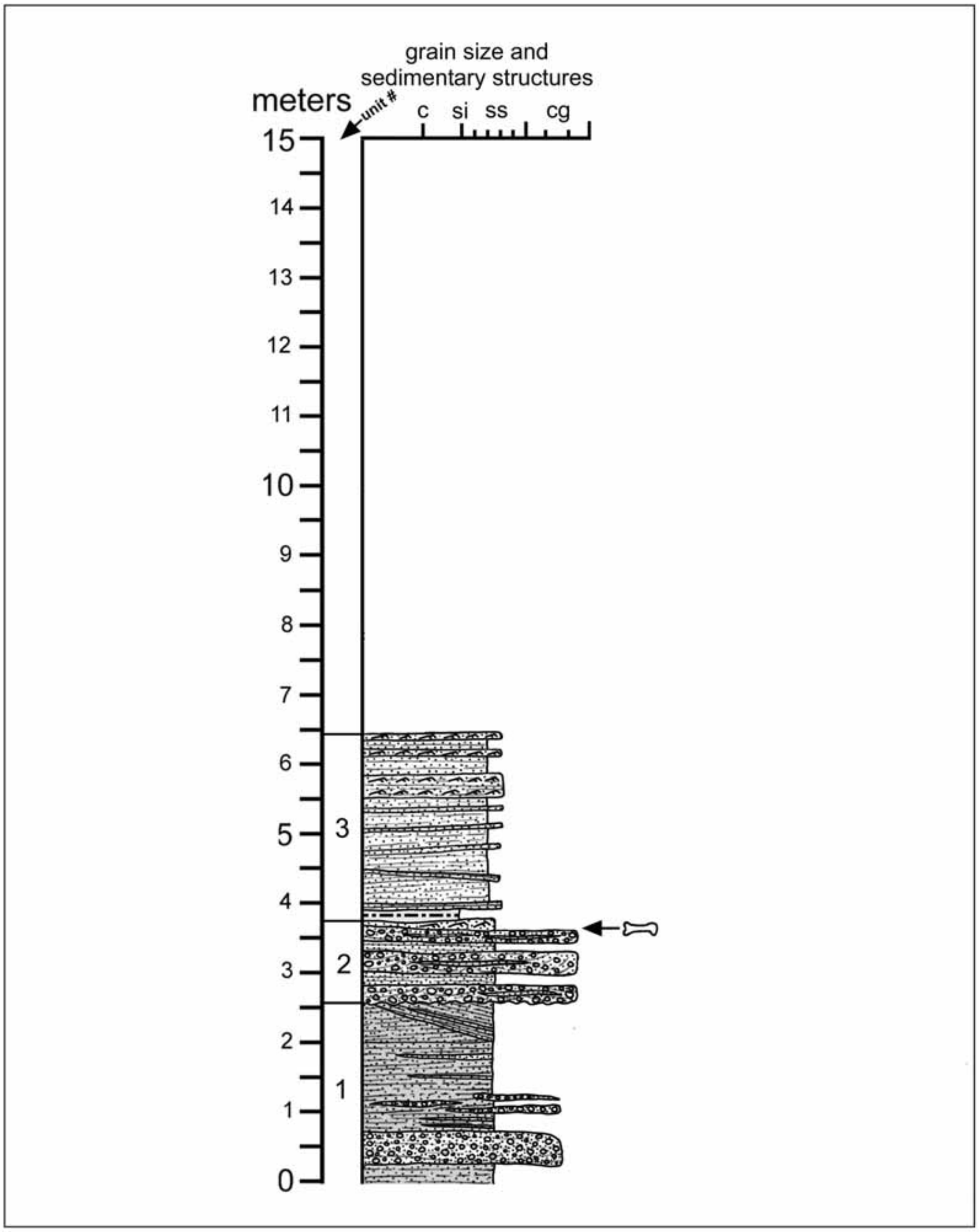

Fig. A1.7. MOTT 3879 (Lott Hill) measured section.

1) 0 m → 2.6 m (thickness: 2.6 m) **middle unit of the Cooper Canyon Formation**
Muddy fine to medium-grained sand with horizontal parallel lamination, intensely interbedded with thin (less than 1 cm) discontinuous layers of fine to medium-grained clast-supported sandstone (also horizontal parallel laminated) and fairly well-cemented sedimentary rock clast granule-pebble conglomerate, all with some reduction mottling. In the top meter or so, the well-cemented sandstone layers show higher degrees of dip and cross cutting. Overbank deposits, sheet floods, and channel gravels.

2) 2.6 m → 3.75 m (thickness: 1.15 m) **middle unit of the Cooper Canyon Formation**
Trough cross-bedded sedimentary rock clast pebble conglomerate, coarser than the lenses seen below (larger grain size generally 1-2 cm) although vertebrate bones and mudstone rip-up clasts also present, interbedded with fine to medium-grained, horizontal parallel laminated and (near the top) ripple cross laminated micaceous sandstones, mostly clast-supported although thin lenses of muddy sandstone are also interbedded. The vertebrate material recovered from this locality came from the conglomeritic beds of this unit, either in situ or as float.

3) 3.75 m → 6.45 m (thickness: 2.7 m) **middle unit of the Cooper Canyon Formation**
Siltstone and muddy fine-grained horizontal parallel laminated fine-grained sandstone, interbedded with horizontal parallel laminated and ripple cross-laminated clast-supported fine to medium-grained sandstone.

MOTT 3881 (MEYER'S HILL)

N32°58'47" W101°11'57"

Vertebrate fossils, mudstone samples

Fluvanna Quadrangle

Total thickness: 39.45 m

Fig. A1.8

The Meyer's Hill section represents the lower part of the section continued in the Parks Cliffside section, and together they span almost the entire thickness of the Cooper Canyon Formation in southeast Garza County except for the very base capping the Boren

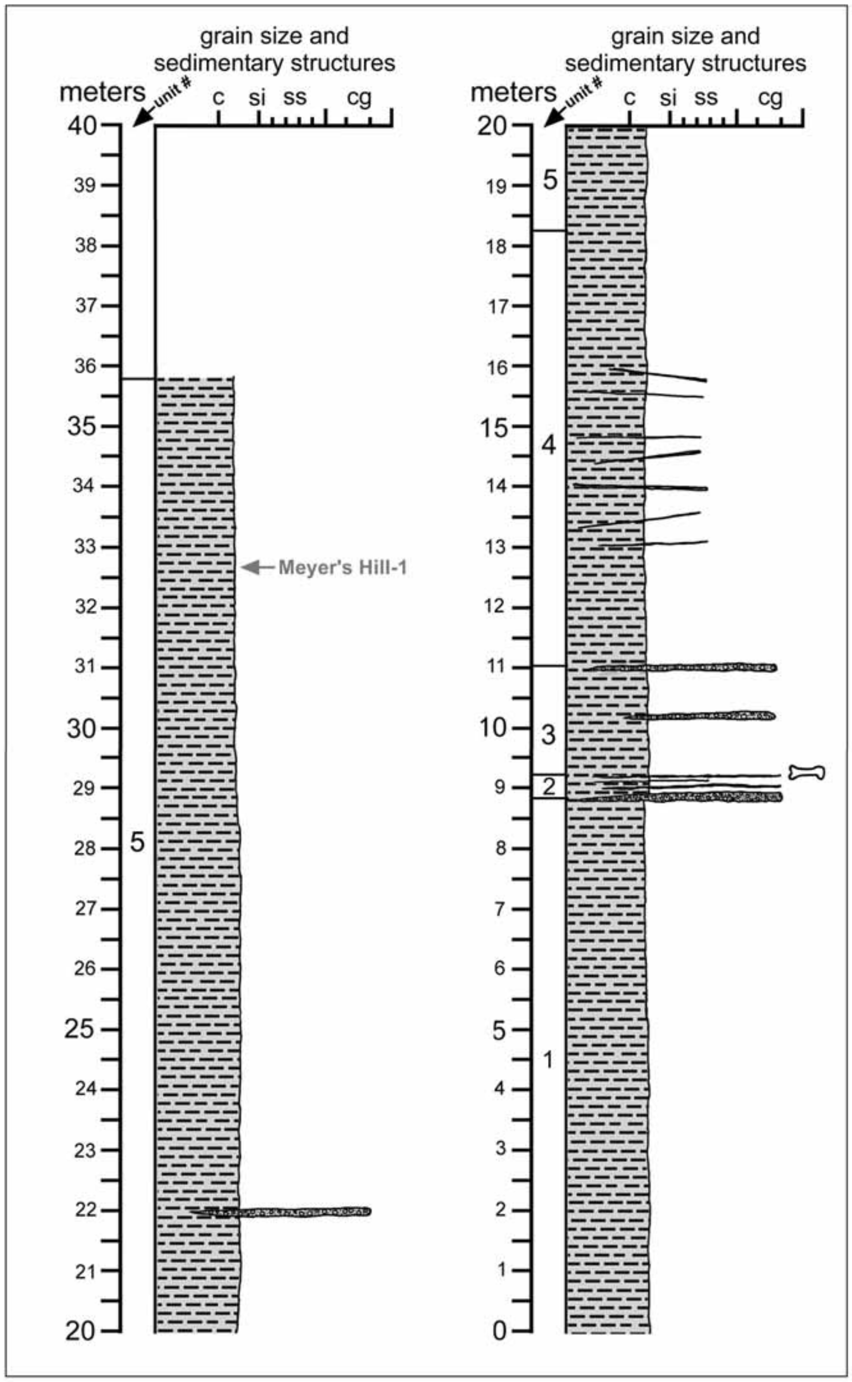

Fig.A1.8. MOTT 3881 (Meyer's Hill) measured section.

Ranch sandstone a short distance to the north. What is striking about these combined sections is that laterally persistent sandstone and conglomeritic units are strikingly rare with the exception of the Dalby Ranch sandstone, and the transition between the middle and upper units of the Cooper Canyon Formation (which is arbitrary anyway) is difficult to place. Consequently, these units are simply referred to jointly here as the “Cooper Canyon Formation.” Sandstone and gravel channel deposits and sheet sands occur throughout the section, but tend to be very thin and are not laterally extensive. At Meyer’s Hill itself, the Dalby Ranch sandstone is eroded away, leaving only a few remnants on top of the hill.

1) 0 → 8.8 m (thickness: 8.8 m) **lower unit of the Cooper Canyon Formation**
Dark reddish brown (10R 3/4) silty claystone with greenish gray (5GY 6/1) reduction mottling. Thick but laterally confined sandstone units are present at this level in nearby exposures, but not at Meyer’s Hill itself. Overbank deposits.

2) 8.8 m → 9.2 m (thickness: .4 m) **lower unit of the Cooper Canyon Formation**
Muddy very coarse-grained sandstone and pebble conglomerate, densely interbedded with ripple cross-laminated fine to medium-grained sandstone and silty claystone. This coarse-grained unit is laterally discontinuous. The dicynodont humerus (TTU P-10241) was recovered from the top of this unit. Channel deposits.

3) 9.2 m → 11.05 (thickness: 1.85 m) **lower unit of the Cooper Canyon Formation**
Siltstone interbedded with discontinuous lenses of muddy very coarse-grained sand and pebble conglomerate. Overbank deposits and small channel sandstones.

4) 11.05 m → 18.25 m (thickness: 7.2 m) **lower unit of Cooper Canyon Formation**
Siltstone, color alternating between pale reddish brown (10R 5/4) and medium reddish brown (10R 4/6), with random mottles of greenish gray (5GY 6/1) reduction and dark yellowish orange (10YR 6/6). In the middle of the unit is a section about three meters thick containing numerous thin (only a couple centimeters thick) discontinuous lenses of ripple cross laminated very fine to medium-grained sandstone, often mottled greenish gray (5GY 6/1). Overbank deposits and sheet sands.

5) 18.25 m → 35.75 m (thickness: 17.5 m) **lower unit of Cooper Canyon Formation**
Siltstone with a subtle color change from the previous unit to dark reddish brown (10R 3/4), with thin stringers of greenish gray (5GY 6/1) reduction, sometimes containing gypsum (probably postdepositional). There are a couple scattered lenses of pebble conglomerate. The upper meter or so (measured on adjacent Cliffside immediately below the Dalby Ranch sandstone) is mottled light greenish gray (5GY 8/1), dusky yellow (5Y 6/4), and dark reddish brown (10R 3/4). Mudstone sample **Meyer's Hill-1** was taken from the upper part of this unit. Scraps of the Dalby Ranch sandstone remain on top of Meyer's Hill, but the unit is not intact there (see Parks Cliffside Section).

MOTT 3882 (UU SAND CREEK)

Vertebrate fossils, mudstone samples

Post East Quadrangle

Total thickness: 6.26 m

Fig. A1.9

The conglomeritic sandstone which produced the holotype of *Libognathus* and the new aetosaur specimen is assigned, with reservations, to the Miller Ranch sandstone. The Miller Ranch sandstone seems to consist of two or more closely associated sandstones in this area, and it may be that more detailed mapping will reveal that this discontinuous conglomeritic bed is better considered to be associated with the Miller Ranch sandstone rather than being assigned to it.

1) 0→1 m (thickness: 1 m) **middle unit of the Cooper Canyon Formation**
Moderate brown (5YR 4/4) siltstone to very fine-grained sand with no obvious bedding, containing large (10-20 cm across), widely spaced, very light gray (N8) reduction mottles in a random pattern. Overbank deposits.

2) 1→1.53 m (thickness: .53 m) **Miller Ranch sandstone?**
Base of unit is a mostly moderate reddish brown (10R 4/6) matrix-supported pebble-granule conglomerate, thin here (10-20 cm) but thickening to 1 m or more nearby, with sparse light bluish gray (5B 7/1) reduction mottling, fining upward into moderate brown

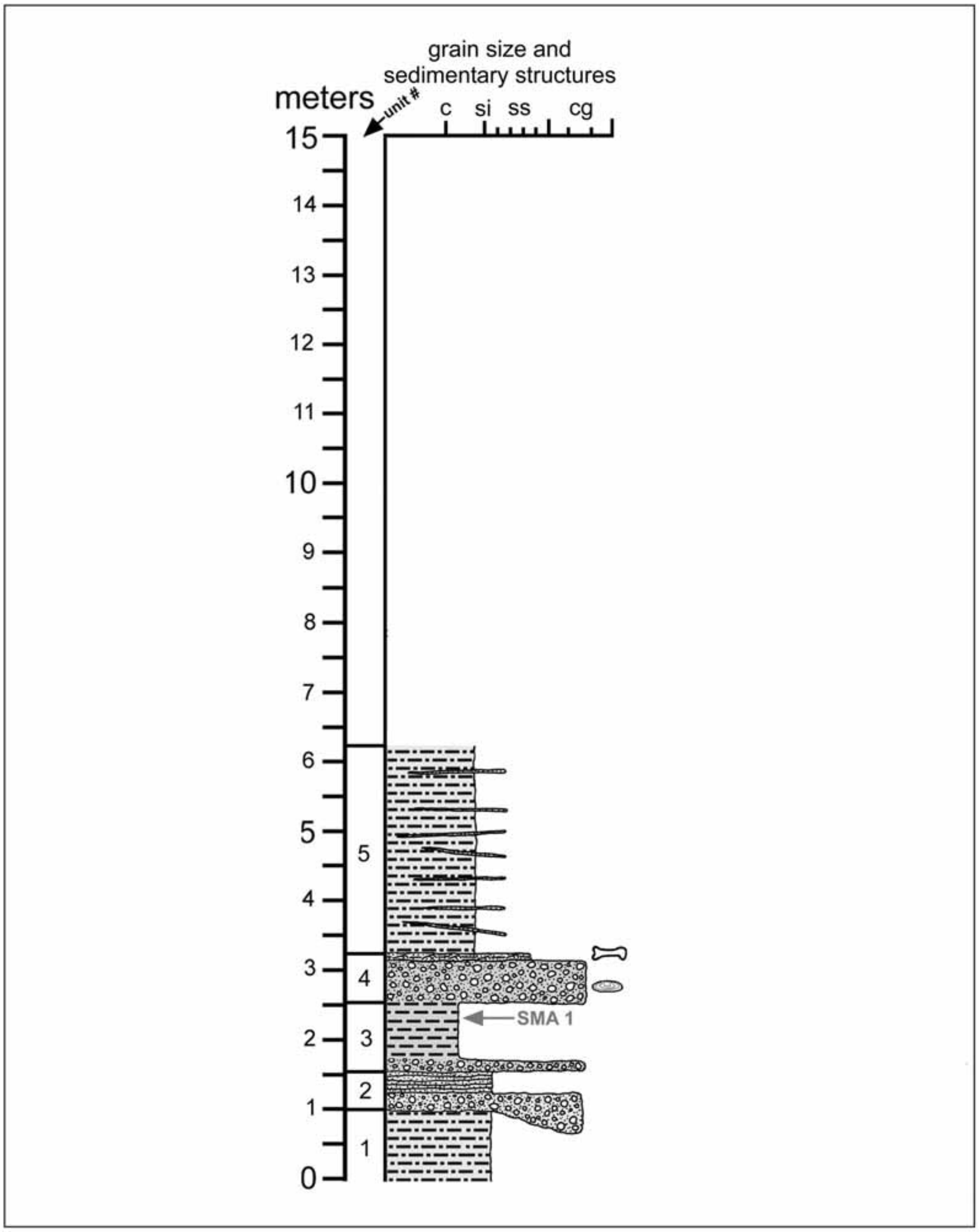

Fig. A1.9. MOTT 3882 (UU Sand Creek) measured section.

(5YR 4/4) matrix supported silt to very fine-grained sand with faint horizontal planar bedding. The contact with the overlying unit is somewhat gradational. Channel deposits.

3) 1.53→2.56 m (thickness: 1.03 m) **Miller Ranch sandstone?**

Base of unit a matrix-supported granule-pebble reworked sedimentary rock clast conglomerate, grading upward moderate reddish brown (10R 4/6) very silty claystone with occasional coarse to very coarse-grained sandstone clasts, with very fine (millimeter scale) light bluish gray (5B 7/1) reduction mottling. Channel deposits. Mudstone sample **SMA-1** (not analyzed) was collected from the top of the unit.

4) 2.56→3.26 m (thickness: .7 m) **Miller Ranch sandstone?**

Mostly moderate reddish brown (10R 4/6) matrix-supported granule-pebble conglomerate, made up in some places almost entirely of bivalves, fines upwards into a 10 cm thick medium to coarse-grained sandstone with horizontal planar bedding and ripple cross lamination containing patchy reduction mottling. The specimen of cf. *Rioarribasuchus* (TTU P-10449) and the holotype of *Libognathus sheddi* (DMNS 20491) comes from the top of this unit. Channel gravels.

5) 3.26→6.26 m (thickness: ~3 m) **upper? unit of the Cooper Canyon Formation**

Moderate brown (5YR 4/4) siltstone with a few very thin (a few centimeters or less thick) interbedded layers of reduced very fine to fine-grained horizontal planar-bedded sandstone, some tilted a few degrees. Overbank deposits.

MOTT 3883 (UU RAILROAD FLATS)

Vertebrate fossils, mudstone samples

Post East Quadrangle

Total thickness: 11.5 m

Fig. A1.10

This section was measured as a transect from the vertebrate localities, located on the flats north of the railroad just southeast of Post, to the side of a nearby low cliff to the southwest capped by a complexly interbedded series of sandstones and mudrocks considered to be part of the Miller Ranch sandstone. Though they probably lie

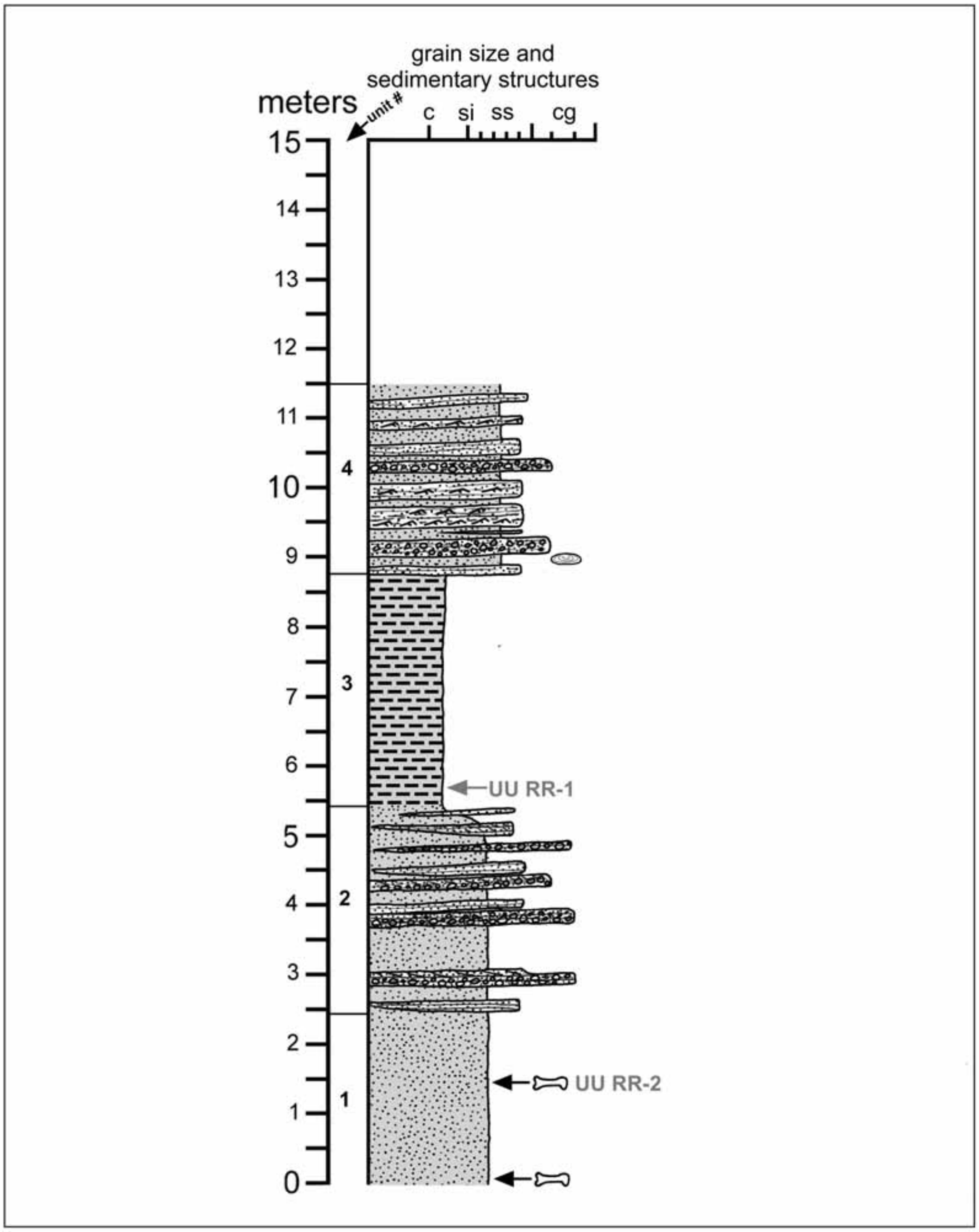

Fig. A1.10. MOTT 3883 (UU RR Flats) measured section.

stratigraphically a little below the distinct sandstones capping mesas along Highway 84, they are still distinctly above the Dalby Ranch sandstone. The thickness of unit 2, which covers the part of the section between the localities and the cliff face, must be considered an approximation.

1) 0 m → 2.4 m (thickness: 2.4 m) **middle unit of the Cooper Canyon Formation**

Muddy fine to very fine-grained, mostly nonresistant sandstone, changing in color from reduced greenish gray (5GY 6/1) in the lower .5 m to moderate brown (5YR 4/4) with sparse random greenish gray (5G 6/1) reduction mottling, gets increasingly muddy near the top. An un-excavated phytosaur skull is still present in lower gray part of the unit, and the rest of the vertebrate material from this locality comes from about 1.5 m above the base of the unit. Mudstone sample **UURR-2** come from about the same level as the latter. Proximal overbank deposits?

2) 2.4 m → 5.4 m (thickness: 3.0 m) **middle unit of the Cooper Canyon Formation**

Complexly interbedded unit. Moderate brown (5YR 4/4) muddy fine to very fine-grained sandstone, complexly interbedded with more resistant horizontal planar bedded and cross bedded sandstone and conglomeratic units generally between about 10 and 40 cm thick, with largest grain size ranging from coarse sand to pebble. Proximal overbank deposits and small channel sandstones and conglomerates?

3) 5.4 m → 8.7 m (thickness: 3.3 m) **middle unit of the Cooper Canyon Formation**

Dark reddish brown (10R 3/4) silty claystone with very fine greenish gray (5G 6/1) reduction mottling. Mudstone sample **UURR-1** comes from about 20 cm above the base of the unit. Overbank deposits.

4) 8.7 m → 11.5 m (thickness: 2.8 m) **Miller Ranch sandstone**

Complexly interbedded unit. Dominantly somewhat resistant horizontal planar and ripple cross laminated sandstone and conglomeritic units generally between 10 to 30 cm in thickness, with maximum grain size generally ranging from medium sand to granule, interbedded with less resistant very muddy fine to medium grained sand. The ground below the unit is littered with bivalves, which appear to be mostly weathering out of the lowest muddy sandstone layer. Channel deposits?

MOTT 3890 (LAKE ALAN HENRY-CEDAR HILL)

N33°02’44” W101°06’26”

Vertebrate fossils, mudstone samples, petrographic samples

Justiceburg SE Quadrangle

Total thickness: 25.5 m

Fig. A1.11

Cedar Hill (not to be confused with Cedar Mountain in Crosby County) is located in the Lake Alan Henry Sam Wahl Recreational Area. The section consists entirely of the Boren Ranch Sandston, which is divided by a thick mudstone lens separating the lower and upper parts of the unit. The *Paleorhinus scurriensis* skull (TTU P-11422) was allegedly recovered from the top of the cliff capped by the upper sandstone.

1) 0 m → 6 m (thickness: 6 m) **Boren Ranch sandstone (lower sandstone)**

Primarily clast-supported, fine-grained to medium-grained grayish sandstone. The lower 1.5 meters is massive without any obvious structure, followed by 1 meter of horizontal planar bedded sandstone with a few interbedded thin (10-15 cm thick) lenses of clast supported granule to pebble sedimentary rock clast conglomeratic sandstone, followed by 3.3 m of cross-bedded sandstone containing petrified wood associated with orange-brown concretions. Channel deposits. Thin section sample <u>LAH (ss) 1</u> came from the cross-bedded unit.

2) 6 m → 18.5 m (thickness: 12 m) **Boren Ranch sandstone (mudstone unit)**

Dominated by almost pure claystone with minor siltstone. Colors in the lower part of the unit vary from moderate olive brown (5Y 4/4) to dark greenish gray (5GY 4/1) to brownish gray (5YR 4/1). Above about 13 m, the color is dominantly moderate brown (5YR 3/4). There are a few thin, coarser grained lenses of siltstone and very fine to medium-grained sandstone, mostly less than 10 cm thick, scattered throughout. The color shift in the claystone takes place directly above one of these, a medium-grained sandstone layer. Mudstone sample **Cedar Hill-1** comes from the lower two meters of the section. Lacustrine and/or overbank deposits?

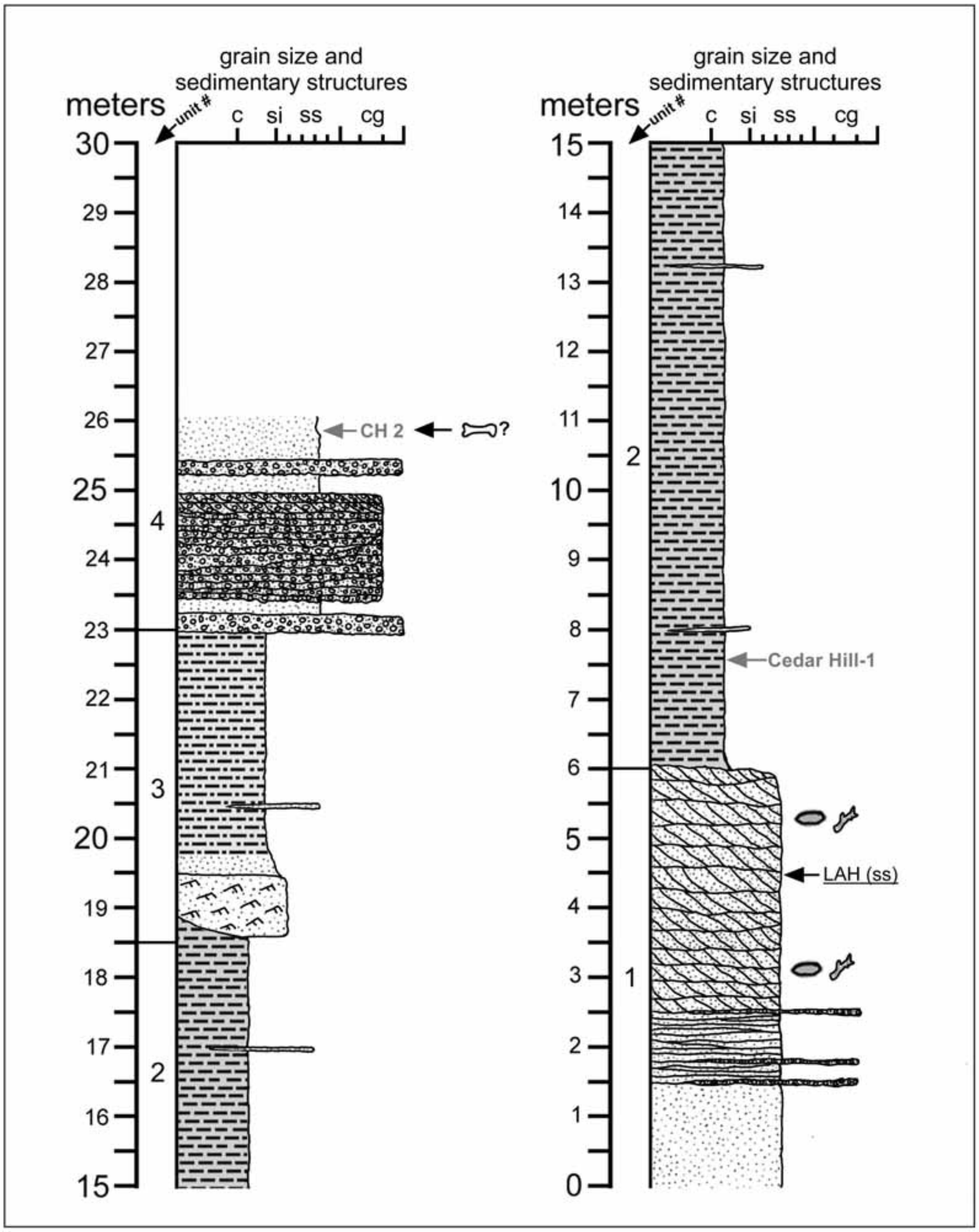

Fig. A1.11. MOTT 3890 (Lake Alan Henry-Cedar Hill) measured section.

3) 18.5 m → 19.5 m (thickness: .75 m) **Boren Ranch sandstone (mudstone unit)** Prominent well-cemented, very fine-grained, reddish-brown sandstone with ripple bedding. The thickness of this unit varies across the outcrop. Small channel deposits?

4) 19.5 m → 23 m (thickness: 3.5 m) **Boren Ranch sandstone (mudstone unit)** Generally fining upward sequence; about 30 cm of muddy very fine-grained sandstone followed by muddy silt, all moderate brown (5YR 3/4). There is a siliceous medium-grained to coarse-grained sandstone lens about 1.25 meters above the previous unit. Overbank deposits.

5) 23 m → 26 m (thickness: 3 m) **Boren Ranch sandstone (upper sandstone)** Dominantly sedimentary rock clast conglomeritic sandstone. The thickest part of the unit is pebble conglomerate dominated by faint horizontal planar bedding, except for about 20 cm of cross-bedding at the top, but some thinner conglomeritic layers have clasts reaching cobble size, and there are thin layers of friable medium grained to coarse-grained sandstone. The upper 75 cm or so is all sandstone, and thin section sample <u>LAH (ss) 2</u> was collected here. This is the top of the hill, and the outcrop becomes concealed by vegetation. The *Paleorhinus* skull was allegedly collected from somewhere at the top of the hill.

MOTT 3892 (HEADQUARTERS SITE)

Vertebrate fossils

Middle Creek Quadrangle

Total thickness: 6.0 m

Figs. 2.24b, A1.12a

The drainage in which the Headquarters sites are located is capped by the Miller Ranch sandstone, and criss-crossed by numerous low order channel sands and gravels interbedded in overbank deposits. The Headquarters Site and the Headquarters South Site are less than 100 feet apart, with the bone bed at both localities coming from the same gravelly low-order ribbon sand exposed in cross-section across the face of the outcrop. To the north of the main site (the first discovered), the channel sand is thickest,

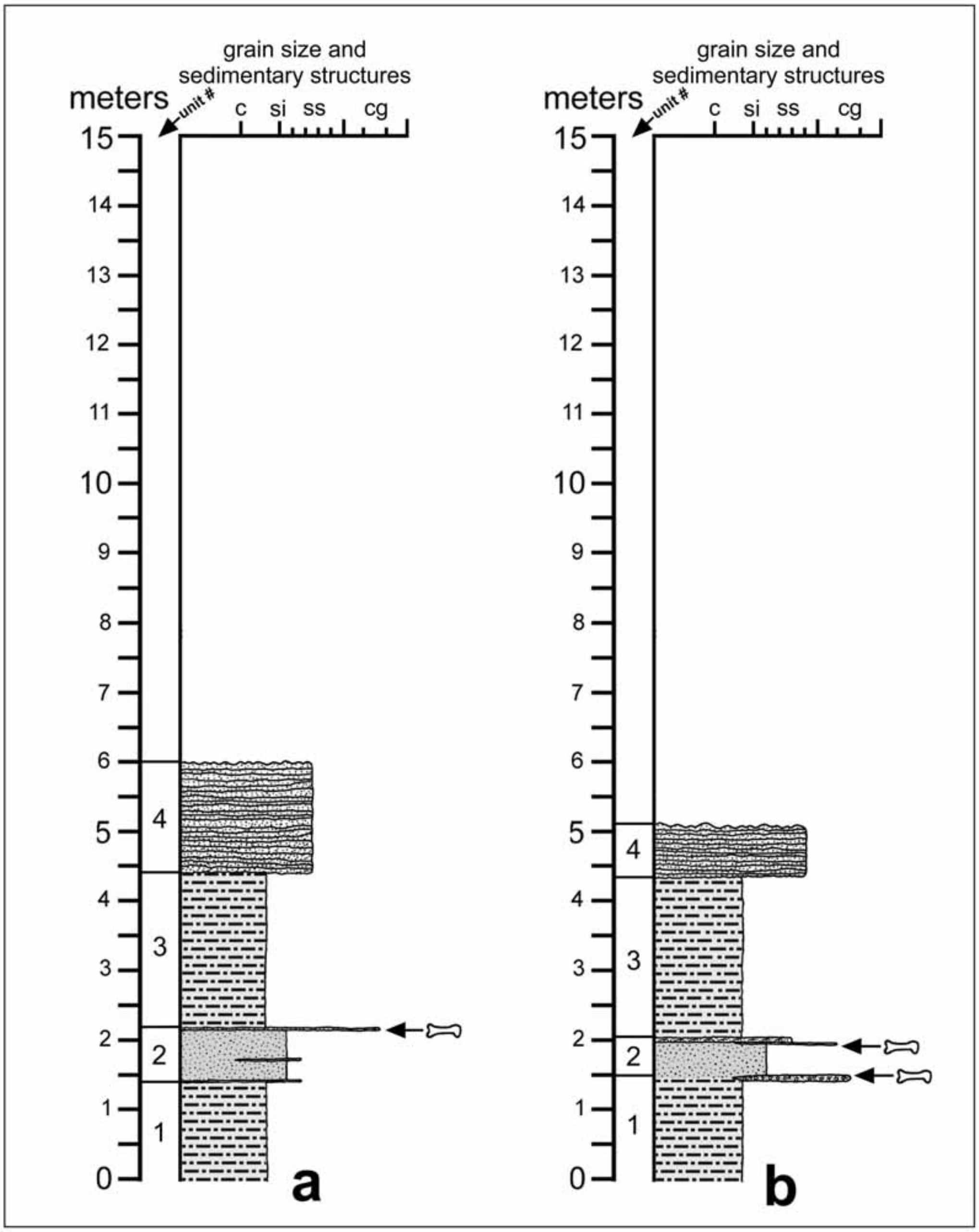

Fig. A1.12. Headquarters vertebrate localities measured sections: *a*, MOTT 3892 (Headquarters) measured section; *b*, MOTT 3898 (Headquarters South) measured section.

and it thins laterally. Not surprisingly, the main site (Fig. 2.24b), which is closest to the main body of the channel sand and therefore represents more high-energy conditions, produces larger vertebrate material, and the south site, more distal from the main channel and therefore representing low-energy conditions, produces mostly microvertebrate material with the exception of a semi-articulated sphenosuchian skeleton. Material comes from both the top and bottom of this sandstone. The Headquarters North (MOTT 3900), Headquarters NW (MOTT 3899), and Green Tooth Arroyo (MOTT 3901) vertebrate localities do not come out of exactly the same channel sandstone, but are at approximately the same stratigraphic level.

1) 0 m → 1.4 m (thickness: 1.4 m) **middle unit of the Cooper Canyon Formation**
Medium reddish brown (MRB 4/6) clay-rich siltstone with light greenish gray (5GY 8/1) mottling. The upper surface of the unit is unconformable with unit 2. Overbank deposits.

2) 1.4 m → 2.2 m (thickness: 0.8 m) **middle unit of the Cooper Canyon Formation**
Interbedded mudstone, sandstone, and conglomerate. The lower part is very thin (about 5 cm thick) discontinuous lenses of light gray (N7) horizontal planar bedded very fine to fine-grained sandstone interbedded with clay-rich medium reddish brown (MRB 4/6) siltstone to very fine-grained sandstone. This is capped with a more laterally extensive granule pebble conglomerate bed about the same thickness as the sandstone lenses, which is the actual bone bed. Material is derived from the upper and lower surfaces of the conglomerate. Small channel sandstone and sheet sand.

3) 2.2 m → 4.4 m (thickness: 2.2 m) **middle unit of the Cooper Canyon Formation**
Medium reddish brown (MRB 4/6) clay-rich siltstone with light greenish gray (5GY 8/1) reduction mottling, identical to unit 1. Channel sandstone.

4) 4.4 m → 6.0 m (thickness: 1.6 m) **Miller Ranch sandstone**
Light gray (N7) fine to medium-grained clast-supported sandstone with horizontal planar bedding. Channel sandstone. The top is truncated by Quaternary alluvium.

MOTT 3898 (HEADQUARTERS SOUTH)

Vertebrate fossils

Middle Creek Quadrangle

Total thickness: 5.08 m

Fig. A1.12b

1) 0 m → 1.5 m (thickness: 1.5 m) **middle unit of the Cooper Canyon Formation**
Medium reddish brown (MRB 4/6) clay-rich siltstone with light greenish gray (5GY 8/1) reduction mottling. Overbank deposits.

2) 1.5 m → 2.05 m (thickness: .55 m) **middle unit of the Cooper Canyon Formation**
Light gray (N7) interbedded sandstone and conglomerate. There is a pocket (not even a lens) of light gray (N7) granule to pebble conglomerate at the base of the unit, about 15 cm thick. The un-numbered sphenosuchian specimen was found at the top of this pocket. Above is muddy very fine-grained sandstone about 30 cm thick, capped by a ripple cross-laminated fine to medium-grained sandstone layer about 10 cm thick, with discontinuous granule conglomerate at the base. This sandstone is the main bone bed, traceable to the conglomeritic bone bed at the Headquarters Site, with most microvertebrate material coming from its base. Lag deposit(?) and sheet sand.

3) 2.05 m → 4.35 m (thickness: 2.3 m) **middle unit of the Cooper Canyon Formation**
Medium reddish brown (MRB 4/6) clay-rich siltstone with faint light greenish gray (5GY 8/1) mottling. Overbank deposits.

4) 4.35 m → 5.1 m (thickness: 0.75 m) **Miller Ranch sandstone**
Light gray (N7) horizontal planar-bedded coarse-grained sandstone. Channel sandstone. The unit is truncated by Quaternary alluvium.

MOTT 3903 (RED MUD METOPOSAUR)

N33°02’42” W101°22’45”

Vertebrate fossils

Middle Creek Quadrangle

Total thickness: 20.5 m

Fig. A1.13

The Red Mud Metoposaur site is located below the Miller Ranch sandstone, probably slightly above the level of the Route 669 Roadcut sandstone, which pinches out a short distance to the west. Metoposaur material has been noted at the site, though it has not been collected, and *Typothorax* osteoderms were collected from near the base of the unit.

1) 0 m →3.5 m (thickness: 3.5 m) **middle unit of the Cooper Canyon Formation**
Dark reddish brown (10R 3/4) silty claystone with light greenish gray (5GY 8/1) very fine reduction mottling. There is a reduced zone about 10 cm thick at the top of the unit, directly underneath the unconformity dividing this unit from the next. Overbank deposits.

2) 3.5 m → 16 m (thickness: 12.5 m) **middle unit of the Cooper Canyon Formation**
The base of the unit is a layer of sedimentary rock pebble conglomerate and very coarse sand usually about 1-2 cm thick but up to 10 cm thick, containing bivalves and vertebrate fossils, resting on an unconformable surface. This layer produced the *Typothorax* osteoderms. The rest is medium reddish brown (10R 4/6) muddy siltstone with large reduction mottles, and thin lenses of muddy sedimentary rock pebble conglomerate and very coarse sand., also containing bivalves and vertebrate fossils. A lens which produced fragmentary metoposaur remains (not collected) is at about 4.8 m, and one producing abundant bivalves is at 5.4 m. This unit also contains gypsum beds, which may be syndepositional. Overbank deposits.

3) 16 m → 20.5 m (thickness: 4.5 m) **Miller Ranch sandstone**
Medium reddish brown (10R 4/6) horizontal planar bedded sandstone, mostly very fine to fine grained but becoming coarser in the upper part of the unit, interbedded with

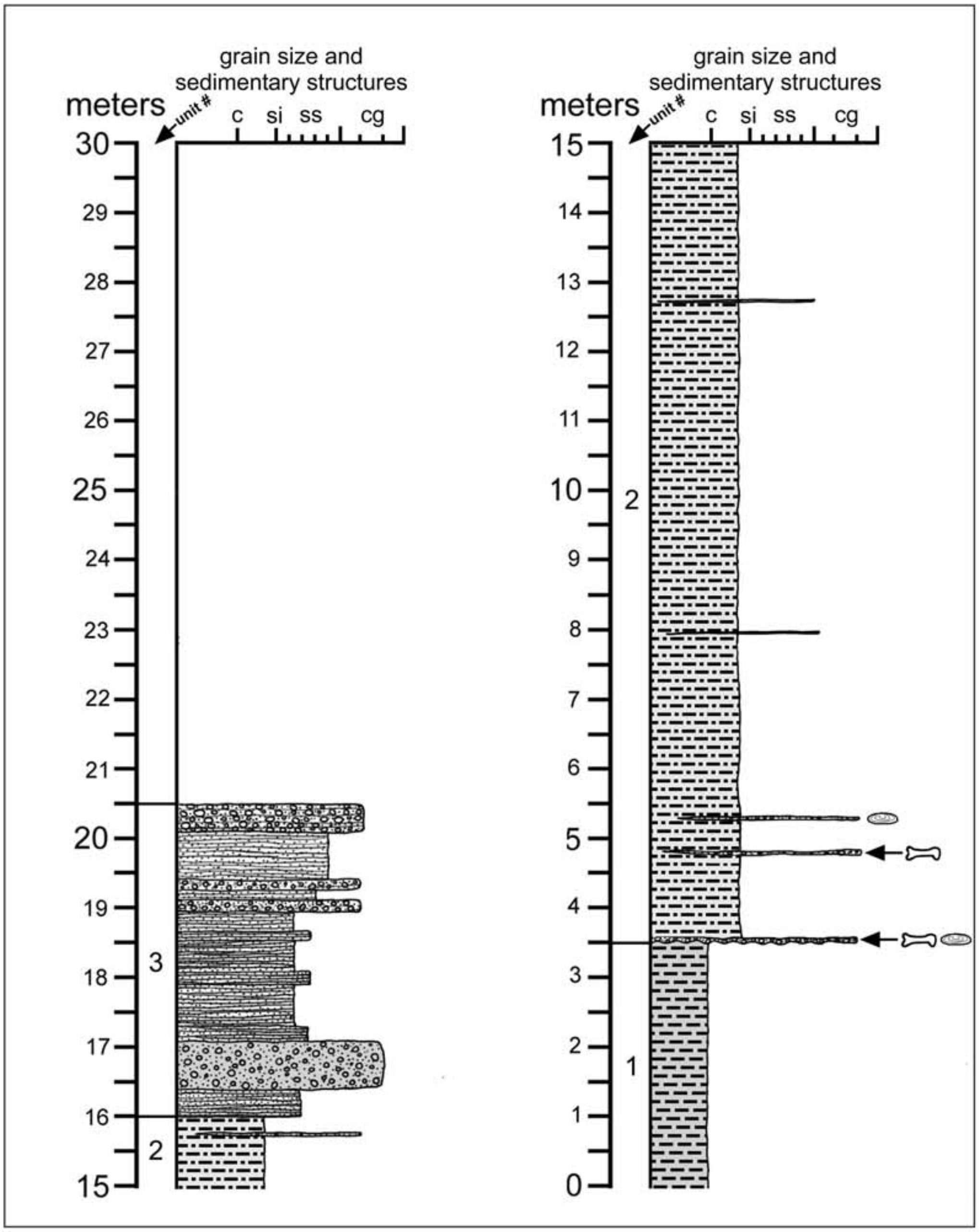

Fig. A1.13. MOTT 3903 (Red Mud Metopossaur) measured section.

sedimentary rock clast granule conglomerate and pebble conglomerate, the latter often very muddy. Channel deposits.

MOTT 3921 (PROBLEMATIC HILL)

Vertebrate fossils, mudstone samples

N33º08’46” W101º22’28”

Post East Quadrangle

Total thickness: 19.61 m

Fig. A1.14

1) 0 → 3.4 m (thickness: 3.4 m) **middle unit of the Cooper Canyon Formation**
Moderate reddish brown (10R 4/6) siltstone with large pale greenish yellow (10Y 8/2) reduction mottling, mostly in a random pattern, some mottles more elongate and criss-crossing. One discontinuous layer of very fine to fine-grained horizontal planar bedded and ripple cross-laminated sandstone about 10 cm thick, reduced color, about 1.9 m up. About .65 m above that is a discontinuous matrix-supported pebble conglomerate (reworked sedimentary rock clasts) about 20-30 cm thick. Overbank deposits with sheet sand and small channel deposits. Sample **Problematic Hill-1** comes from near the base of the unit.

2) 3.4 → 7.46 m (thickness: 4.06 m) **middle unit of the Cooper Canyon Formation**
Moderate reddish brown (10R 4/6) siltstone with pale greenish yellow (10Y 8/2) elongate horizontal reduction mottling mostly associated with numerous very thin (mostly 1 cm thick or less) layers of very fine to fine-grained sandstone, mostly of which are horizontal, although some steeply dips and faint random reduction mottling is present above it. One sandstone about 3.7 m above the base of the unit thickens to a more prominent unit westward through the drainage, and can be traced for some distance. A thicker sandstone unit (about 5 cm thick) of the same kind marks the top of the unit. A layer of matrix- supported pebble conglomerate (as in unit 1) about 15 cm thick sits about 2.45 meters above the base of the unit. Overbank deposits with sheet sands and small channel deposits.

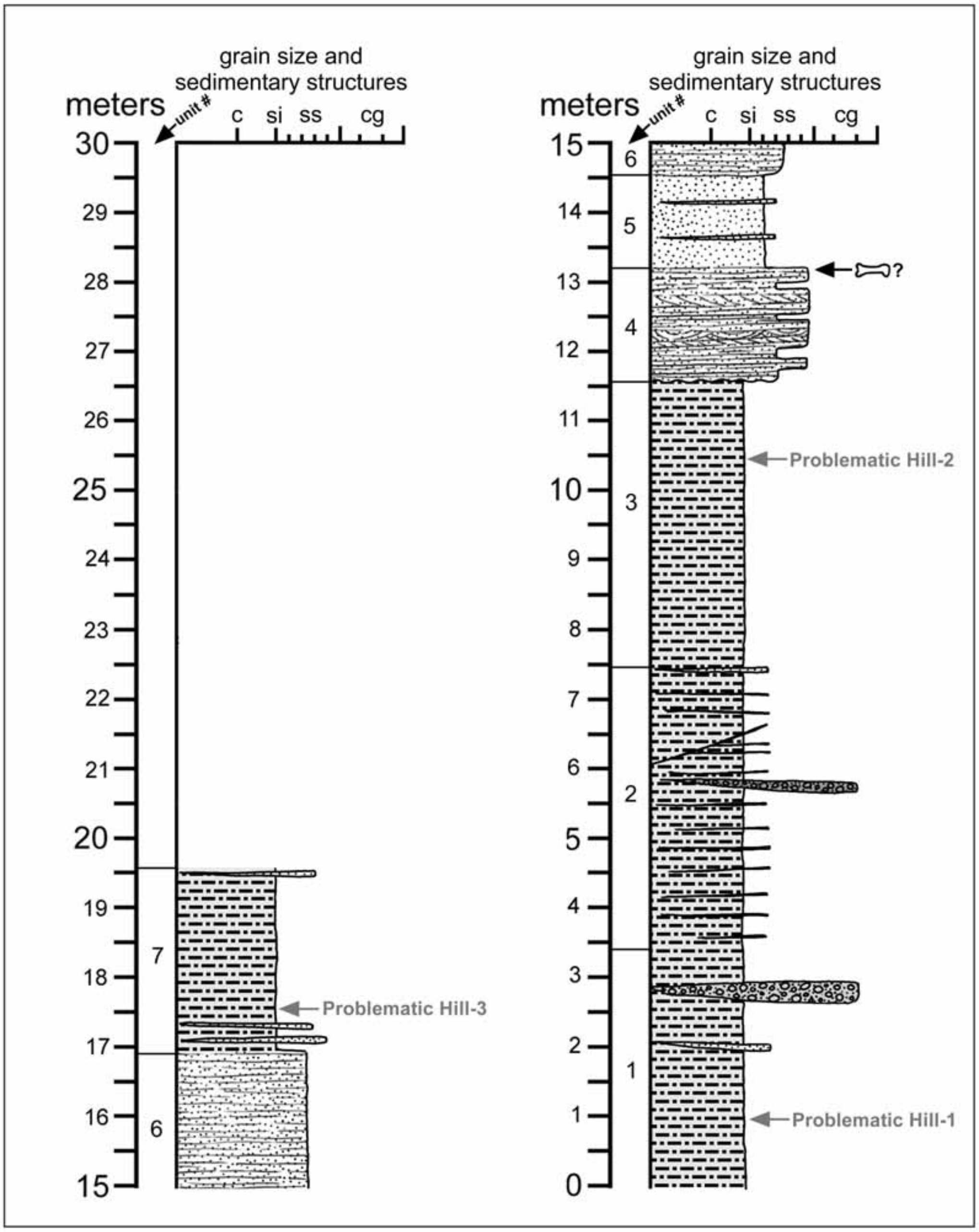

Fig. A1.14. MOTT 3921 (Problematic Hill) measured section.

3) 7.46 → 11.56 m (thickness: 4.1 m) **middle unit of the Cooper Canyon Formation**
Moderate reddish brown (10R 4/6) siltstone with pale greenish yellow (10Y 8/2) very faint, horizontally oriented reduction mottling, with a thicker reduced band below the base of unit 4. Mudstone sample **Problematic Hill-2** comes from about a meter below the top of the unit.

4) 11.56 → 13.21m (thickness: 1.65 m) **middle unit of the Cooper Canyon Formation**
Somewhat friable, coarse to very coarse-grained clast-supported sandstone with horizontal planar bedding, planar cross bedding, and some trough cross bedding, with some interbedded slightly mottled fine-grained sandstone. Float indicates a bone bed is probably located either about the level of this sandstone or higher up. This unit is very similar to the Kirkpatrick Ranch sandstone, and may be equivalent.

5) 13.21 → 14.51 m (thickness: 1.3 m) **middle unit of the Cooper Canyon Formation**
Friable very fine-grained moderate reddish brown (10R 4/6) sandstone, with a couple more resistant thin, fine-grained, horizontal planar-bedded, pale greenish yellow (10Y 8/2) sandstone.

6) 14.51 → 16.91 m (thickness: 2.4 m) **middle unit of the Cooper Canyon Formation**
Resistant, horizontal planar bedded, fine to medium-grained, moderate reddish brown (10R 4/6) sandstone with sparse, usually horizontal pale greenish yellow (10Y 8/2) mottling.

7) 16.91 → 19.61 m (thickness: 2.7 m) **UU Ranch sandstone?**
Moderate reddish brown (10R 4/6) siltstone, with a few interbedded layers of sandstone near the base, one coarse grained and mottled pale greenish yellow (10Y 8/2), the others medium-grained. Top of hill has patches of sandstone and conglomerate, now mostly weathered away. This unit can be faintly traced to the east, and merges with the UU Ranch sandstone. Mudstone sample **Problematic Hill-3** comes from about 1 m above the base of the unit.

MOTT 3928 (EASTERN GARZA COUNTY)

N33°06’39” W101°03’06”

Vertebrate fossils, mudstone samples, petrographic samples

Justiceburg SE Quadrangle

Total thickness: 11.35 m

Fig. A1.15

This locality is just north of the Lake Alan Henry Wildlife Mitigation Area, and is unusual in that the truncated upper surface of the mottled beds of the Santa Rosa Sandstone is overlain by very muddy sandstone probably representing overbank deposits, instead of a lower Boren Ranch channel sandstone, demonstrating that erosional truncation of the Santa Rosa Sandstone predated deposition of the Boren Ranch sandstone/beds. It is listed as a vertebrate locality only because of a single cervical vertebra from the Boren Ranch beds.

1) 0 m → 1.9 m (thickness: 1.9 m) **Santa Rosa Sandstone**

Coarse to very coarse-grained, pale reddish brown (10R 5/4), planar cross-bedded and trough cross-bedded sandstone. This is only the top of the Santa Rosa; discontinuous exposures can be traced down the creek bed, and the total thickness of the unit is probably about 15 meters (50’). Channel sandstone. Petrographic sample Beggs (ss) 1 was collected from this unit.

2) 1.9 m → 5.7 m (thickness: 3.8 m) **Mottled beds** (see Fig. 2.12b)

Intensely mottled pale red purple (5RP 6/2), medium light gray (N6), dark reddish brown (10R 3/4), and dark yellowish orange (10YR 6/6) sandstone and conglomerate with interbedded mudstone. The lower two meters or so are mostly medium to coarse-grained sandstone with occasional tiny pockets of claystone. The rest is pebble conglomerate (chert clasts up to a couple centimeters, the sandstone matrix varies from medium to very coarse sand), with frequent thin lenses of claystone, usually purple. Because of the denser claystone lenses, the upper part of the unit creates more of an impression of bedding than the lower part, but overall the entire unit appears to have had any sedimentary structures eliminated or obscured by the mottling. Pedogenically altered

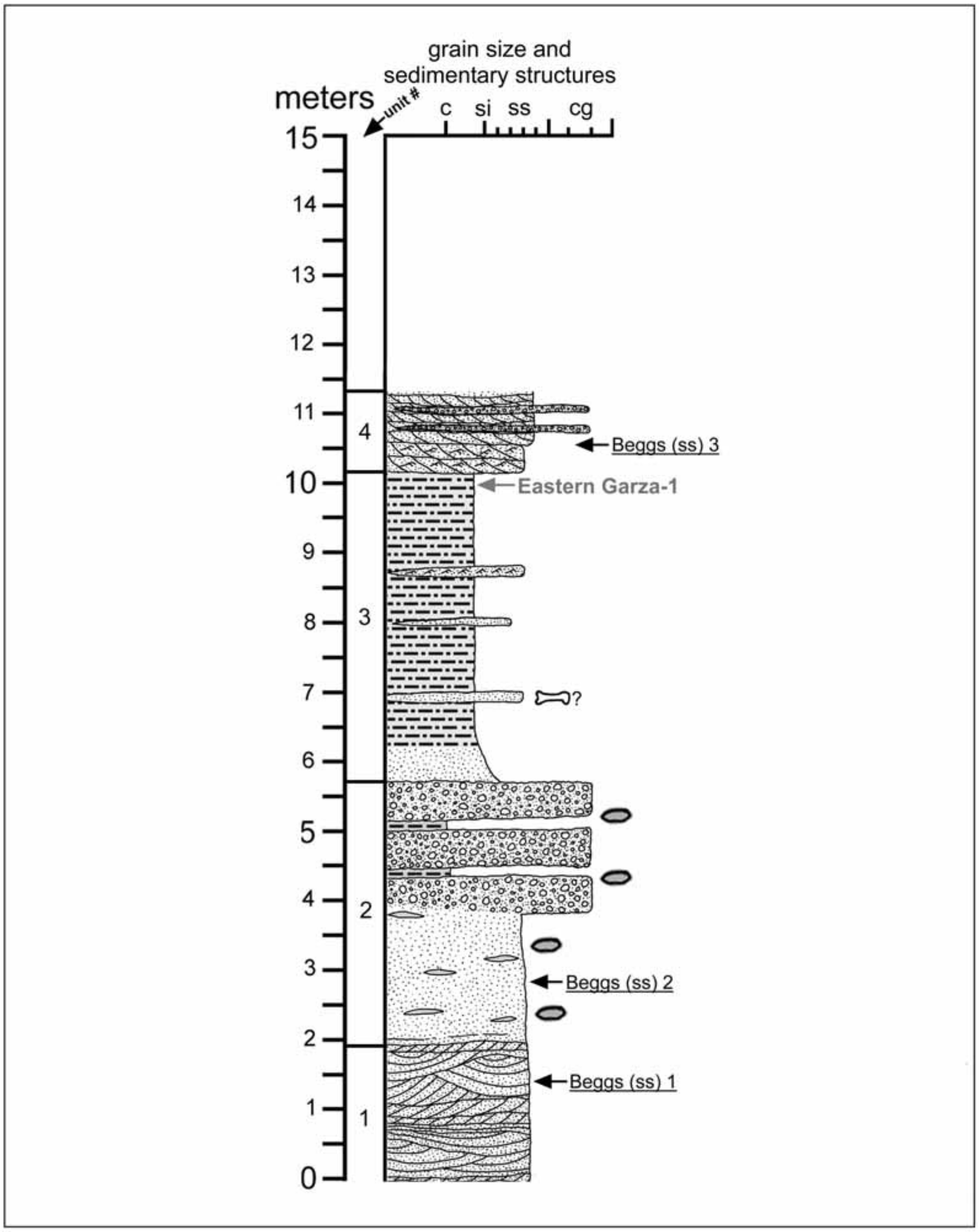

Fig. A1.15. MOTT un-numbered (Eastern Garza) measured section.

channel sandstone. Thin section Beggs (ss) 2 was collected from the lower part of this unit.

3) 5.7 m → 10.15 m (thickness: 4.45 m) **Boren Ranch beds**

The base of this unit is muddy, very fine-grained sandstone fining rapidly into silt, all dark reddish brown (10R 3/4). There are three layers of reduced light greenish gray (5GY 8/1), fine to medium-grained ripple bedded sandstone, all less than 20 cm thick. A vertebra centrum was found on the lowest bed, though it is hard to say if it originated here or if it is float from one of the higher sandstones. Proximal? overbank deposits with sheet sandstones. Mudstone sample **Eastern Garza-1** was collected from the very top of this unit.

4) 10.15 m → 11.35 m + (1.2 m +) **upper Boren Ranch sandstone**

Light greenish gray (5GY 8/1) sandstone and conglomerate. The lower 50 centimeters or so is fine to medium-grained, planar cross bedded and ripple bedded sandstone, coarsening into medium to coarse-grained planar cross-bedded sandstone with occasional very thin (less than 10 centimeters thick) lenses of pebble conglomerate. Channel sandstone. Thin section Beggs (ss) 3 came from this unit.

MOTT UN-NUMBERED (UU HIGHWAY 84)

Vertebrate fossils, mudstone samples

N33°09’19” W101°20’12”

Post East Quadrangle

Total thickness: 14 m

Fig. A1.16

1) 0 m → 5.7 m (thickness: 5.7 m) **middle unit of the Cooper Canyon Formation**

Fining upward sequence, grading from moderate brown (5YR 4/4) siltstone to moderate brown (5YR 3/4) slightly silty claystone in the upper 2 meters or so, all with sparse and random light olive gray (5Y 6/1) reduction mottling. At least one very thin (3-4 cm thick) faintly horizontal planar-bedded very fine to fine-grained sandstone lens is present near the bottom of the section, surrounded by reduction of the same color as the mottling.

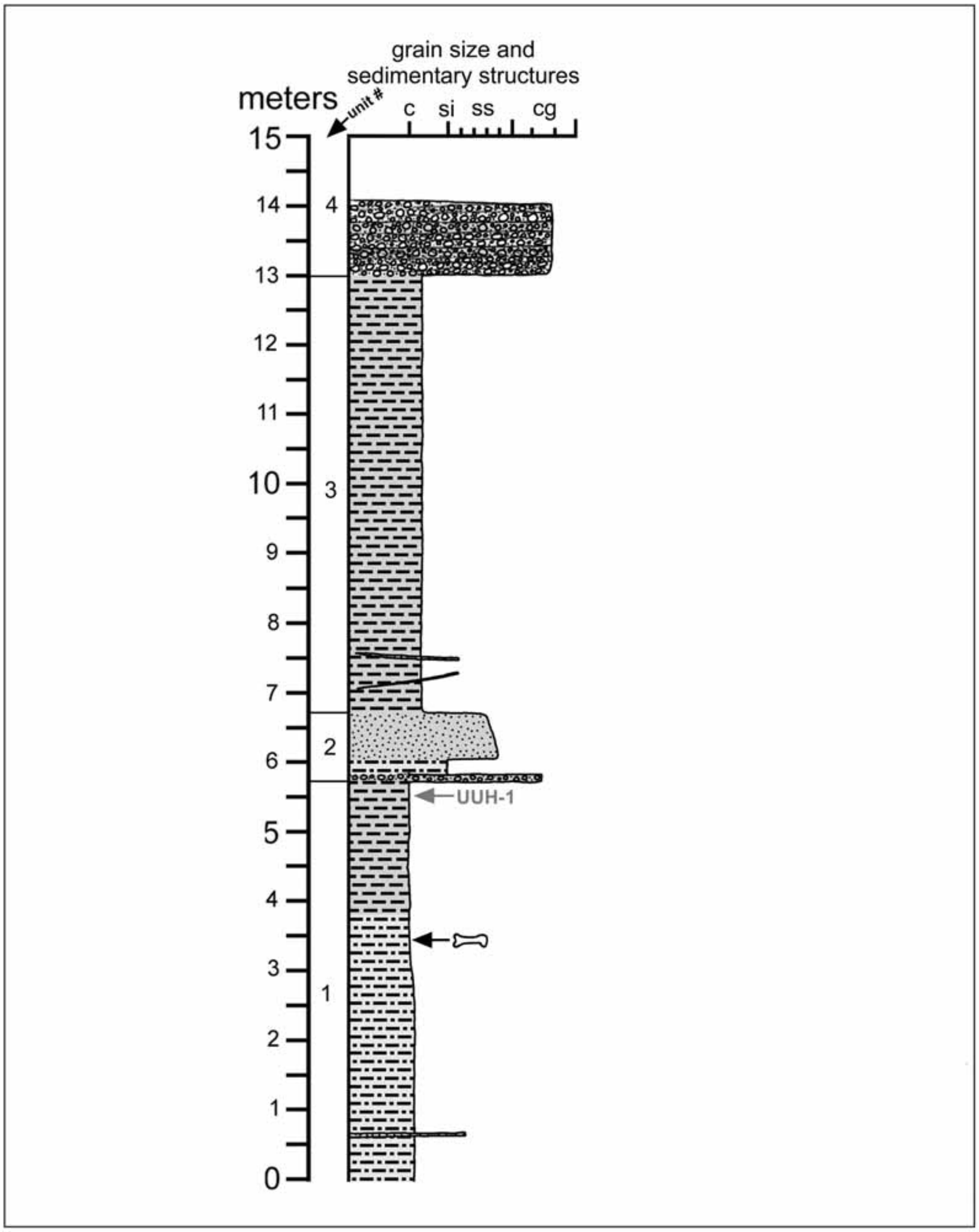

Fig. A1.16. MOTT un-numbered (UU Highway 84) measured section.

At least some gypsum also found above this lens, although it is probably post-depositional. Most of the vertebrate material was found in this unit. Mudstone sample **UUH-1** comes from about 20 cm below the top of the unit.

2) 5.7 m → 6.7 m (thickness: 1 m) **middle unit of the Cooper Canyon Formation**

Generally coarse-grained sequence, the base is a resistant, roughly 10 cm thick matrix supported granule-pebble conglomerate surrounded by greenish gray (5G 6/1) reduction, followed by about 20 cm of grayish red (10R 4/2) siltstone, then about 70 cm of moderate brown (5YR 3/4) matrix-supported sandstone grading from generally well-cemented coarse-grained sand, to more friable medium-grained sand. Contact with overlying unit is somewhat gradational.

3) 6.7 m → 13 m (thickness: 6.3 m) **middle unit of the Cooper Canyon Formation**

Moderate brown (5YR 4/4) slightly silty claystone with sparse random greenish gray (5G 6/1) reduction mottling, at least a couple very thin (a few centimeters thick) and strongly tilted layers of very fine-grained sandstone in the lower 1.5 m.

4) 13 m → 14 m + (thickness: 1 m) **Miller Ranch sandstone**

Roughly horizontal planar and cross-bedded conglomeritic sandstone, mostly highly resistant and clast-supported but with a few muddier and less resistant interbedded layers.

BOREN CENTRAL HILL

N32°59’52” W101°08’28”

Fluvanna Quadrangle

Total thickness: 14.9 m

Fig. A1.17

1) 0→5.9 m (thickness: 5.9 m) **lower unit of the Cooper Canyon Formation**

Generally fining upward sequence. Moderate brown (5YR 3/4) siltstone containing in its lower 1.3 meters a few thin lenses of ripple cross laminated fine-grained sandstone, mostly less than 10 cm thick, all with random greenish gray (5GY 6/1) reduction mottling. 20 centimeters above the lenses there is a color shift to moderate reddish brown (10R 4/6) with sparse reduction mottling, grading up at about 3 m into moderate brown

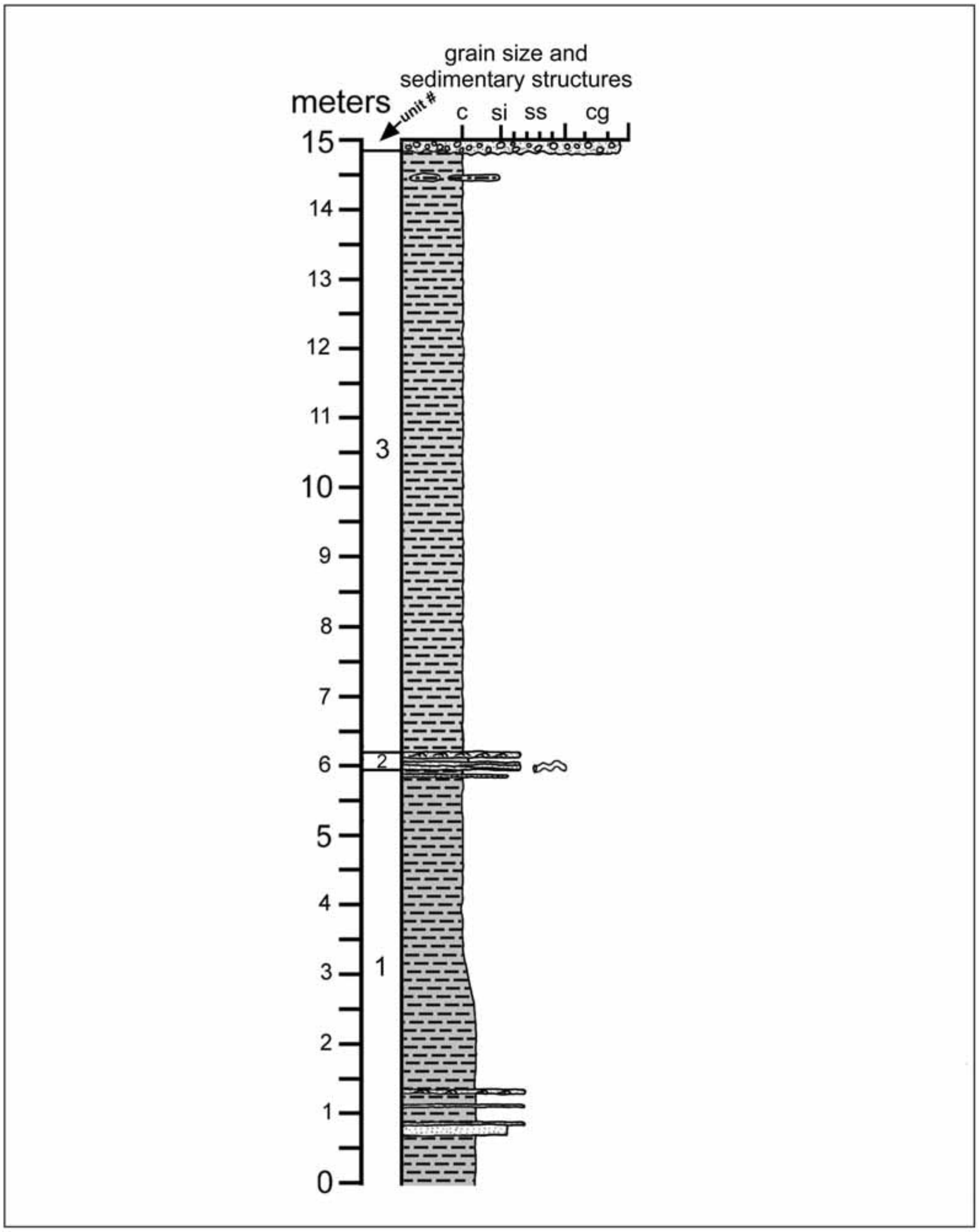

Fig. A1.17. Boren Central Hill measured lection

(5YR 3/4) almost pure claystone containing soft medium to coarse sand-sized mudstone clasts (dark yellowish orange 10YR 6/6). There is a very conspicuous color shift at about 5.2 meters to moderate reddish brown (10R 4/6) accompanied by the loss of the yellowish-orange clay clasts, and a thin (about 3 centimeters thick) planar-bedded, greenish gray (5GY 6/1) siltstone to very fine-grained sandstone lens at about 5.8 m. Overbank deposits

2) 5.9 → 6.2 m (thickness: .3 m) **lower unit of the Cooper Canyon Formation**

Very fine to fine-grained, well cemented, weakly horizontal planar-bedded and ripple cross-laminated reddish brown (10R 4/6) sandstone, interbedded with dark reddish brown (10R 4/6) siltstone. The sandstone contains abundant but not very closely packed vertical burrowing trace fossils; elsewhere, there are also abundant trails. The top is discolored (greenish gray, 5GY 6/1). This sandstone is locally traceable and informally named "Neyland sandstone 2", and caps the nipple-shaped hill nearby. The unit is apparently about 7 m above the "Neyland sandstone."

3) 6.2→14.9 (thickness: 8.7 m) **lower unit of the Cooper Canyon Formation**

Mudstone (moderate reddish brown, 10R 4/6), filled with conspicuous soft medium to coarse sand-sized clay clasts. These are greenish gray (5GY 6/1) between about 7.5-10.0 m and 11.6-12.8 m, and moderate reddish brown (10R 4/6, the same color as the surrounding mudstone) otherwise. There are discontinuous pockets of silt about .15 m thick near the top of the unit. Overbank deposits. The upper contact is disconformable with Quaternary pebble-cobble stream terrace conglomerate.

CARING IS CREEPY CLIFF

Mudstone samples

N33°09'27" W101°23'29"

Post West Quadrangle

Total thickness: ~30 m

Fig. A1.18

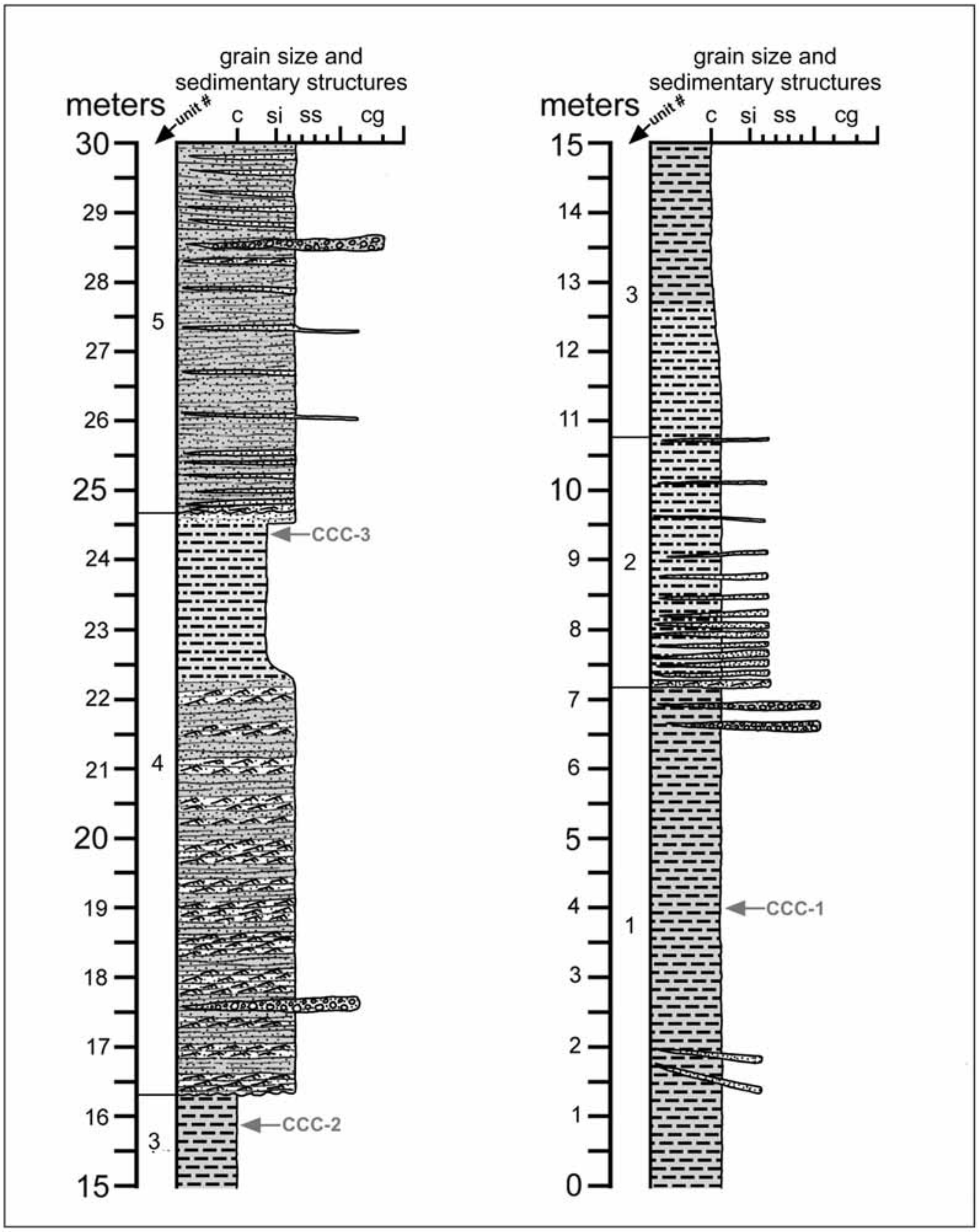

Fig. A1.18. Caring is Creepy Cliff measured section.

1) 0 m →7.15 m (thickness: 7.15 m) **upper unit of the Cooper Canyon Formation**
Moderate reddish brown (10R 4/6) slightly silty claystone. There are coarser discontinuous lenses, a couple strongly tilted very fine-grained sandstone lenses about 10 cm thick with horizontal planar bedding and ripple cross-lamination near the bottom of the unit, and two more in the top 70 cm that are granule conglomerate and coarse sand with horizontal planar bedding. There is greenish gray (5G 6/1) reduction mottling throughout the unit, mostly in a random pattern, but there are more linear horizontal reduction layers in the upper part of the unit, including two marking the coarse upper lenses. Overbank deposits. Mudstone sample **CCC-1** comes from about 4 m above the base of the unit.

2) 7.15 m →10.75 m (thickness: 3.6 m) **upper unit of the Cooper Canyon Formation**
Moderate reddish brown (10R 4/6) silty claystone, interbedded with lenses of very fine grained to fine grained planer and ripple bedded sandstone, which are thicker (the lowest is about 15 cm thick) and more densely spaced near the bottom of the unit (especially the first ten or so in the lowest 1.5 m) but thinner (about 3-4 cm thick) and more spaced out higher up. The higher and thinner units tend to show patchy greenish gray (5G 6/1) reduction mottling. Overbank deposits.

3) 10.75 m →16.35 m (thickness: 5.6 m) **upper unit of the Cooper Canyon Formation**
Moderate brown (5YR 4/4) silty claystone with patchy greenish gray (5G 6/1) reduction mottling, that shifts in color after three meters to grayish red (10R 4/2) silty claystone that is somewhat calcified, and continues to fine upwards to almost pure claystone near the top with dark greenish gray (5G 4/1) reduction mottling in the top 20 cm or so. Overbank deposits. Sample **CCC-2** comes from just below the mottling.

4) 16.35 m →24.65 m (thickness: 8.3 m) **upper unit of the Cooper Canyon Formation**
Base is greenish gray (5GY 6/1) friable, matrix supported, fine grained to very fine grained horizontal planar bedded sandstone, complexly interbedded with more resistant fine grained to very fine grained sandstone showing horizontal planer bedding and ripple cross lamination. At least one 20 cm thick layer also has interbedded sedimentary rock clast granule conglomerate. After about 2 meters, the color of the sandstone shifts to

moderate brown (5YR 4/4), and after another 4 meters, everything fines to clayey siltstone of the same color. Just below the next unit, the sandstone returns to friable greenish gray (5GY 6/1) fine to very fine grained sandstone. Channel deposits and/or proximal overbank deposits? Sample **CCC-3** comes from the top of the siltstone, just below the upper grayish sandstone.

5) 24.65→~30 m (thickness: 3.85 m) **Macy Ranch sandstone**

Unconformable surface overlain by greenish gray (5GY 6/1) friable, matrix supported, fine grained to very fine-grained horizontal planar bedded sandstone, complexly interbedded with more resistant fine gained to very fine grained discontinuous sandstone layers generally less than about 10 cm thick, showing horizontal planer bedding and ripple cross lamination. A few of these resistant beds have coarse sand and granule conglomerate at the base, and there rare matrix-supported sand and pebble conglomerate. The upper two meters are dark reddish brown (10R 3/4) with large greenish gray (5GY 6/1) reduction mottling. Channel deposits.

HEADQUARTERS HILL

Mudstone samples

N33°02’34” W101°25’09”

Middle Creek Quadrangle

Total thickness: 24.2 m

Figs. 2.29b, A1.19

Headquarters Hill is the southernmost spot along Middle Creek where the superpositional relationship between the Miller Ranch sandstone and Route 669 Roadcut sandstone can be directly observed. Although the base of the Route 669 Roadcut sandstone is well exposed along the edges of Middle Creek a short distance below where the section began to be measured, exposures were poor between the base of the sandstone and the base of the hill, so I simply decided to start the section from the upper part of the Route 669 Roadcut sandstone at the base of the hill.

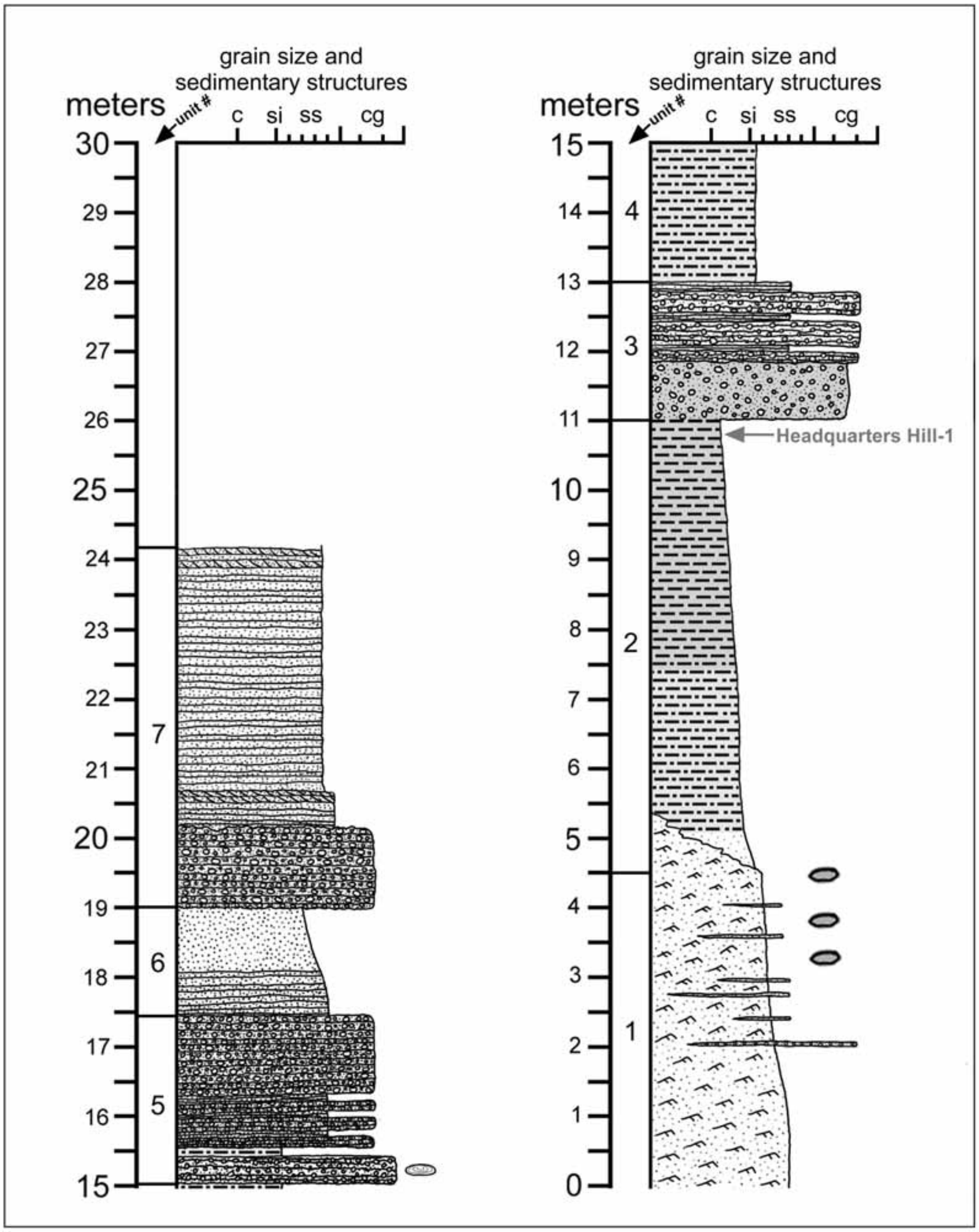

Fig. A1.19. Headquarters Hill measured section.

1) 0 m → 4.5 m (thickness: 4.5 m) **Route 669 Roadcut sandstone**

Sandstone and conglomerate, mostly ripple-bedded. Approximately 1.9 meters of light greenish gray (5GY 8/1) friable fine to medium-grained ripple-bedded sandstone, which fines to very fine to fine-grained ripple cross laminated sandstone, interbedded with more resistant ripple cross laminated or structureless medium to fine-grained sandstone and pebble conglomerate (mostly reworked sedimentary rock clasts), mostly in lenses about 10 cm thick. There are numerous dark yellow orange (10YR 6/6) concretions, mostly in the upper, interbedded part of the section. Large channel sandstone.

2) 4.5 m → 11.0 m (thickness: 6.5 m) **middle unit of the Cooper Canyon Formation**

Dark reddish brown (10R 3/4) clay-rich siltstone and very fine-grained sandstone, grading up after a few meters into silty claystone. The lower meter or so is laterally gradational with the top of unit 1, which is locally yellowish gray (5Y 8/1). Overbank deposits. Mudstone sample **Headquarters Hill-1** was taken from near the top of this unit.

3) 11.0 m → 13.0 m (thickness: 2 m) **middle unit of the Cooper Canyon Formation**

Reddish-brown horizontal planar-bedded layers of granule and pebble conglomerate, some matrix-supported and some well-cemented and clast-supported, interbedded with medium-grained sandstone, also horizontal planar bedded. The basal contact with unit 2 is slightly gradational. Channel sandstone.

4) 13.0 m → 15.05 m (thickness: 2.05 m) **middle unit of Cooper Canyon Formation**

Dark reddish brown (10R 3/4) siltstone to very fine-grained sandstone. Overbank deposits.

5) 15.05 m → 17.45 m (thickness: 2.4 m) **Miller Ranch sandstone**

Conglomerate interbedded with sandstone. The base is a 45 cm thick horizontal planar-bedded pebble to cobble conglomerate containing abundant bivalves, in places making up nearly all the clasts. This is followed by 10 cm of siltstone to very fine-grained sandstone, followed by 75 cm of interbedded granule- pebble conglomerate and coarse-grained sandstone, all horizontal planar bedded, followed by 110 cm of granule-pebble conglomerate. Channel sandstone.

6) 17.45 m → 19 m (thickness: 1.55 m) **Miller Ranch sandstone**
Fining upward sequence of dark reddish brown (10R 3/4) horizontal planar bedded sandstone, starting with medium to very coarse-grained sandstone fining into fine-grained sandstone that looses the planar bedding. Channel sandstone.
7) 19 m → 24.2 m (thickness: 5.2 m) **Miller Ranch sandstone**
Generally fining upward sequence of horizontal planar bedded and planar cross-bedded conglomerate and sandstone. About 1.2 m of horizontal planar bedded granule to pebble conglomerate, the upper surface of which is highly irregular, followed by 50 cm of horizontal planar bedded and cross bedded coarse to very coarse-grained sandstone, and the rest is horizontal planar bedded medium to coarse-grained sandstone with a little cross bedding near the top. The sandstones are greenish gray (5GY 6/1). Channel sandstone.

MARTS GRAZING

Mudstone samples

N33°10’09” W101°20’26”

Post East Quadrangle

Total thickness: 11.53 m

Figs. 2.19c, A1.20

This outcrop (Fig. 2.19c), capped by the Miller Ranch sandstone, shows a good exposure of overbank mudstones relatively uninterrupted by low order sandstones and conglomerates. The color shift between units 1 and 2 in an unconformity probably representing a transition between periods of floodplain degradation and aggradation as described by Frehlier (1986).
1) 0→4.2 m (thickness: 4.2 m) **middle unit of the Cooper Canyon Formation**
Medium brown (5YR 4/4) muddy siltstone, with a couple zones of light greenish gray (5GY 8/1) reduction mottling, some random (larger ones about 20 cm wide) and some in horizontal bands. Overbank deposits. Mudstone sample **Marts-3** comes from about 1.5 m.

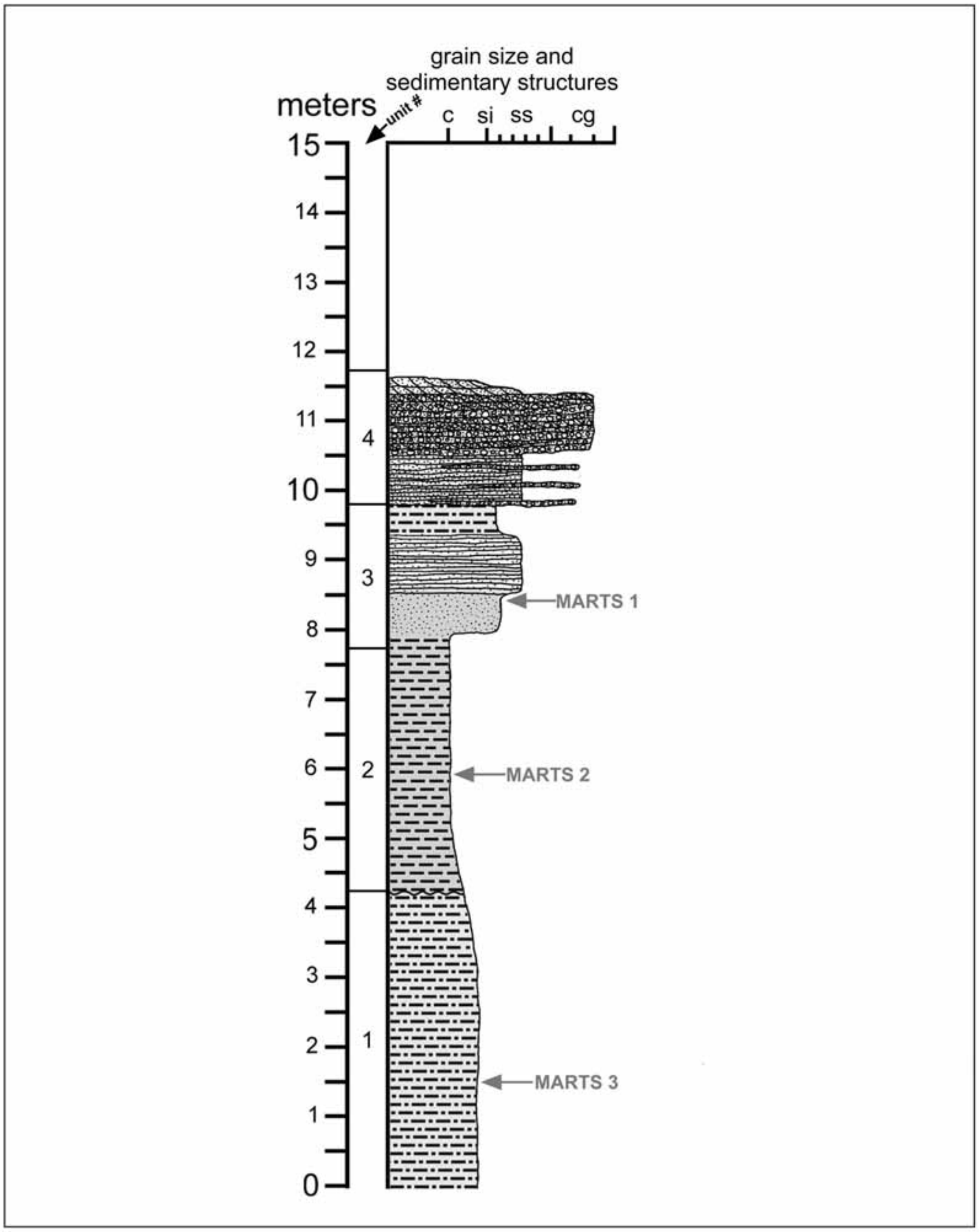

Fig. A1.20. Marts Grazing measured section.

2) 4.2→7.65 m (thickness: 3.45 m) **middle unit of the Cooper Canyon Formation**
Dark reddish brown (10R 3/4) almost pure claystone. Overbank deposits. Mudstone sample **Marts-2** comes from about 1.5 m below the color change at the top of the unit.
3) 7.65→9.82 m (thickness: 2.17 m) **middle unit of the Cooper Canyon Formation**
Greenish gray (5GY 6/1) almost pure mud, grading into extremely muddy very fine grained sand of the same color. This is followed by horizontal planar bedded fine to medium grained sandstone of the same color, varying between more and less resistant layers even though there is no obvious difference in lithology, grading into medium reddish brown (10R 4/6) silt to very fine grained sand. Sample **Marts-1** comes from about .9 m, at the top of the sandy mud. Overbank deposits.
4) 9.82→11.53 m (thickness: 1.71 m) **Miller Ranch sandstone**
Fine to medium grained sand with very faint horizontal bedding, complexly interbedded with discontinuous lenses of matrix supported granule pebble conglomerate, grading after 60 cm into more clast supported pebble conglomerate with faint cross bedding about 86 cm thick, topped by fine to medium grained cross bedded sandstone about 25 cm thick. Channel sandstone.

MONTFORD DAM

Mudstone samples

N33°03’55” W101°02’49”

Justiceburg SE Quadrangle

Total thickness: 28.2 meters

Figs. 2.8b, 2.11, A1.21

This section was measured in the roadcut leading from the western rim of the Montford Dam down below it, within the Lake Allen Henry Wildlife Mitigation Area (LAHWMA). The sandstone/conglomerate dominated section capping the Permian section are more easily accessible and well exposed at this particular spot than in most places in the LAHWMA, but investigations in the gully to the north of the dam show the same series of lithologies: an intensely interbedded lower redbed unit representing the top

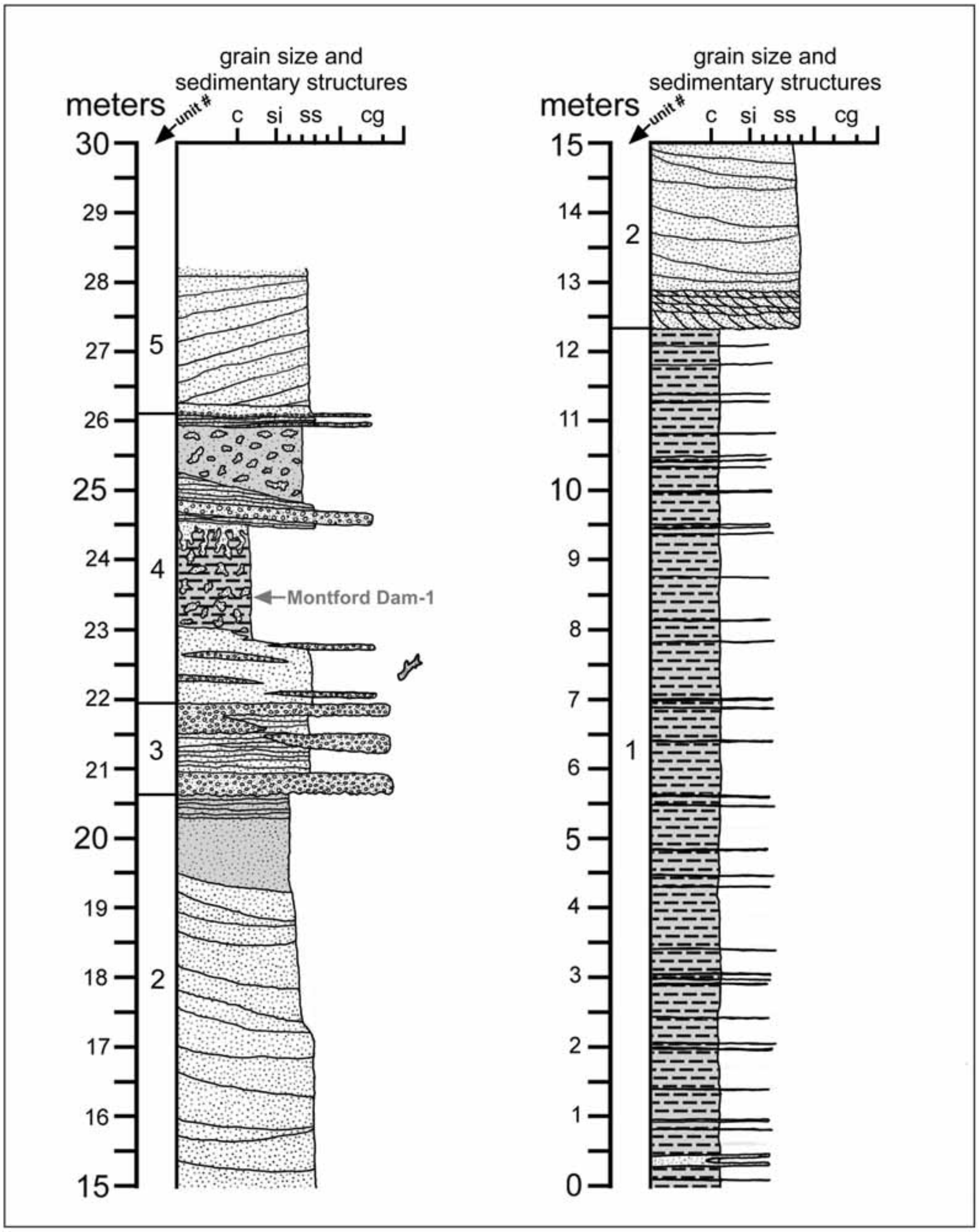

Fig. A1.21. Montford Dam measured section.

of the Permian, followed by a reddish superficially aeolian-looking unit probably representing the base of the Santa Rosa Sandstone, followed by highly quartzose sandstones and conglomerates, also part of the Santa Rosa Formation.

1) 0 → 12.3 m (thickness: 12.3 m) **Quartermaster Formation**

Medium reddish brown (10R 4/6) mudstone showing blocky weathering, shifting in composition between claystone and siltstone, becoming mostly clay-dominated near the top where the color darkens to dark reddish brown (10R 3/4). The unit is extremely densely interbedded with nearly horizontal, sub-parallel, and laterally extensive beds usually a few centimeters thick and generally spaced out on average at about 20 cm or so. These beds are usually reduced (greenish gray 5GY 8/1) and generally coarser grained then the rest of the unit (usually very fine-grained to fine-grained sand, although they may also include claystone), and often have a somewhat irregular, almost nodular appearance in weathering. The top of this unit is truncated by the TR-3 unconformity.

2) 12.3 m → 20.65 m (thickness: 8.35 m) **Base of Santa Rosa Sandstone?**

Moderate reddish brown (10R 4/6) unit consisting of at least three distinct sequences that are consecutively finer grained, and separated by thin zones of greenish gray reduction (5GY 8/1). The lowermost sequence starts off as coarse-grained clast-supported sandstone fining into medium-grained clast-supported sand, containing badly weathered and unidentifiable phytosaur? teeth. The next sequence is fine-grained to very fine-grained clast-supported sand, and the uppermost sequence is very fine-grained matrix supported sandstone. The lower, coarser sequences look superficially like aeolian sandstone in their weathering pattern, and the bedding consists of faintly visible, weakly dipping planar bedding and trough cross bedding, and the base of the coarse lowermost unit shows very distinct layers of cross bedding only 10-20 cm thick. The uppermost, very fine-grained sequence weathers more like a mudstone, and is capped by a thin planar-bedded zone (about 30 cm thick) exhibiting variegated coloration of yellowish-gray (5Y 8/1), grayish purple (5P 4/2), and dark yellowish orange (10YR 6/6) as seen in the mudstones above. Channel? sandstones.

3) 20.65 m → 21.95 m (thickness: 1.3 m) **Santa Rosa Sandstone**

Dominantly clast-supported quartz-rich conglomeritic sandstone. The largest clasts are mostly pebble-sized although there are some cobbles, and the sand is mostly medium to fine-grained, and faintly horizontal planar bedded. Compositionally the bigger gravel clasts and at least the larger sand grains are mostly chert, although there are some clasts of reworked fine-grained sedimentary rock as well. Interbedded with the conglomerates are thinner lenses of clast-supported, well-cemented, fine-medium grained sandstones that weather out as botyroidal "salt hoppers," and extremely muddy sandstones with variegated grayish purple (5P 4/2), and dark yellowish orange (10YR 6/6) coloration. Channel conglomeritic sandstone.

4) 21.95 m → 26.1 m (thickness: 4.15 m) **Santa Rosa Sandstone**

Complexly interbedded unit, essentially gradational with the unit below but with finer-grained lithologies being dominant. The sandstones and conglomeritic sandstones appear to be compositionally similar or identical with those below, being dominated by quartz with some re-worked sedimentary clasts. The larger conglomerate clasts are somewhat smaller than seen below, usually in the granule to pebble range, and the conglomerates are mostly thin lenses inside the sandstones. The sandstones are generally medium-grained, and may be friable or well cemented and weathering into "salt hoppers." There are also large (over a meter thick) mud-rich lenses, mainly grayish purple (5P 4/2) and varying from slightly silty mudstone to extremely muddy fine-grained sandstone. Mixed in are yellow gray (5Y 7/2) patches of muddy fine to medium-grained sandstone that resemble mottling but are clearly lithologically distinct from the purple sediments. In some places, the yellow-gray sands dominate and form vertical tendrils that surround the purple muds, possibly representing solid solution structures; these occur below sand beds and are presumably derived from them. Both sands and muds may include splotches of dark yellowish orange (10YR 6/6). Poorly preserved petrified wood has been observed weathering out of sands here and elsewhere in the LAHWMA. Channel deposits. Element sample **Montford Dam-1** came from a purple mudstone in this unit.

5) 26.1 m → 28.2 m + (thickness: 2.1 m) **Boren Ranch sandstone**

Sandstone dominated unit (mostly fine to medium grained sand) capping the visible section here, similar or identical to sands below. The sands are fairly siliceous, but also micaceous. The top and bottom of the unit is well cemented sandstone weathering into "salt hoppers." The base of the upper cemented bed is very thin granule-pebble conglomerate, most bigger clasts composed of quartz. The lower cemented unit was in some places apparently cemented and broken into chunks before the middle sand was deposited, similar to the large sedimentary clasts at the base of the Boren Ranch beds at OS Ranch. The middle of the unit is thicker and composed of friable yellowish gray (5Y 8/1) sandstone, exhibiting very faint cross bedding that might represent lateral accretion beds. It contains extremely thin lenses of grayish purple (5P 4/2) and dark yellowish orange (10YR 6/6/) muddy fine-grained sand. Channel sandstone.

NEW SLANG HILL

Mudstone samples

N33°09'01" W101°23'14"

Post West Quadrangle

Total thickness: 23.37 m

Fig. A1.22

1) 0→4.6 m (thickness: 4.6 m) **upper unit of the Cooper Canyon Formation**

Silty mudstone (light brown, 5YR 5/6) with large mottles (light olive gray, 5Y 6/1) mostly in a random pattern. There are several layers (about 10 cm thick or less) or very fine-grained discontinuous sandstone lenses with horizontal planar bedding and ripple cross lamination in the lower 2 meters, and an extremely muddy coarse grained sand (really just mud with some sand in it) at about 3.7 m, all reduced (light olive gray, 5Y 6/1). Overbank deposits and sheet sands. Mudstone sample NSH-1 comes from about 10 cm below the top of the unit.

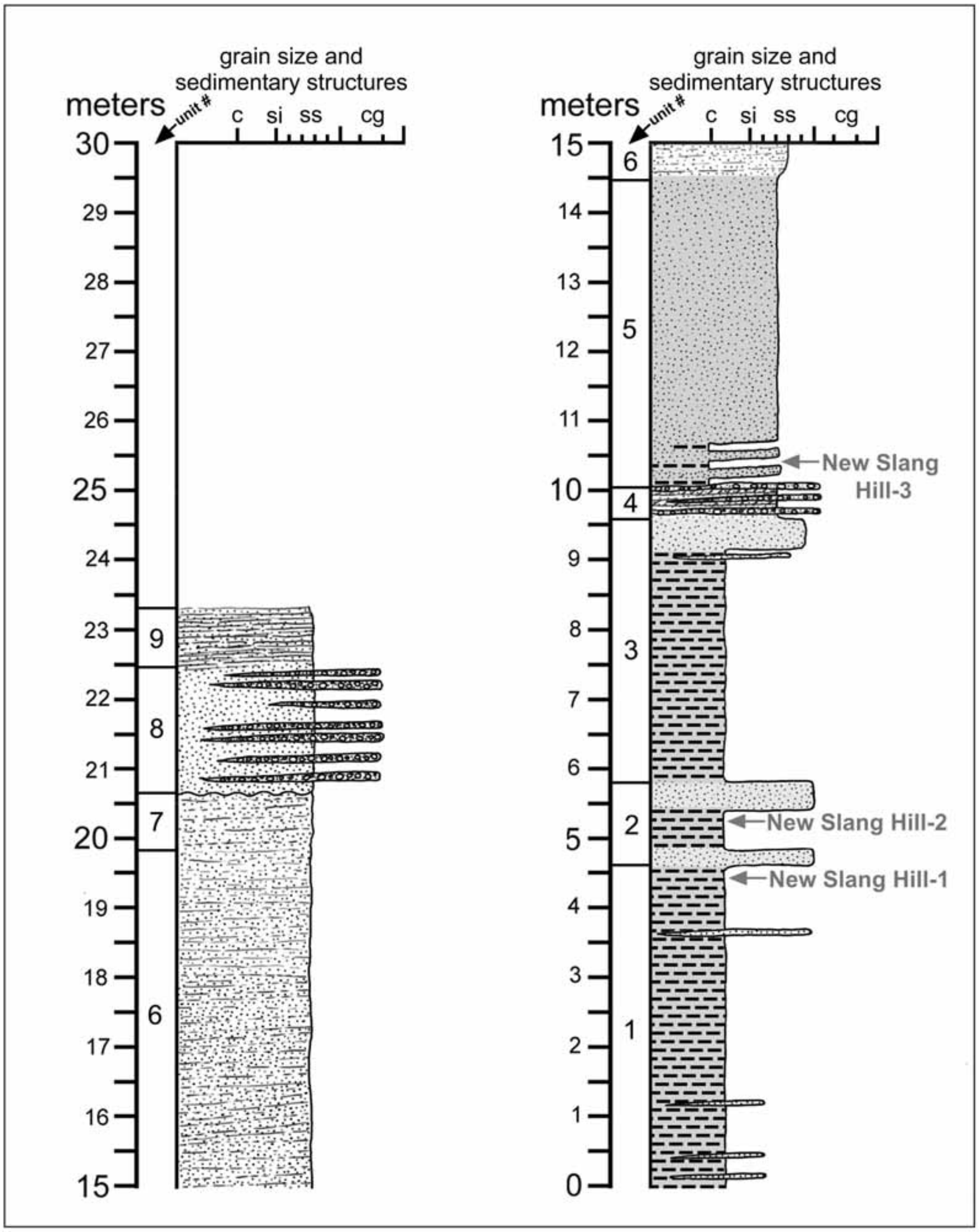

Fig. A1.22. New Slang Hill measured section.

2) 4.6→5.8 m (thickness: 1.2 m) **upper unit of the Cooper Canyon Formation**
A slightly silty claystone (reddish brown, 10R 3/4) with faint mottling (grayish green, 5G 5/2) about .5 m thick, sandwiched between two very coarse-grained matrix-supported mudstone clast "sandstones" (dark reddish brown, 10R 3/4). The lower and upper matrix- supported mudstone clast sandstones are respectively .3 and .4 m thick. The boundaries of all three layers (including the upper and lowermost) are reduced (grayish green, 5G 5/2). Small channel and overbank deposits. Mudstone sample NSH-2 comes from about 10 cm from the top of the muddy middle layer.

3) 5.8→9.6 m (thickness: 3.8 m) **upper unit of the Cooper Canyon Formation**
Silty mudstone (light brown, 5YR 5/6), with fine elongate and horizontally oriented reduction mottles (light olive gray, 5Y 6/1). About 30 cm from the top is a thin (about 5 cm thick), reduced, well cemented clast-supported sandstone layer. Above this is a zone of matrix-supported, coarse to very coarse-grained sandstone (dark reddish brown, 10R 3/4), with clasts of reworked sedimentary rock. Overbank deposits.

4) 9.6→10.07 m (thickness: 0.47 m) **upper unit of the Cooper Canyon Formation**
Resistant fine-grained, horizontal planar bedded and cross-bedded sandstone, with interbedded very coarse grained sand-granule conglomerate (dark reddish brown, 10R 3/4) similar to in previous units, with thin, sub-horizontal reduction mottling. Channel deposits.

5) 10.07→14.47 m (thickness: 4.4 m) **upper unit of the Cooper Canyon Formation**
Very muddy fine grained sandstone with fine reduction mottling, complexly interbedded with almost pure claystone in the lower 60 cm. Overbank deposits. **Mudstone sample NSH-3** comes from these mud layers.

6) 14.47→19.87 m (thickness: 5.4 m) **upper unit of the Cooper Canyon Formation**
Friable fine to medium-grained sandstone showing more or less horizontal bedding with fine horizontal reduction mottling. Channel or proximal overbank deposits.

7) 19.87→20.67 m (thickness: 0.8 m) **upper unit of the Cooper Canyon Formation**
Resistant fine to medium-grained sandstone with horizontal bedding and reduction mottling, similar to unit 6. Channel or proximal overbank deposits.

8) 20.67→22.47 m (thickness: 1.8 m) **Macy Ranch sandstone**

Well cemented fine to medium-grained sandstone complexly interbedded with well cemented pebble conglomerate, sandstone dominating. Channel deposits.

9) 22.47→23.37 m (thickness: 0.9 m) **Macy Ranch sandstone**

Friable very fine to medium-grained horizontal planar bedded sandstone, complexly interbedded with well- cemented fine to medium grained sandstone.

NORTH FORK

Mudstone samples

N33°11’30” W101°12’16”

Justiceburg NW Quadrangle

Total thickness: 32 m

Figs. 2.25, A1.23

1) 0 m → 9 m (thickness: 9 m) **orangeish lower beds of the lower unit of the Cooper Canyon Formation**

Light brown (5YR 5/6) silty claystone, with occasional unusually large (half a meter or so across) yellowish gray (5Y 8/1) reduction mottles, usually surrounded by a thin halo of medium reddish brown (10R 4/6). Carbonate nodules of probable pedogenic origin are scattered throughout the section. Gradational shift to unit 2. Overbank deposits. Mudstone sample **North Fork-1** came from this unit.

2) 9 m → 13.5 m (thickness: 4.5 m) **reddish upper beds of lower unit of the Cooper Canyon Formation**

Moderate brown (5YR 3/4) claystone with little or no silt, with reduction zones and pedogenic carbonate nodules in lower part similar to those in unit 1 in the lower part becoming more scarce higher up in the unit. The uppermost meter or so is reduced greenish gray (5GY 6/1) claystone, and oddly the contact with the base of the Dalby Ranch sandstone here appears to be somewhat gradational. Overbank deposits.

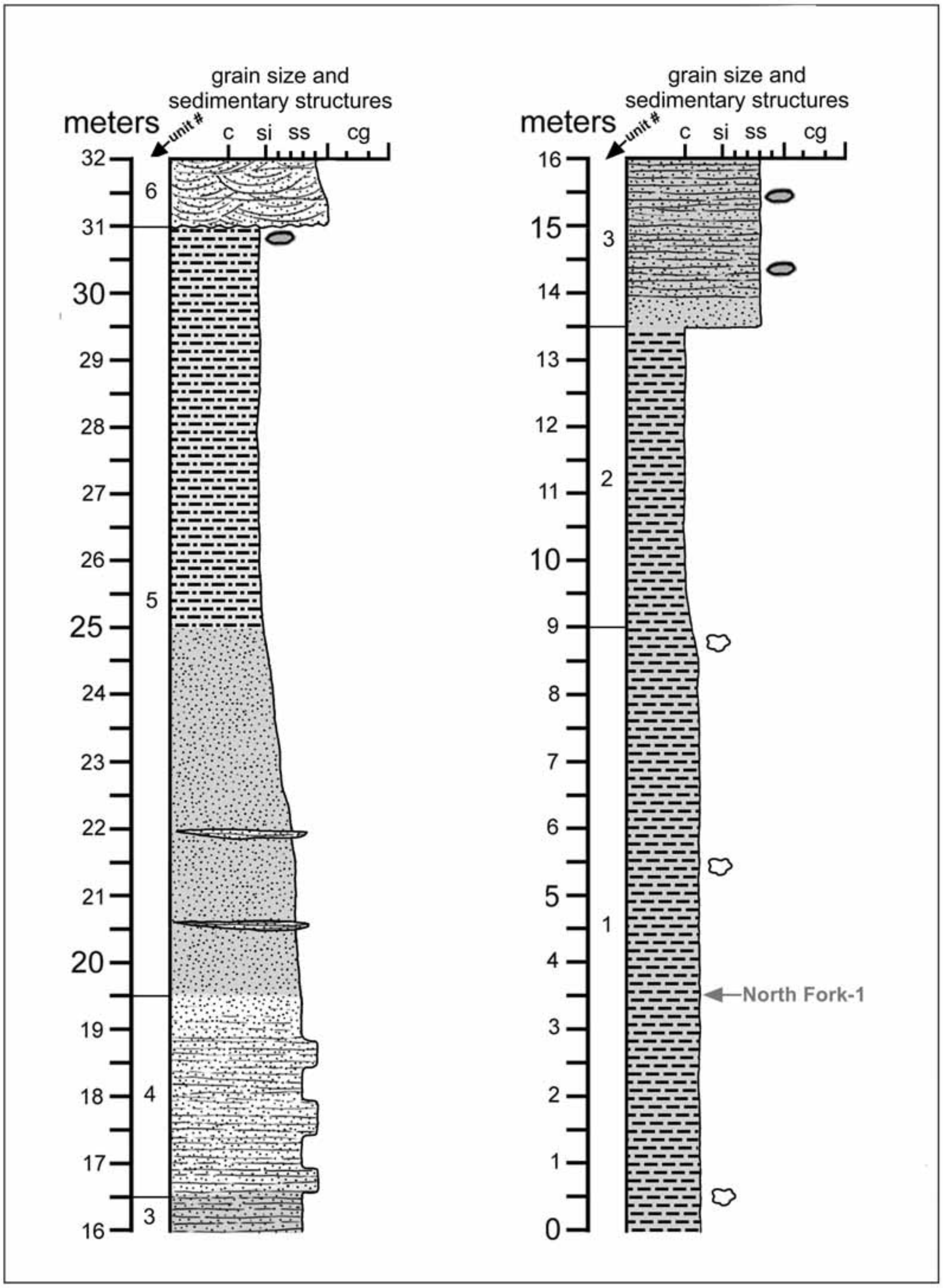

Fig. A1.23. North Fork measured section.

3) 13.5 m → 16.5 m (thickness: 3 m) **Dalby Ranch sandstone**

Greenish gray (5GY 6/1) muddy medium-grained sand lacking obvious bedding, becoming more clearly micaceous and developing horizontal parallel laminations higher up. Occasional small dark yellowish orange (10YR 6/6) concretions. Channel sandstone.

4) 16.5 m → 19.5 m (thickness: 3 m) **Dalby Ranch sandstone**

Greenish gray (5GY 6/1) interbedded medium and coarse-grained sandstone, mostly horizontal parallel laminated. Contact with next unit is more or less gradational. Channel sandstone.

5) 19.5 m → 31 m (thickness: 11.5 m) **middle unit of the Cooper Canyon Formation**

Generally fining upward sequence. About three meters of pale reddish brown (10R 5/4) muddy fine to medium-grained micaceous sandstone with lenses of reduced light greenish gray (5GY 8/1) medium to coarse grained horizontal parallel laminated sandstone, grading into dark reddish brown (10R 3/4) muddy very fine-grained sand, and then to siltstone of the same color, all with some light greenish gray (5GY 8/1) reduction spots and banding. Color shifts to yellowish gray (5Y 7/1) and becomes sandier, with dark yellowish orange (10YR 6/6) concretions, in uppermost one and a half meters or so. Proximal to distal overbank deposits.

6) 31 m → 32 m (thickness: 1 m) **middle unit of the Cooper Canyon Formation**

Mostly trough cross-bedded, very coarse-grained, generally light greenish gray (5GY 8/1) sandstone fining to coarse-grained sandstone, unusually siliceous although there are at least some sedimentary rock clasts. Channel sandstone.

OS RANCH GULLY

Mudstone samples, petrographic thin sections

N33°07’47” W101°07’51”

Justiceburg NW Quadrangle

Total thickness: 32.4 m

Fig. A1.24

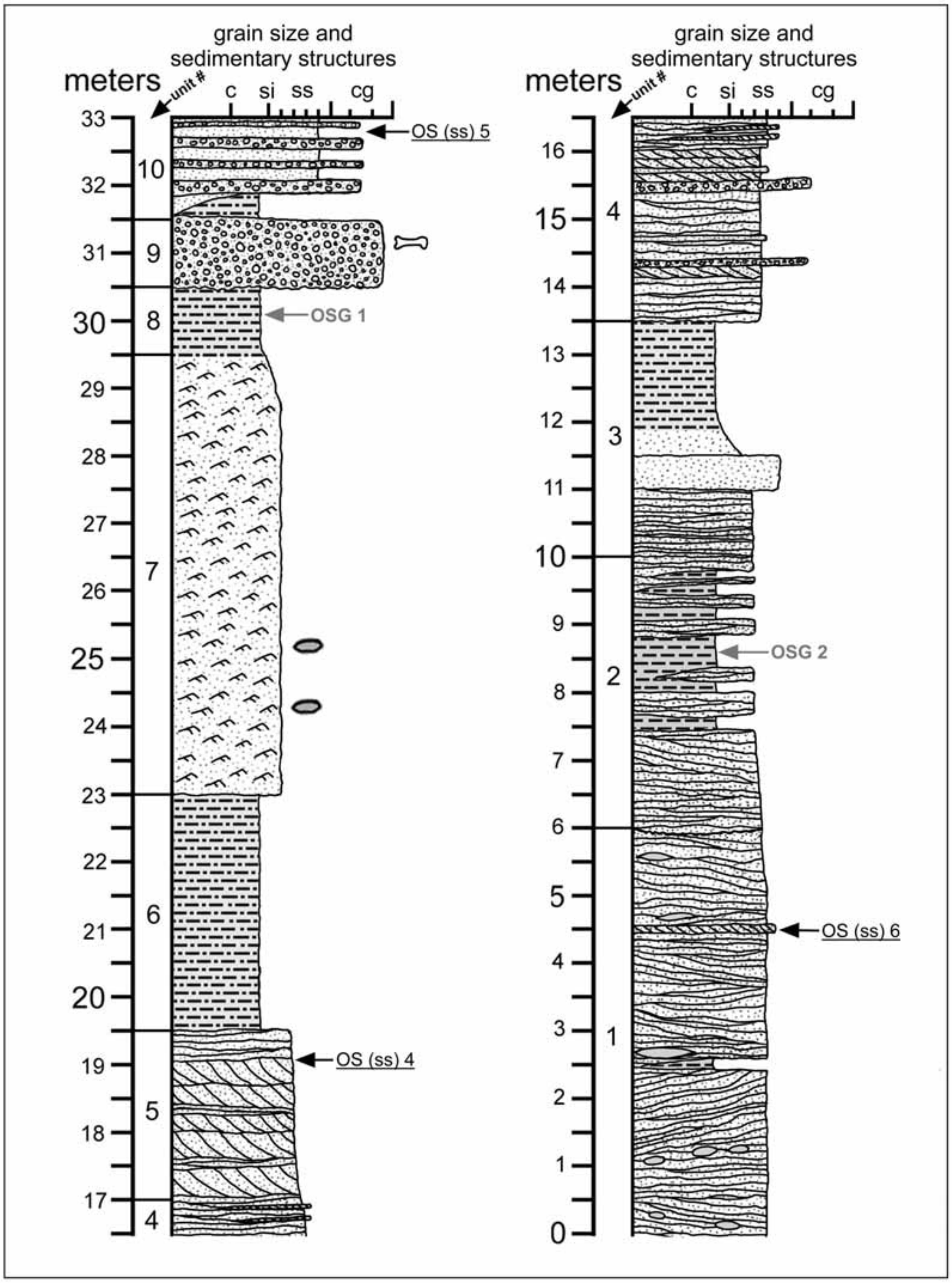

Fig. A1.24. OS Ranch Gully measured section.

This section, measured along the North Fork of the Double Mountain Fork of the Brazos, is shown in Fig. 2.14. Thin sections OS (ss) 2a-e came from a cliffside a short distance to the north of the OS Ranch Gully section, and represents roughly the same stratigraphic interval. Thin section OS (ss) 3 came from a short distance to the southwest, and is probably equivalent to the upper part of the Santa Rosa Sandstone in OS Ranch Gully section, below the lower Boren Ranch sandstone. The approximate stratigraphic position of these thin sections is noted, as are thin sections OS (ss) 4-6, which were obtained from the OS Ranch Gully section itself.

1) 0 → 6 m (thickness: 6 m) **Santa Rosa Sandstone**

Dominated by friable medium reddish brown (10R 4/6) and yellowish gray (5Y 8/1) medium grained sandstone with horizontal and gently dipping bedding, although there are also numerous lenses of well-cemented, medium grained sandstone, and round pockets and lenses of medium reddish brown (10R 4/6) mudstone. The resistant sandstone and mudstone lenses become generally less common above 3 m, although petrographic thin section OS (ss) 6 came from a resistant bed at about 4.5 m. The upper 1.5 meters of friable sandstone lightens to yellowish gray (5Y 8/1), grayish orange (10YR 7/4), and lesser medium reddish brown (10R 4/6), with some interbedded mudstone. Channel sandstone. Thin sections OS (ss) 2a-c come from approximately the same stratigraphic interval.

2) 6.0 m → 10.0 m (thickness: 4.0 m) **Santa Rosa Sandstone and mottled beds**

Generally fining upward sequence, friable planar bedded fine-grained sandstone banded yellowish gray (5Y 8/1) and dark reddish brown (10R 3/4), with very thick interbedded medium reddish brown (10R 4/6) muddy siltstone. Petrographic thin section OS (ss) 2d came from a stratigraphic level probably roughly equivalent to this unit. Mudstone sample **OSG-2** came from one of the mudstone lenses. This fining upwards sequence is truncated by a lower Boren Ranch sandstone, but laterally this lens pinches out at the margins of the lower Boren Ranch sandstone lens are mottled beds of gray, brown, and purple. Pedogenically altered channel sandstone.

3) 10.0 m → 13.5 m (thickness: 3.5 m) **lower Boren Ranch sandstone**

Generally fining upward sequence. About 1 m of friable grayish horizontal planar bedded fine-grained sandstone, followed by .5 m of coarse-grained, well-cemented sandstone, followed by medium reddish brown (10R 4/6) and yellowish gray (5Y 8/1) banded muddy very fine-grained sandstone grading into medium reddish brown (10R 4/6) muddy silt. Channel sandstone.

4) 13.5 m → 17.0 m (thickness: 3.5 m) **lower Boren Ranch sandstone**

Resistant grayish fine to medium grained, horizontal planar and cross-bedded sandstone, with some thin, less resistant interbedded lenses of friable granule conglomerate and medium-grained sandstone. In the upper meter, becomes dominated by the friable grayish horizontal planar bedded medium-grained sandstone, interbedded with more resistant cross-bedded medium to coarse-grained sandstone. A few gravel-sized clasts are scattered throughout the sandstones, mostly reworked sedimentary rock clasts, but some are siliceous. Channel sandstone.

5) 17.0 m → 19.5 m (thickness: 2.5 m) **lower Boren Ranch sandstone**

Very resistant, strongly cross-bedded fine-grained sandstone. <u>OS (ss) 4</u> was collected from this sandstone, which has excellent exposure up the gully. This may be the same sandstone forming the base of the section measured for the Petrified Grove and OS Ranch vertebrate localities. Channel sandstone.

6) 19.5 m → 23.0 m (thickness: 3.5 m) **Boren Ranch beds**

The strata between the lower and upper gray sandstones are very poorly exposed here. Directly above the lower Boren Ranch sandstone is greenish gray (5GY 6/1) to light olive gray (5Y 6/1) muddy silt. Lacustrine and/or overbank deposits

7) 23.0 → 29.5 m (thickness: 6.5 m) **Boren Ranch beds**

Ripple cross-laminated very fine-grained sandstone. The base is a resistant yellowish gray (5Y 7/2) lens, followed by friable greenish gray (5GY 6/1) containing abundant yellowish concretions; petrographic thin section sample <u>OS (ss) 3</u> came from a sandstone probably roughly equivalent to this interval. At about 3.0 m, there is a color shift to yellowish gray (5Y 7/2). Lacustrine and/or overbank deposits.

8) 29.5 → 30.5 m (thickness: 1.0 m) **Boren Ranch beds**

Dark reddish brown (10R 3/4) siltstone. Mudstone sample **OSG-1** came from this level. Overbank deposits.

9) 30.5 m → 31.5 m (thickness: 1.0 m) **upper Boren Ranch sandstone**

Massive, resistant, pebble-cobble (some clasts reach 10 cm or more) conglomeritic sandstone, dominated by reworked sedimentary rock clasts but also with some siliceous clasts and vertebrate bone. Channel gravels.

10) 31.5 m → ~33.0 m (thickness: 1.5 m) **upper Boren Ranch sandstone**

Interbedded granule-pebble conglomerate and medium to very coarse-grained sandstone. There is a very thick (about 40 cm) discontinuous lens of silty mudstone at the base of the unit. Channel deposits. Thin section OS (ss) 5 came from this unit.

PARKS CLIFFSIDE

Mudstone samples

N32°57’59” W101°12’34”

Fluvanna Quadrangle

Thickness: 227.03 m

Figs. A1.25, A1.26

This section begins immediately above the Meyer’s Hill section, and covers the middle and upper units of the Cooper Canyon Formation up to where it is truncated by the Cretaceous, measured along the east side of one of the massive Cretaceous-capped cliffs in southern Garza County. This is an enormously thick section of strata, and above the Dalby Ranch sandstone it is generally poorly exposed along this cliffside except for a few large outcrops. The section is striking in its generally monotonous mudstone-dominated nature except for a couple somewhat prominent sandstone units exposed near the very top, which can probably be traced around to the west side of the cliff. As already noted, there is no clear transition between the middle and upper units, so these are simply referred to here as the “Cooper Canyon Formation.” Most of the upper part of the section exposed on these cliffs in southern Garza is inaccessible. It should be borne in

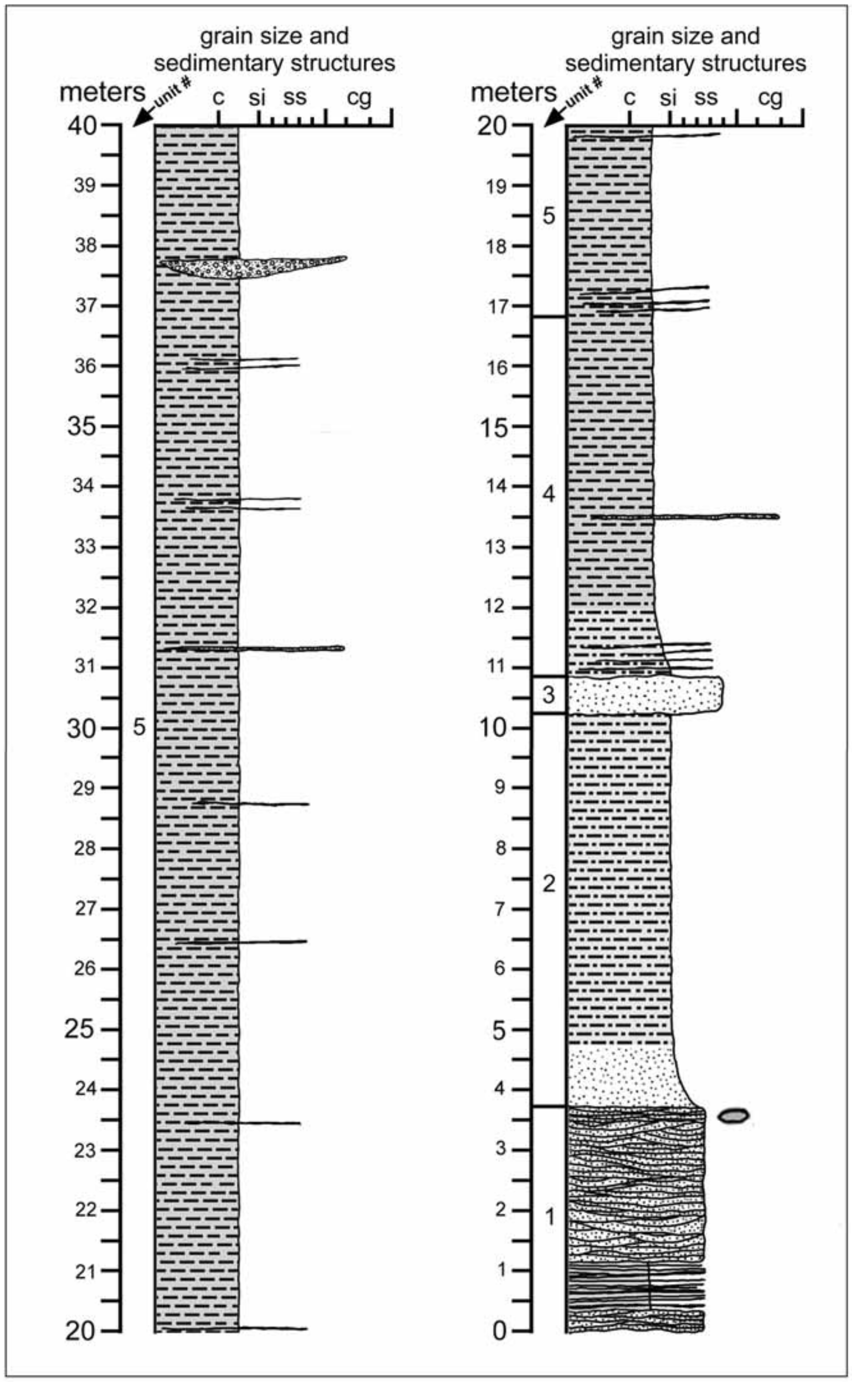

Fig. A1.25. Parks Cliffside measured section (lower part)

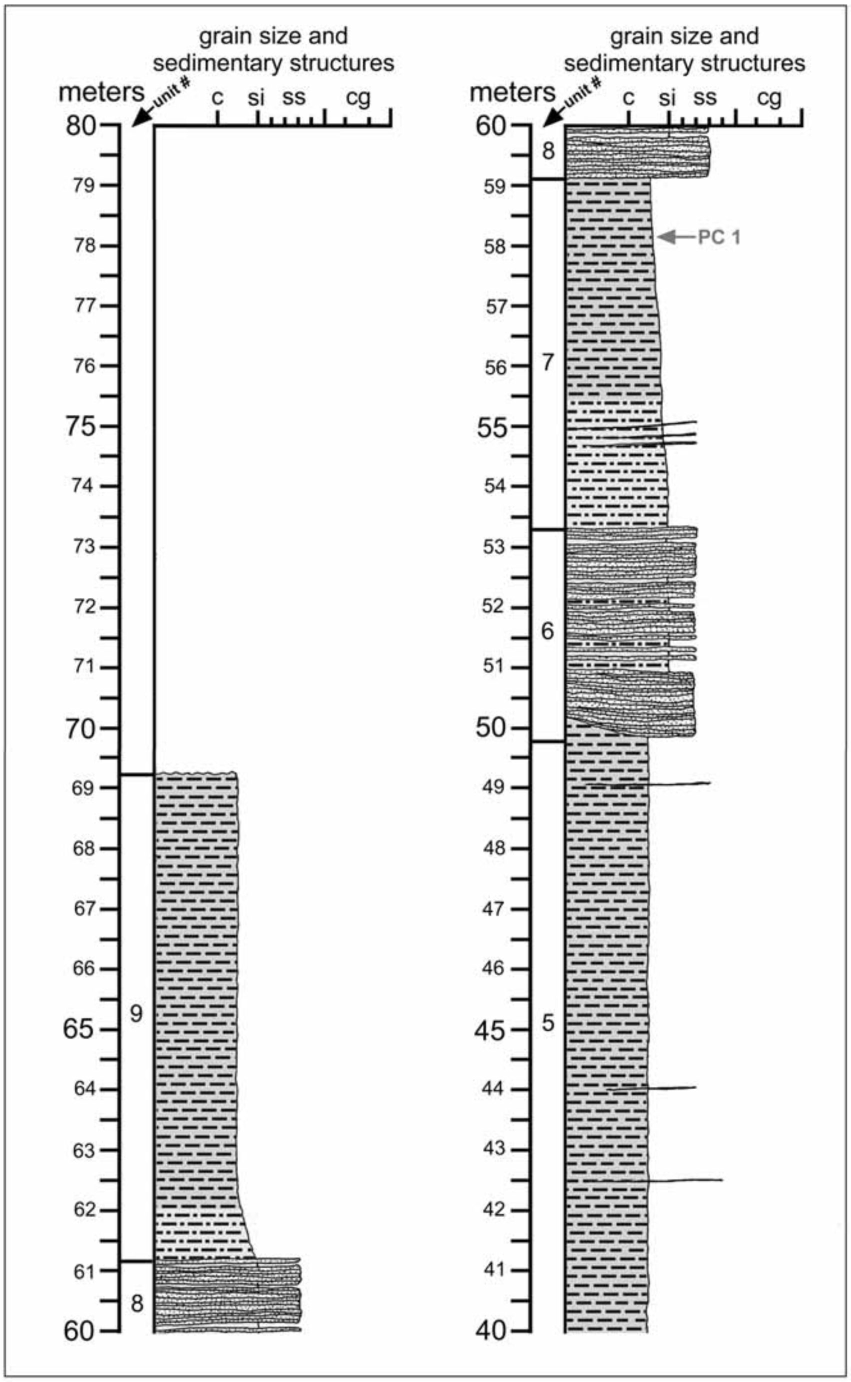

Fig. A1.26. Parks Cliffside measured section (upper part).

mind that this section represents a composite of several patchy outcrops measured along gullies along the cliff, and there is considerable lateral heterogeneity in the section. In a section this thick, especially given the composite nature of it, some degree of error should be taken into account. I get a total of 344.37 feet for the combined Meyer's Hill and Parks Cliffside sections, or 227.03 feet just for the Parks Cliffside section, including the Dalby Ranch. Drake's (1892, pl. V) section 5 was probably measured a few kilometers to the west of here, along the northwest facing surface of an adjacent cliff capped by Cretaceous strata and the Ogallala Formation.

1) 0 m → 3.7 m (thickness: 3.7 m) **Dalby Ranch sandstone**

Light greenish gray (5GY 8/1) horizontal planar bedded and shallow trough cross-bedded fine to medium-grained sandstone, finely interbedded in the lower part of the unit with siltstone of the same color, sometimes occurring as rip-up clasts. Large mottles of dusky yellow (5Y 6/9) occur throughout, and the upper part of the unit contains numerous small (generally grape-sized) concretions of the same color. Large channel sandstone.

2) 3.7 m → 10.2 m (thickness: 6.5 m) **Cooper Canyon Formation**

Mottled medium reddish brown (10R 4/6) and dusky yellow (5Y 6/4) muddy fine-grained sandstone, grading into silt of the same color. Overbank deposits.

3) 10.2 m → 10.8 m (thickness: 0.6 m) **Cooper Canyon Formation**

Fairly structureless well-cemented medium to coarse-grained sandstone about 60 cm thick. This seems to be a laterally discontinuous lens. Small channel sandstone.

4) 10.8 m → 16.8 m (thickness: 6 m) **Cooper Canyon Formation**

Dark reddish brown (10R 3/4) siltstone fining up into silty claystone containing a few thin (couple centimeter thick) lenses of medium-grained sandstone in the lower 50 cm or so and a lens about 10 cm thick of granule pebble conglomerate higher up. Overbank deposits with interbedded sheet sands and small channel gravels.

5) 16.8 m → 49.8 m (thickness: 33 m) **Cooper Canyon Formation**

Medium reddish brown (10R 4/6) silty claystone containing greenish gray (5GY 6.1) reduction mottling, similar to most of previous unit except for a subtle color shift. Scattered throughout are thin, discontinuous lenses of generally fine to coarse grained sandstone (sometimes ripple bedded), and granule conglomerate, nearly all less than five centimeters thick, although at least one conglomeritic lens 60 cm thick was noted. Overbank deposits with interbedded sheet sands and small channel gravels.

6) 49.8 m → 53.3 m (thickness: 3.5 m) **Cooper Canyon Formation**

Mostly horizontal planar-bedded fine-grained sandstone, complexly interbedded with siltstone. Channel sandstone.

7) 53.3 m → 59.1 m (thickness: 5.8 m) **Cooper Canyon Formation**

Medium reddish brown (10R 4/6) siltstone containing a few thin (couple centimeters thick) lenses of fine-grained sandstone, fining up into silty claystone, all with sparse greenish gray (5GY 6/1) reduction mottling. Overbank deposits. Sample **Parks Cliffside-1** was taken from about a meter below the top of the unit.

8) 59.1 m → 61.2 m (thickness: 2.1 m) **Cooper Canyon Formation**

Mostly horizontal planar-bedded, medium-grained sandstone, complexly interbedded with siltstone. Channel sandstone.

9) 61.2 m → 69.2 m (thickness: 8 m) **Cooper Canyon Formation**

Medium reddish brown (10R 4/6) silty claystone with sparse greenish gray (5GY 6/1) reduction mottling. Overbank deposits.

PENNINUSLA HILL

N33º02’07” W101º25’06”

Miller Creek Quadrangle

Total thickness: 18.11 m

Figs. 2.19b, A1.27

1) 0 m → 3.0 m (thickness: 3.0 m) **middle unit of the Cooper Canyon Formation**

Moderate brown (5YR 4/4) silty claystone with abundant fine sand-sized mica flakes and a few very thin (less than 10 cm thick) lenses of well-cemented, clast-supported, very fine to fine-grained micaceous sandstone, and extremely large sporadic light greenish gray (5G 8/1) reduction mottles sometimes but not always associated with the sandstone. The sandstone lenses become especially dense in the upper 10-20 cm of the unit. Overbank

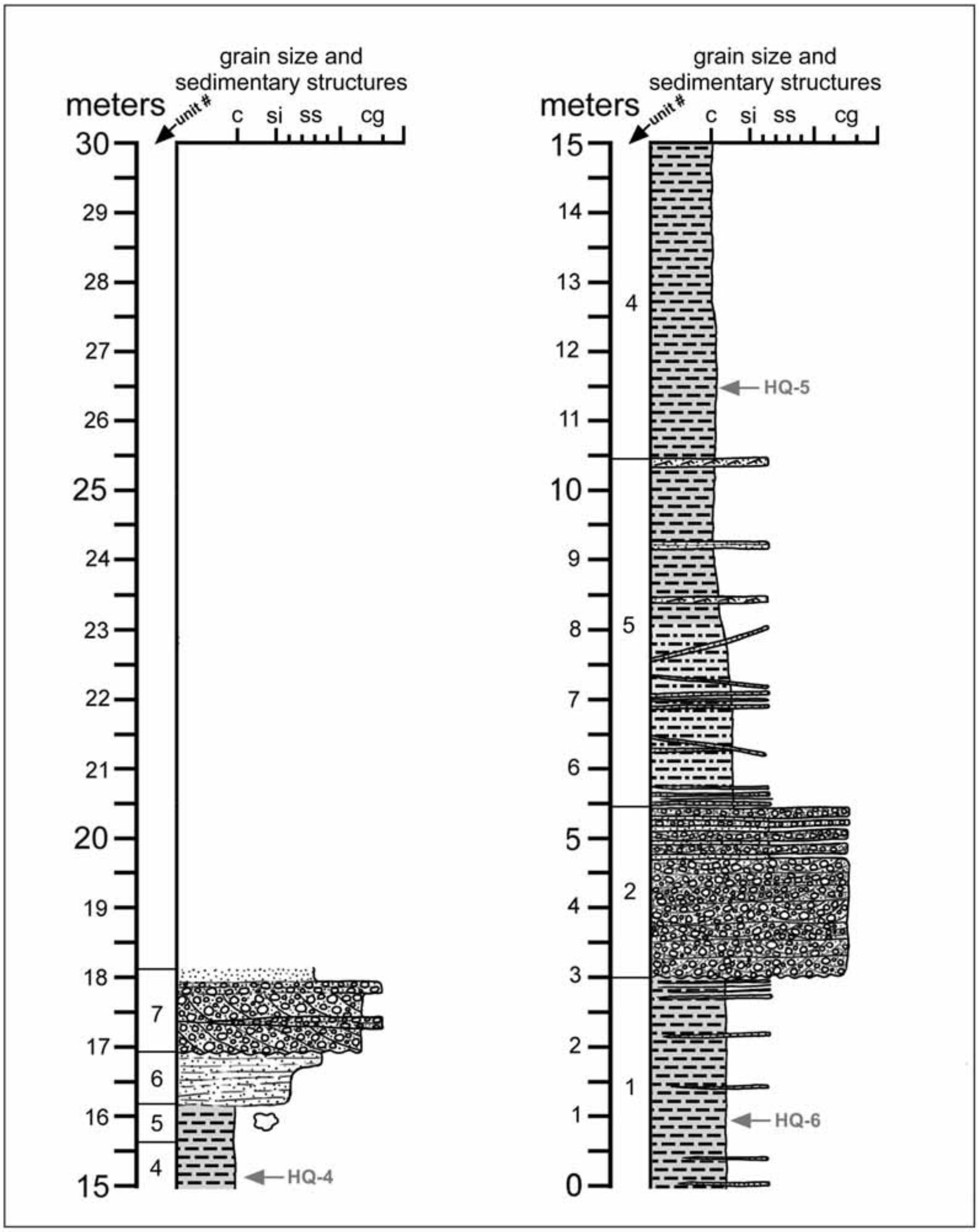

Fig. A1.27. Penninsula Hill measured section.

deposits and sheet sands. Mudstone sample HQ-6 comes from about a meter above the base of the unit.

2) 3.0 m → 5.45 m (thickness: 2.45 m) **middle unit of the Cooper Canyon Formation**
Trough cross-bedded clast-supported granule to pebble conglomerate, becoming interbedded near the top with a thick booklet (about 25 cm thick) of very fine-grained to fine-grained horizontal planar bedded and ripple cross-laminated sandstone and of siltstone. Channel conglomeritic sandstone. This sandstone may be equivalent to the conglomeritic sandstone unit at Lott Hill a few kilometers to the south.

3) 5.45 m → 10.45 m (thickness: 5.0 m) **middle unit of the Cooper Canyon Formation**
Moderate brown (10R 4/6) silty claystone as in unit 1 but becoming less silty higher in the section, interbedded with thick horizontal or slightly dipping booklets (1 or more cm thick) of horizontal planar bedded and ripple cross-laminated clast-supported very fine to fine-grained sandstone, with light greenish gray (5G 8/1) reduction mottling finer then in unit 1, and more obviously parallel to the sandstone layers.

4) 10.45 m → 15.61 m (thickness: 5.16 m) **middle unit of Cooper Canyon Formation**
Moderate brown (5YR 4/4) slightly silty claystone with fine, somewhat random greenish gray (5G 8/1) mottling as in unit 3, grading to moderate brown (5YR 3/4) almost pure claystone about halfway through the unit. Mudstone sample **HQ-5** comes from about a meter above the base of the unit, and sample **HQ-4** comes from near the top of the unit.

5) 15.61 m → 16.21 m (thickness: 0.6 m) **middle unit of Cooper Canyon Formation**
Greenish gray (5GY 6/1) mudstone with abundant pedogenic carbonate nodules.

6) 16.21 m → 16.91 m (thickness: 0.7 m) **middle unit of Cooper Canyon Formation**
Greenish gray (5GY 6/1), friable, clast supported, very fine-grained quartzose and micaceous sandstone, with extremely faint planar bedding, grading into better cemented, medium to coarse-grained sandstone.

7) 16.91 m → 18.11 m (thickness: 1.2 m) **Route 669 Roadcut sandstone**
Conglomerate, mostly reworked sedimentary rock clasts, consisting of interbedded granule conglomerate with large scale planar cross-bedding and pebble conglomerate

with at best faint planar cross bedding, capped with a structureless medium-grained sandstone. Forms top of hill.

SOUTH CYCLE RANCH

Mudstone samples

N33º04’44” W101º25’19”

Miller Creek Quadrangle

Total thickness: 27.3 m

Fig. A1.28

The section was measured on the western side of the hill, although scrappy vertebrate material was collected by Doug Cunningham on the east side, in beds equivalent to the base of the section. Unlike most places where it was examined, the Kirkpatrick Ranch sandstone here is unusually conglomeritic.

1) 0 →7.3 m (thickness: 7.3 m) **upper unit of the Cooper Canyon Formation**
Fairly uniform moderate reddish brown (10R 4/6) slightly silty claystone with prolific light greenish gray (5GY 8/1) reduction spots in a random pattern, with a few thin (only a few centimeters thick) discontinuous lenses of slightly coarser-grained planer bedded silt. The top of the unit, at the base of unit 2, is a heavily reduced layer with the same color as the reduction spots. Overbank deposits and sheet flood deposits. Mudstone sample **Patty-7** comes from about 4.5 m.

2) 7.3 → 7.7 m (thickness: .5 m) **upper unit of the Cooper Canyon Formation**
Horizontal planar-bedded silt to very fine-grained sandstone, the lower part mostly horizontal planar-bedded and the upper part mostly ripple cross-laminated, with structureless beds interbedded. Sheet sand.

3) 7.7 → 12.7 m (thickness: 5 m) **upper unit of the Cooper Canyon Formation**
Silty claystone (10R 4/6) with reduction spots (5GY 8/1) similar to unit 1, except that the reduction spots seem to be arranged in a more layered fashion, with interbedded coarser lenses. The lower lenses are matrix-supported conglomeritic sandstone 10 cm or less thick, mostly medium to coarse-grained sandstone but with some larger pebble-sized

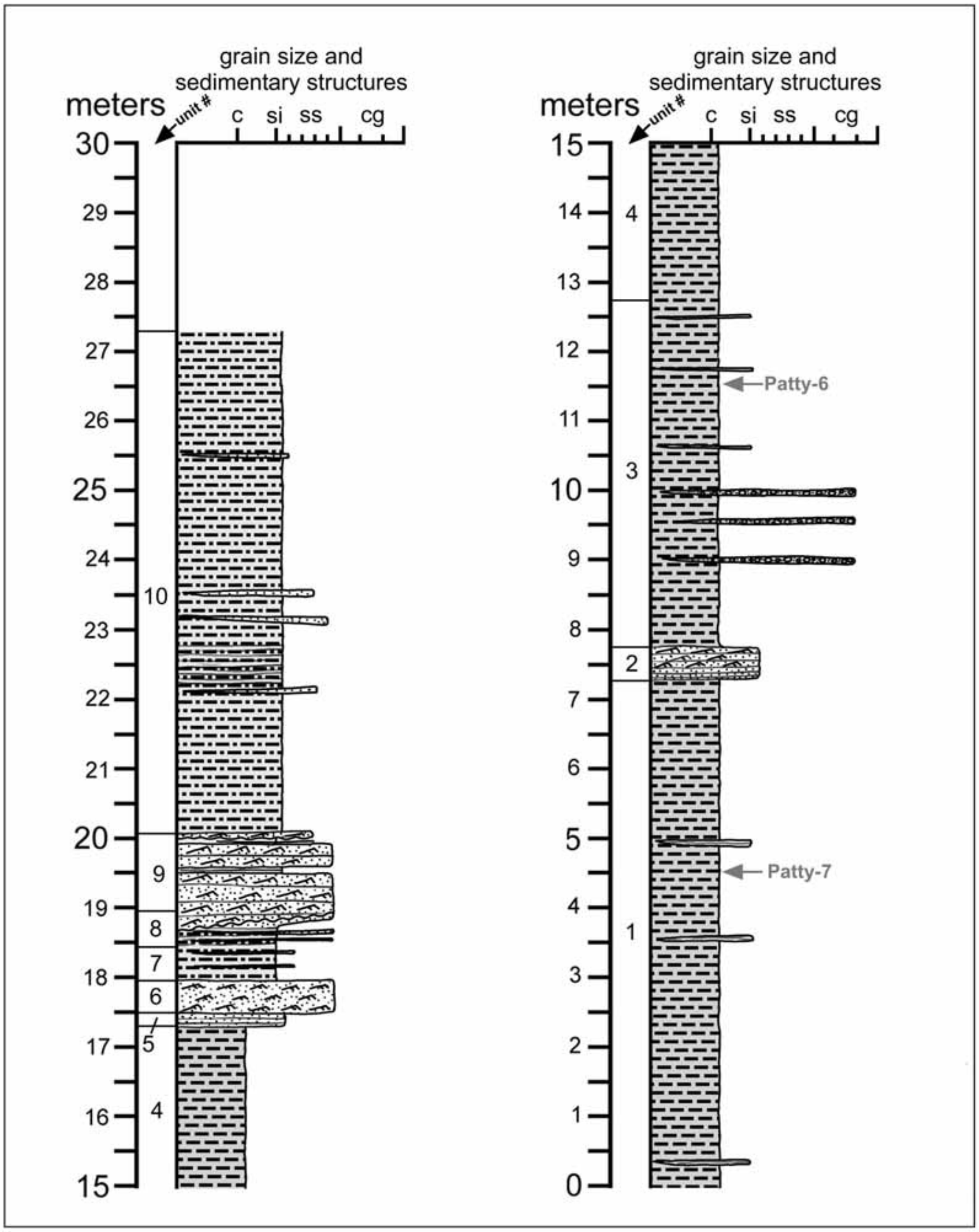

Fig. A1.28. South Cycle Ranch measured section.

(about 1-2 cm in diameter) sedimentary rock clasts. Higher up the lenses are finer, planar laminated silt. Overbank deposits and sheet flood deposits. Mudstone sample **Patty-6** comes from about 11.5 m.

4) 12.7 → 17.3 m (thickness: 4.6 m) **upper unit of the Cooper Canyon Formation**

Silty claystone as in unit 4, but lacking the coarser lenses. The top .8 m shows a color change to dark reddish-brown (10R 3/4) with the reduction mottling becoming thin ribbons of greenish gray (5G 6/1), topped by a thick reduced layer of the same color under the base of unit 6 about .2 m thick.

5) 17.3 →17.5 m (thickness: .2 m) **Kirkpatrick Ranch sandstone**

Horizontal planar bedded silt to very fine-grained sand.

6) 17.5 → 17.9 m (thickness: .4 m) **Kirkpatrick Ranch sandstone**

Faintly ripple cross-laminated coarse to very coarse-grained sand.

7) 17.9 → 18.4 m (thickness: .5 m) **Kirkpatrick Ranch sandstone**

Reduction mottled extremely micaceous siltstone, interbedded with horizontal planar-bedded fine to very fine-grained sandstone lenses a few cm thick.

8) 18.4 → 18.9 m (thickness: .5 m) **Kirkpatrick Ranch sandstone**

Horizontal planar-bedded siltstone with lenses of muddy coarse to very coarse-grained sandstone, grading up into ripple cross-laminated coarse to very coarse-grained sandstone. In places, the ripple cross-laminated sandstone is truncated by unit 9.

9) 18.9 → 20.3 m (thickness: 1.4 m) **Kirkpatrick Ranch sandstone**

Ripple cross-laminated sandstone, mostly coarse to very coarse sand with a few gravel-sized clay clasts a few millimeters in diameter. An extremely thin horizontal planar-bedded layer of siltstone to very fine-grained sandstone is sandwiched in about 60 cm from the top. On top is siltstone with a very fine-grained sandstone lens inside, topped by a ripple cross-laminated fine to medium-grained sandstone.

10) 20.3 → 27.3 m (thickness: 7 m) **upper unit of the Cooper Canyon Formation**

Moderate red-orange (10R 6/6) siltstone to very fine-grained sandstone with greenish gray (5GY 6/1) random reduction mottling, mostly structureless although with some horizontal planar bedding. Contains sandstone lenses varying from very fine-grained to coarse-grained. Most are horizontal planar-bedded, but the coarse grained sandstone lens at about 23 m contains cross bedding. This unit forms the top of the hill (truncated by erosion).

SOUTH MIDDLE CREEK

Mudstone samples

N33°01’44” W101°25’15”

Miller Creek Quadrangle

Total thickness: 21.90 m

Fig. A1.29

This section was measured near the north bank of the South Fork of the Double Mountain Fork of the Brazos River close to where Middle Creek flows into it, in sight of the Lott Hill vertebrate locality near the south bank. The somewhat monotonous overbank deposits below the Route 669 Roadcut sandstone are arbitrarily assigned to the base of the Upper Cooper Canyon Formation, although at least the lower part of the sequence could arguably be assigned to the Lower unit. The Route 669
Roadcut sandstone is remarkable siliceous here judging from hand samples, which is interesting given that the extremely siliceous Bauchier Ranch sandstone outcrops a few kilometers to the south not much lower in the section.

1) 0 m → 8.15 m (thickness: 8.15 m) **middle unit of the Cooper Canyon Formation**
Moderate reddish brown (10R 4/6) silty claystone with tiny light greenish gray (5G 8/1) reduction spots, becoming siltstone with more prominent reduction spots in the upper 1.5 meters, with two sandstone layers at the top. First sandstone at 7.85 m is about 10 cm thick and a light greenish gray (5G 8/1) matrix supported, medium to coarse-grained sandstone. The second, sandstone is a well-cemented, clast-supported, fine- grained sandstone less than 1 cm thick. Overbank deposits and sheet sands. Mudstone sample **HQ-3** comes from about 2.0 m above the base of the unit.

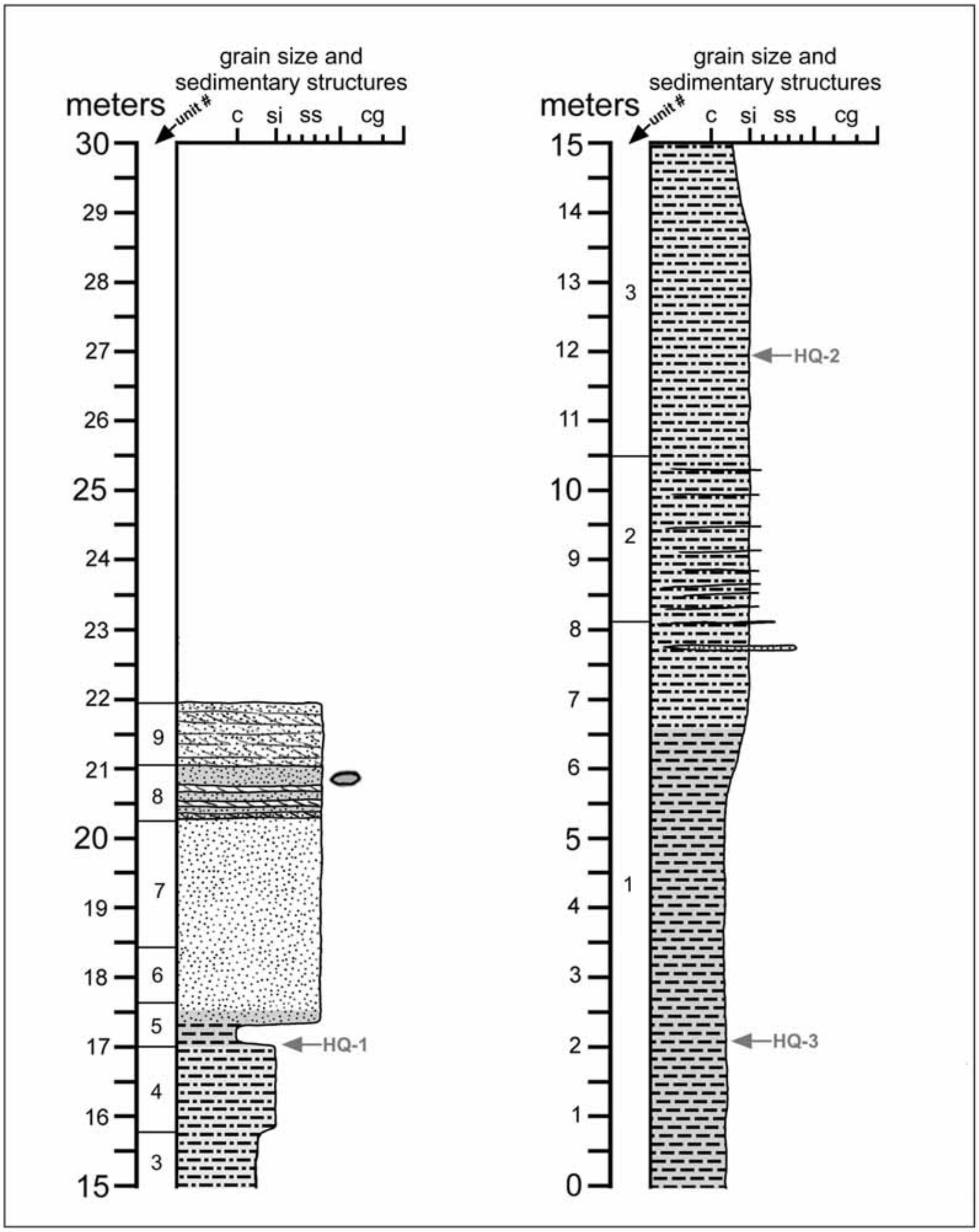

Fig. A1.29. South Middle Creek measured section.

2) 8.15 m → 10.5 m (thickness: 2.35 m) **middle unit of the Cooper Canyon Formation**
Light brown (5YR 5/6) siltstone with a little very fine-grained sand and light greenish gray (5G 8/1) reduction spots, containing about several thin (about 1 cm thick) discontinuous lenses of well-cemented, clast supported, horizontal planar-bedded, fine-grained sandstone, becoming more widely spaced near the top. Overbank deposits and sheet sands.

3) 10.5 m → 15.75 m (thickness: 5.25 m) **middle unit of Cooper Canyon Formation**
Light brown (5YR 5/6) siltstone with light greenish gray (5G 8/1) reduction spots, becoming increasing claystone near the top. The reduction spots are more widely-spaced and particularly massive near the bottom of the unit, and get much finer near the top. Overbank deposits. Mudstone sample **HQ-2** comes from about 1.5 m from the base of the unit.

4) 15.75 m → 17.0 m (thickness: 1.25 m) **middle unit of Cooper Canyon Formation**
Dark reddish brown (10R 3/4) siltstone, color shift from previous unit drastic. Overbank deposits. Mudstone sample **HQ-1** come from the top of the unit.

5) 17.0 m → 17.65 m (thickness: 0.65 m) **middle unit of Cooper Canyon Formation**
Moderate greenish yellow (10Y 7/4) almost pure claystone grading into pale olive (10Y 6/2) muddy medium to coarse-grained quartz-rich micaceous sandstone containing large clasts of the gray mudstone, capped with well cemented, 15 cm thick sandstone layer of same type and color. Proximal overbank deposits?

6) 17.65 m → 18.4 m (thickness: 0.75 m) **Route 669 Roadcut sandstone**
Light bluish gray (5B 7/1), mostly friable, very well-sorted siliceous medium to coarse-grained sandstone, with one 20 cm thick well-cemented layer about 15 cm above the base. Channel deposits?

7) 18.4 m → 20.2 m (thickness: 1.8 m) **Route 669 Roadcut sandstone**
Well-sorted, siliceous pale olive (10Y 6/2) friable sandstone, with some well cemented patches in the top 70 cm. Channel deposits?

8) 20.2 m → 21.1 m (thickness: 0.9 m) **Route 669 Roadcut sandstone**
Somewhat muddy, medium to coarse-grained greenish gray (5G 6/1) sandstone, with a few interbedded layers of well-sorted, siliceous, well-cemented sandstone, medium to coarse grained sandstone of the same type with cross-bedding, each 10 cm or less thick. Light brown (5YR 5/6) concretions are present in the muddy sandstone near the top of the unit. Channel deposits.

9) 21.1 m → 21.9 m (thickness: 0.8 m) **Route 669 Roadcut sandstone**
Well-sorted, well-cemented, cross-bedded, siliceous, medium to coarse-grained sandstone as in the interbedded layers in previous unit. Channel deposits.

SOUTH WOOLAM RANCH

N33°02’27” W101°20’14”

Cooper Creek Quadrangle

Total thickness: 61.65 m

Figs. A1.30, A1.31

This section was measured very close to Riley Miller’s fenceline at the southeastern tip of the Caprock Finger. Here, a gulley is deeply incised through the Miller Ranch sandstone to the base of a mesa capped by the Macy Ranch sandstone and Ogallala, so a section including both the Miller Ranch sandstone and Macy Ranch sandstone is possible. The Miller Ranch sandstone consists of two closely associated sandstones, both of which can be traced for several kilometers northeast along the Caprock Finger. The Dalby Ranch sandstone and Cooper Creek Beds are absent here, or possibly just slightly down section in the subsurface. In the middle of the gully, the Miller Ranch sandstone itself is thinned almost to nothing, so the lower part of the section was measured along the eastern side of the gully. Drake’s (1892, pl. V) section 6 was probably measured somewhere very close to here.

1) 0 m → 12.6 m (thickness: 12.6 m) **middle unit of the Cooper Canyon Formation**
Dark reddish brown (10R 3/4) mudstone with greenish gray (5G 6/1) reduction mottling. The lower 5.5 m is siltstone with especially dense mottling, changing abruptly to silty

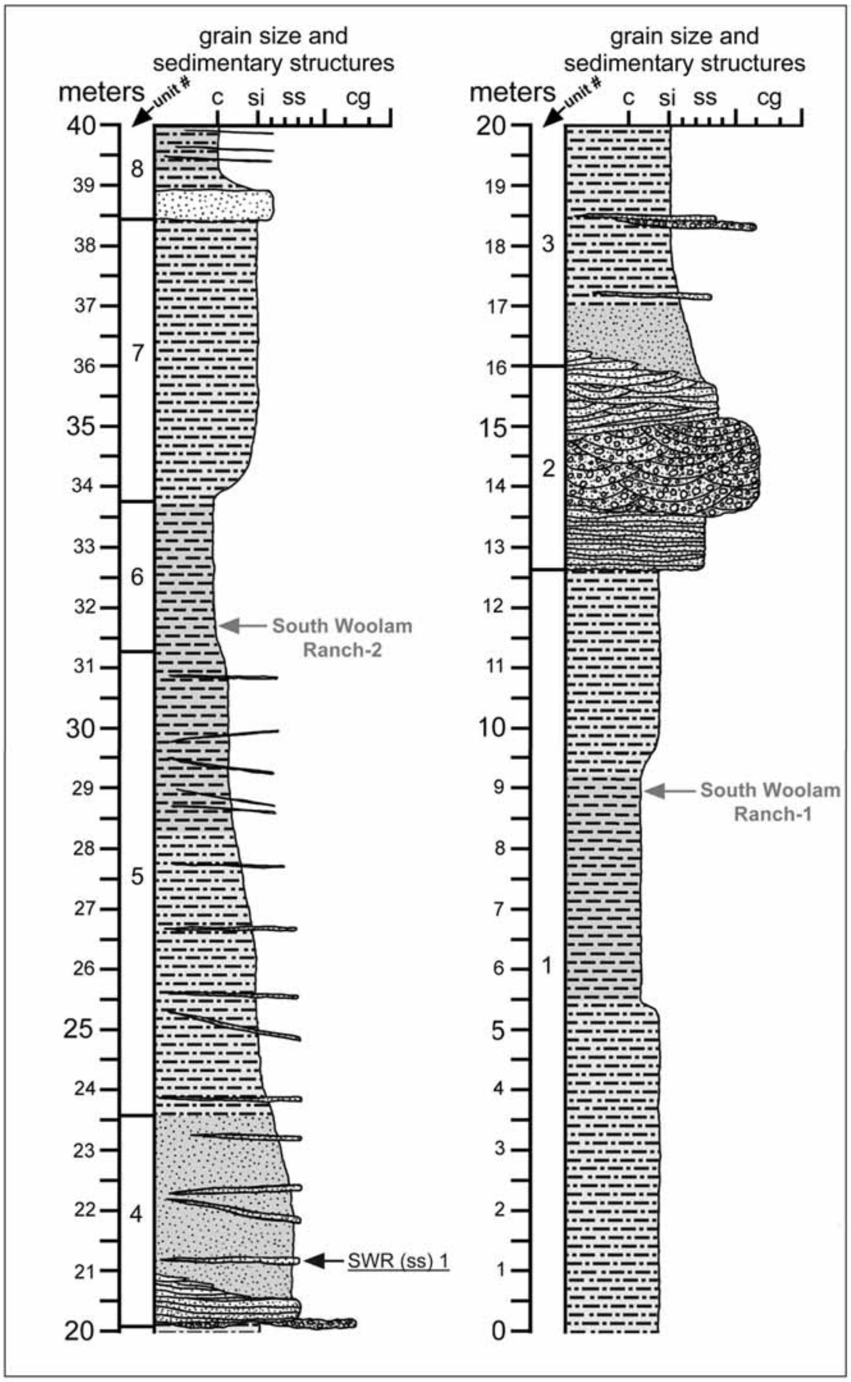

Fig A1.30. South Woolam Ranch measured section (lower part)

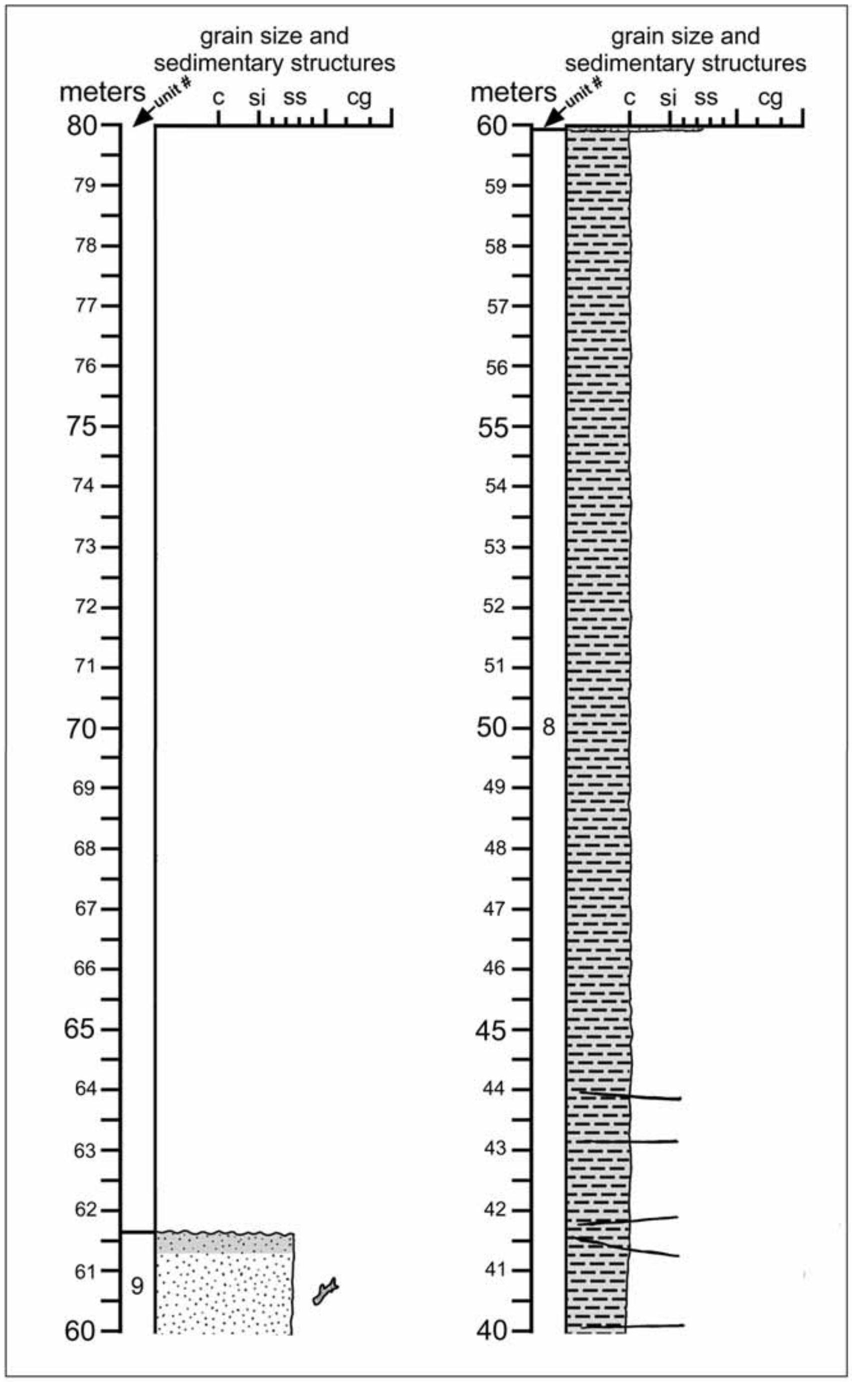

Fig. A1.31. South Woolam Ranch measured section (upper part).

claystone, and then grading back into muddy siltstone in the upper 4 meters. The reduction mottling is less dense above the lower muddy siltstone. There is a irregular zone of greenish gray reduction in the topmost 50 cm, sometimes with a very thin layer of dark yellowish orange (10YR 6/6) within it containing gypsum; unlike most gypsum in the Dockum Group, this layer seems to be horizontal, and may have been formed syndepositionally. Overbank deposits, possibly with ephemeral pools? Mudstone sample **South Woolam Ranch-1** (not analyzed) was taken from the top of the silty claystone.

2) 12.6 m → 16 m (thickness: 3.4 m) **Miller Ranch sandstone**

Complexly interbedded sandstone and conglomerate. The lower meter or so is dominantly horizontal planar bedded fine to medium-grained sandstone, followed by trough cross-bedded and planar cross-bedded granule conglomerate with some pebble-sized clasts (mostly reworked sedimentary rock clasts, although there is also quite a bit of quartzite) and medium to coarse-grained sandstone. The top of the unit is gradational with the overlying unit. Channel sandstone.

3) 16 m → 20.15 m (thickness: 4.15 m) **middle unit of the Cooper Canyon Formation**

Friable dark reddish brown (10R 3/4) and greenish gray (5G 6/1) muddy fine to medium-grained sandstone, grading up into siltstone. There are discontinuous lenses of well-cemented sandstone and conglomerate, generally 10-20 cm thick, mostly horizontal planar-bedded medium-grained sandstone and reworked sedimentary rock clast granule conglomerate. Overbank deposits.

4) 20.15 m → 23.65 m (thickness: 3.5 m) **upper Miller Ranch sandstone**

Medium-grained, mostly horizontal planar bedded sandstone about 40 cm thick, locally with muddy reworked sedimentary rock clast granule to pebble conglomerate at its base, grading up into muddy fine to medium-grained sand interbedded with thin (about 10 cm thick) medium-grained sandstone similar to that at the base, some showing distinct dip of a few degrees. This unit can locally be as thick as the Miller Ranch sandstone proper, and is gradational with the overlying unit. Thin section sample <u>SWR (ss) 1</u> was taken from one of the thinner sandstone lenses. Channel sandstone.

5) 23.65 m → 31.35 m (thickness: 7.7 m) **upper unit of the Cooper Canyon Formation**
Moderate brown (5YR 4/4) siltstone grading up into silty claystone with greenish-gray reduction mottling arranged in more or less horizontal layers, interbedded with very thin (few centimeters thick) well-cemented sandstone lenses, the lower ones medium-grained sandstone, the upper ones very fine-grained sandstone. Overbank deposits with sheet sands.

6) 31.35 m → 33.75 m (thickness: 2.4 m) **upper unit of the Cooper Canyon Formation**
Moderate brown (5YR 3/4) claystone with greenish-gray (5G 6/1) reduction mottling in more or less horizontal layers. Overbank deposits.

7) 33.75 m → 38.45 m (thickness: 4.7 m) **upper unit of the Cooper Canyon Formation**
Moderate brown (5YR 4/4) siltstone with greenish-gray (5G 6/1) reduction mottling in more or less horizontal layers. Overbank deposits.

8) 38.45 m → 59.95 m (thickness: 21.5 m) **upper unit of Cooper Canyon Formation**
Very fine-grained sandstone lens about 45 cm thick, grading into dark reddish brown (10R 3/4) claystone with greenish gray (5G 6/1) mottles in more or less horizontal layers, with a few extremely thin (couple centimeter thick) very fine-grained sandstone lenses in the lower part of the unit, zone of greenish gray (5G 6/1) reduction at the top. Overbank deposits with sheet sands.

9) 59.95 m → 61.65 m (thickness: 1.7 m) **Macy Ranch sandstone**
Light gray (N7) fine to medium-grained sandstone, mostly well cemented, almost structureless, containing petrified wood. Channel sandstone. Truncated by the Ogallala Formation.

STINK CREEK TANK

Mudstone samples

N33°10’16” W101°19’27”

Post East Quadrangle

Total thickness: 19.92 m

Fig. A1.32

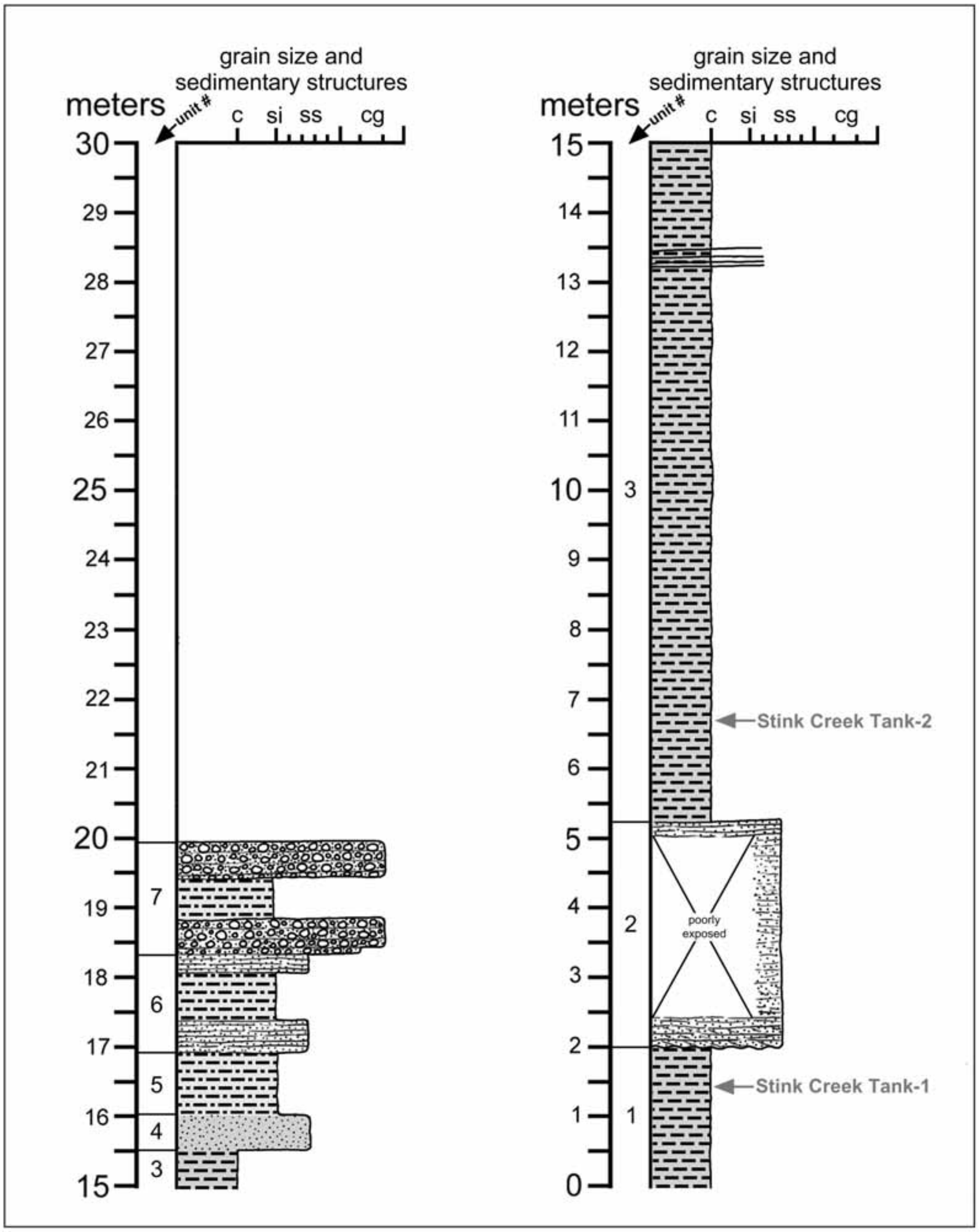

Fig. A1.32. Stink Creek Tank measured section.

Stink Creek Tank and the surrounding area on the UU Ranch and adjacent Kirkpatrick property, north of Highway 84 just east and southeast of Post, is the best area to observe the stratigraphic relationship between the Miller Ranch sandstone and the Dalby Ranch sandstone. The former caps numerous mesas in this area, and the top of the Dalby Ranch sandstone is very well exposed at the base of these mesas. At Stink Creek Tank itself, the base of the Dalby Ranch sandstone is also exposed in places, allowing a measured section which includes the very top of the Lower unit, and a mesa was selected which has the lower contact of the Dalby Ranch sandstone exposed not far from the base.

1) 0 m → 2 m (thickness 2 m) **lower unit of the Cooper Canyon Formation**

Varies between moderate brown (5YR 4/4) almost pure claystone and muddy coarse-grained sand, with a reduced greenish gray (5GY 4/1) layer about 30 cm thick or so at the top of the unit. Overbank deposits. Mudstone sample **Stink Creek Tank-1** was collected from this unit.

2) 2 m → 5.2 m (thickness: 3.2 m) **Dalby Ranch sandstone**

Measured as a short transect from the edge of a creek running into Stink Creek Tank, up a short drainage to the base of one of the mesas surrounding the tank. Most of the sandstone here is generally poorly exposed, but mostly greenish gray (5GY 4/1) fine to medium-grained horizontal planar bedded sandstone with some weak cross bedding, interbedded resistant and friable layers. A 10-20 cm thick resistant layer forms the top of the unit at the base of the hill, and the lithologic change above it is quite abrupt, though apparently conformable. Channel sandstone.

3) 5.2 m → 15.5 m (thickness: 10.3 m) **middle unit of the Cooper Canyon Formation**

Mostly dark reddish brown (10R 3/4) almost pure claystone, extremely fine (millimeter scale) reduction spots. The lower 40 cm is greenish gray (5GY 6/1) reduction, and there are a couple patchy lenses of very light gray (N8) horizontal planar-bedded very fine-grained sandstone just a few centimeters thick at most about 8 m or so above the base of the unit. Overbank deposits. Mudstone sample **Stink Creek Tank-2** was taken about 1.5 m above the base of the unit, not far above the reduced zone.

4) 15.5 m → 16.02 m (thickness: 0.52 m) **middle unit of Cooper Canyon Formation**
Dark reddish brown (10R 4/4) very muddy fine to medium-grained sand with some reduction mottling, and an extremely thin (few millimeters thick) reduced layer at the base. Sheet sand?

5) 16.02 m → 16.92 m (thickness: 0.9 m) **middle unit of Cooper Canyon Formation**
Medium brown (5YR 4/4) siltstone with a greenish gray reduced zone near the top. Overbank deposits.

6) 16.92 m → 18.32 m (thickness: 1.4 m) **middle unit of Cooper Canyon Formation**
Greenish gray (5GY 6/1) horizontal planar -bedded fine to medium-grained sandstone, mostly friable with extremely thin (millimeter scale) resistant layers, a few thicker (a few centimeters thick) resistant layers near the top, and a layer of siltstone about 70 cm thick in the middle of the unit. Proximal overbank deposits?

7) 18.32 m → 19.92 m (thickness: 1.6 m) **Miller Ranch sandstone**
The base of the unit is a very coarse grained sandstone to clast-supported granule conglomerate a few cm thick, but the rest of the unit is dominantly reddish colored, faintly horizontal planer-bedded, clast-supported pebble conglomerate. A lens of siltstone (similar to that in the middle of the previous unit) about 50 cm thick sits in the middle of the unit. The rest of the Miller Ranch sandstone is weathered away on this mesa, but thicker on other mesas surrounding the reservoir. Channel sandstone.

ZIP SECTION CLIFFSIDE

Mudstone sample

N33°00’09” W101°21’10”

Cooper Creek Quadrangle

Total thickness: 22.75+ m

Fig. A1.33

This locality is one of the western-most exposures of the Dalby Ranch sandstone, which becomes more discontinuous a few kilometers of the northwest and eventually dies

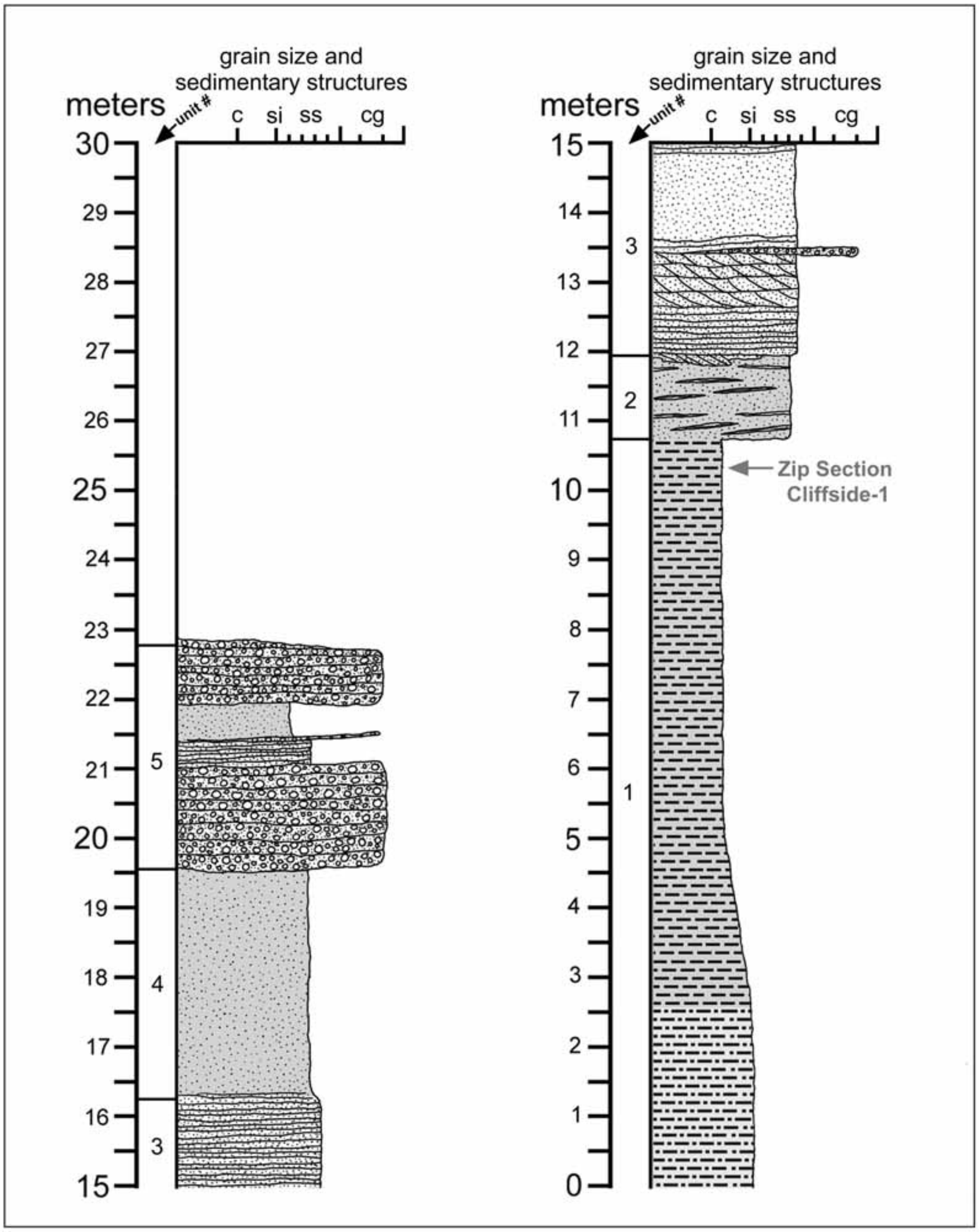

Fig. A1.33. Zip Section Cliffside measured section.

out. As at the North Fork locality, the contact between the Lower unit and the Dalby Ranch sandstone is somewhat gradational here.

1) 0 m → 10.7 m (thickness: 10.7 m) **lower unit of the Cooper Canyon Formation**
Pale reddish brown (10R 5/4) siltstone grading up into medium reddish brown (10R 4/6) silty claystone, all with light greenish gray (5GY 8/1) mottling, large mottles at the base, complexly mixed with the medium reddish brown (10R 4/6) in the top meter or so. In other areas, this section is muddy sand, and interbedded with horizontal planar bedding probably associated with low order sandstones. Overbank deposits. Mudstone sample **Zip Cliffside-1** was collected from the top of this unit.

2) 10.7 m → 11.9 m (thickness: 1.2 m) **lower unit of the Cooper Canyon Formation**
Primarily greenish gray (5G 6/1) micaceous medium-grained sandstone, mostly muddy with a few very thin (couple centimeters thick) clast-supported lenses with horizontal planar bedding and cross bedding. This unit is apparently gradational with the base of the Dalby Ranch sandstone here. Proximal? overbank deposits.

3) 11.9 m → 16.2 m (thickness: 4.3 m) **Dalby Ranch sandstone**
Medium to coarse-grained micaceous sandstone, with no bedding, horizontal planar bedding, and cross bedding, some thin (about 10 cm thick) lenses of sedimentary rock clast pebble conglomerate. Upper contact is gradational with unit 4. Channel sandstone.

4) 16.2 m → 19.55 m (thickness: 3.35 m) **middle unit of Cooper Canyon Formation**
Dark reddish brown (10R 3/4) muddy fine to medium-grained sandstone. Proximal overbank deposits?

5) 19.55 m → 22.75 m + (thickness: 3.2 m +) **Upper Cooper Canyon Formation**
Cross-bedded sedimentary rock clast pebble conglomerate, interbedded with horizontal planar-bedded fine to medium-grained clast-supported sandstone and muddy very fine-grained sand. This unit is one of the discontinuous low order conglomeritic beds seen in the Big Red Mud area between the Dalby Ranch and Miller Ranch sandstones, although it is stratigraphically lower than most of the others. This one can be traced for some distance, although it is not mapped. Channel deposits.

ZIP SECTION GIANT CLAMS

Mudstone sample

N33°00'08" W101°21'18"

Cooper Creek Quadrangle

Total thickness: 3.75 m

Figs. 2.20a, A1.34

This locality is only about a kilometer from the Zip Section Cliffside locality, and it equivalent to the base of that section. The Zip Section Giant Clams locality simply consists of a single small low-order conglomeritic sandstone lens which was measured only for its extraordinarily large bivalves, which may represent a different species from most of the bivalves observed in the Dockum Group in southern Garza County.

1) 0 → 1.85 m (thickness: 1.85 m) **lower unit of the Cooper Canyon Formation**
Dark reddish brown (10R 3/4) siltstone containing some post-depositional gypsum, followed by an irregular layer of intrabasinal pebble conglomerate with a highly irregular thickness (5-30 cm) and erosional contact at base, followed by a layer of grayish red (10R 4/2) silty claystone about 30 cm thick at the top. Mudstone sample **Zip Section Giant Clams-1** was taken from this uppermost claystone. Overbank deposits.

2) 1.85 m → 2.3 m (thickness: .45 m) **lower unit of the Cooper Canyon Formation**
Sedimentary rock clast pebble conglomerate with a couple extremely thin (few centimeters thick) lenses of grayish red (10R 4/2) mudstone. This and the following unit are part of a discontinuous lens of conglomeritic sandstone containing some extremely large bivalves, although only a few were observed in this layer. Channel deposits.

3) 2.3 m → 3.75 m (thickness: 1.45 m) **lower unit of the Cooper Canyon Formation**
Sedimentary rock clast pebble conglomerate, partly massive and the rest with irregular sub-horizontal bedding. The best exposed giant bivalves come from the top of this bed, which pinches out laterally. Channel gravels.

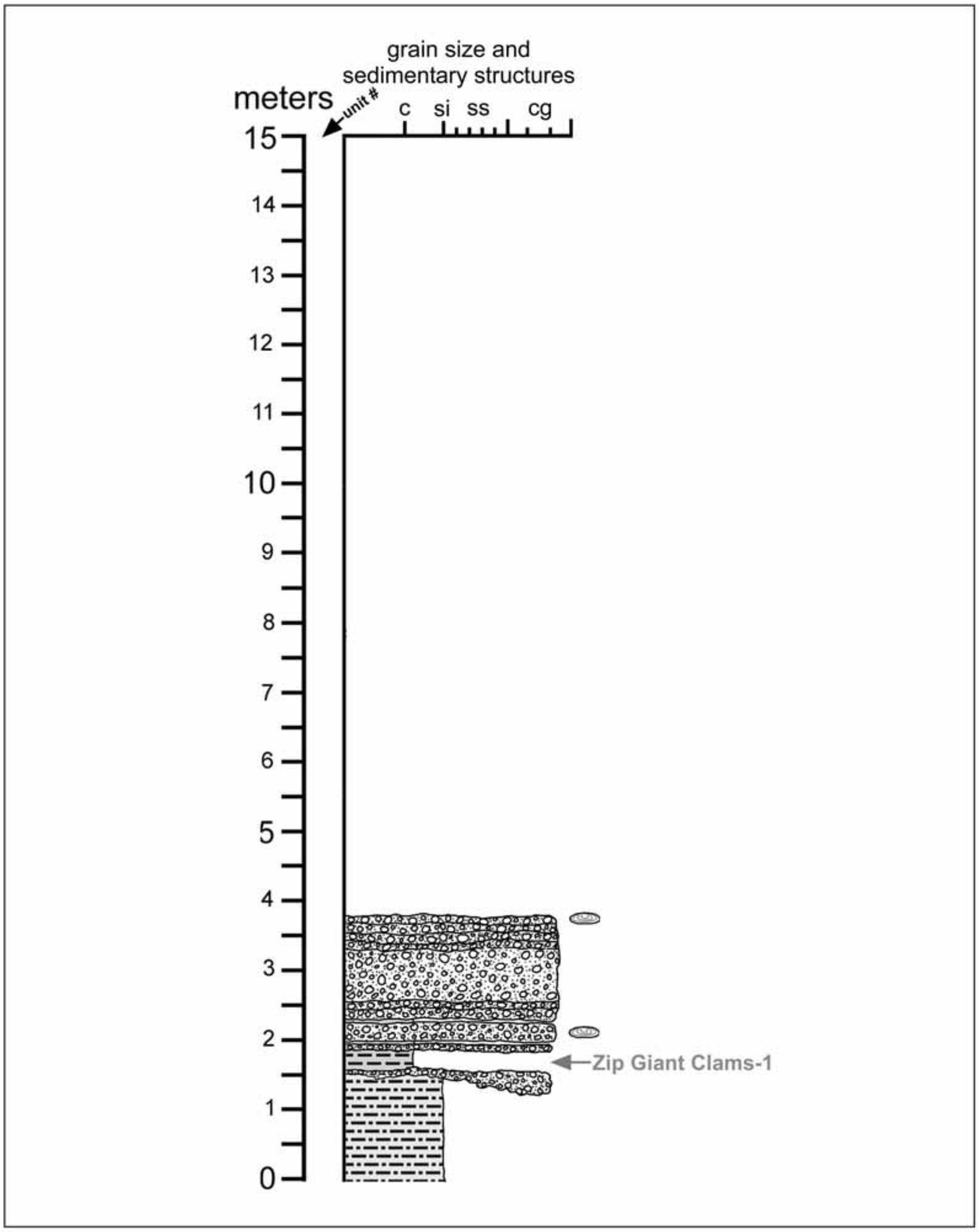

Fig. A1.34. Zip Section Giant Clams measured section.

APPENDIX 2

MAJOR AND TRACE ELEMENT DATA

The first table lists the samples used for geochemical analysis, identifying also the lithostratigraphic unit from which the samples were taken (also see Fig. 2.3 and Appendix 1 for more exact stratigraphic placement), and the lithology of the sample. The samples in the first table are also assigned numbers (far left column) which are used to identify them in the second and third tables, which give values for the major and trace elements. These numbers are also used in the principal component analysis and discriminant analysis graphs (Figs 3.15a-3.20a). All samples are from southern Garza County except for the last six (numbers 49-54), which are from Palo Duro Canyon in Armstrong County.

SAMPLE INFORMATION			
#	**Sample**	**stratigraphic unit**	**composition**
1	Montford Dam-1	Santa Rosa Sandstone	Siltstone
2	OS Gully-2	Santa Rosa Sandstone	Siltstone
3	Cedar Hill -1	Boren Ranch sandstone/beds	Claystone
4	OS Gully-1	Boren Ranch sandstone/beds	Siltstone
5	Eastern Garza-1	Boren Ranch sandstone/beds	Siltstone
6	Meyer's Hill-1	Lower unit of the Cooper Canyon Formation	Siltstone
7	Neyland-1	Lower unit of the Cooper Canyon Formation	Claystone
8	Neyland-2	Lower unit of the Cooper Canyon Formation	Claystone
9	Neyland-3	Lower unit of the Cooper Canyon Formation	Siltstone
10	North Fork-1	Lower unit of the Cooper Canyon Formation	Claystone
11	Stink Creek Tank-1	Lower unit of the Cooper Canyon Formation	Claystone
12	Zip Cliffside-1	Lower unit of the Cooper Canyon Formation	Claystone
13	Zip Giant Clams-1	Lower unit of the Cooper Canyon Formation	Claystone
14	HQ-1	Middle unit of the Cooper Canyon Formation	Siltstone
15	HQ-2	Middle unit of the Cooper Canyon Formation	Siltstone
16	HQ-3	Middle unit of the Cooper Canyon Formation	Claystone
17	HQ-4	Middle unit of the Cooper Canyon Formation	Claystone
18	HQ-5	Middle unit of the Cooper Canyon Formation	Claystone
19	HQ-6	Middle unit of the Cooper Canyon Formation	Claystone
20	Headquarters Hill-1	Middle unit of the Cooper Canyon Formation	Claystone
21	Marts-1	Middle unit of the Cooper Canyon Formation	Muddy sand

22	Marts-2	Middle unit of the Cooper Canyon Formation	Claystone
23	Marts-3	Middle unit of the Cooper Canyon Formation	Siltstone
24	Stink Creek Tank-2	Middle unit of the Cooper Canyon Formation	Claystone
25	UUH-1	Middle unit of the Cooper Canyon Formation	Claystone
26	UURR-1	Middle unit of the Cooper Canyon Formation	Muddy sand
27	UURR-2	Middle unit of the Cooper Canyon Formation	Claystone
28	CCC-1	Most of upper unit of the Cooper Canyon Formation	Claystone
29	CCC-2	Most of upper unit of the Cooper Canyon Formation	Claystone
30	CCC-3	Most of upper unit of the Cooper Canyon Formation	Siltstone
31	NSH-1	Most of upper unit of the Cooper Canyon Formation	Siltstone
32	NSH-2	Most of upper unit of the Cooper Canyon Formation	Claystone
33	NSH-3	Most of upper unit of the Cooper Canyon Formation	Claystone
34	Parks Cliffside-1	Most of upper unit of the Cooper Canyon Formation	Siltstone
35	Patty-3	Most of upper unit of the Cooper Canyon Formation	Claystone
36	Patty-5	Most of upper unit of the Cooper Canyon Formation	Muddy sand
37	Patty-6	Most of upper unit of the Cooper Canyon Formation	Claystone
38	Patty-7	Most of upper unit of the Cooper Canyon Formation	Claystone
39	Problematic Hill-1	Most of upper unit of the Cooper Canyon Formation	Siltstone
40	Problematic Hill-2	Most of upper unit of the Cooper Canyon Formation	Siltstone
41	Problematic Hill-3	Most of upper unit of the Cooper Canyon Formation	Siltstone
42	PSH-1	Most of upper unit of the Cooper Canyon Formation	Siltstone
43	PSH-2	Most of upper unit of the Cooper Canyon Formation	Siltstone
44	PSH-3	Most of upper unit of the Cooper Canyon Formation	Siltstone
45	PSH-4	Most of upper unit of the Cooper Canyon Formation	Claystone
46	Patty-1	Macy Ranch sandstone and uppermost beds	Muddy sand
47	Patty-2	Macy Ranch sandstone and uppermost beds	Muddy sand
48	Patty-4	Macy Ranch sandstone and uppermost beds	Claystone
49	T-2	Palo Duro Tecovas Formation, "magenta shales"	
50	T-1	Palo Duro Tecovas Formation, "magenta shales"	
51	M-2	Palo Duro Tecovas Formation, "variegated shales" (yellow)	
52	M-1	Palo Duro Tecovas Formation, "variegated shales" (yellow)	
53	B-2	Palo Duro Tecovas Formation, "variegated shales" (purple)	
54	B-1	Palo Duro Tecovas Formation, "variegated shales" (purple)	

The following two tables give the major and trace element values used in both the bivariate and multivariate analyses. The values are listed according to the sample numbers given in the previous table.

MAJOR ELEMENT VALUES (WT%)										
#	**SiO2**	**TiO2**	**Al2O3**	**Fe2O3**	**MnO**	**MgO**	**CaO**	**Na2O**	**K2O**	**P2O5**
1	79.54	0.55	7.44	4.73	0.01	0.94	0.78	0.12	0.64	0.00
2	63.21	0.81	14.15	7.19	0.03	1.72	0.22	1.43	2.37	0.00
3	57.21	0.80	17.48	5.15	0.05	3.58	1.28	0.93	3.21	0.19
4	58.26	0.87	16.07	8.77	0.06	2.67	1.18	1.17	3.04	0.13
5	52.63	0.85	17.66	8.93	0.18	3.27	2.37	0.88	3.22	0.11
6	54.54	0.81	16.91	7.20	0.04	3.07	0.91	1.60	2.81	0.20
7	53.02	0.87	19.95	7.84	0.06	2.40	0.50	0.98	3.61	0.11
8	52.04	0.75	17.49	7.01	0.10	3.00	2.75	0.95	2.93	0.20
9	51.12	0.73	17.52	5.55	0.09	2.67	4.06	0.62	2.96	0.16
10	44.75	0.69	15.01	5.48	0.19	4.33	7.05	1.33	2.69	0.13
11	52.28	0.85	18.53	8.40	0.09	2.55	0.83	1.45	3.05	0.13
12	56.82	0.90	17.88	6.95	0.03	2.73	0.46	1.71	2.86	0.16
13	55.08	0.78	17.18	6.66	0.09	2.92	1.35	1.54	3.44	0.25
14	55.39	0.78	16.92	7.54	0.07	2.57	0.93	1.86	2.68	0.18
15	57.70	0.76	15.96	5.97	0.07	2.16	2.20	1.71	2.55	0.15
16	55.01	0.85	18.13	6.79	0.07	2.09	2.45	1.29	2.41	0.10
17	53.98	0.77	16.43	6.50	0.08	2.54	3.14	1.68	2.76	0.19
18	65.91	0.68	12.79	3.80	0.08	1.56	3.56	1.68	1.98	0.15
19	57.35	0.79	15.68	6.49	0.07	2.18	2.46	1.67	2.29	0.15
20	56.50	0.70	13.73	5.01	0.10	2.07	5.79	1.24	1.81	0.13
21	59.34	0.81	15.08	4.14	0.04	2.51	2.05	1.14	1.52	0.13
22	52.49	0.78	16.06	6.71	0.07	2.59	3.41	1.17	2.32	0.20
23	49.37	0.74	14.29	5.27	0.07	1.85	8.84	1.05	2.35	0.15
24	53.05	0.84	18.22	8.20	0.07	2.55	1.80	1.32	3.13	0.19
25	54.45	0.81	15.73	5.72	0.08	2.66	3.99	1.40	1.92	0.22
26	65.59	0.81	13.55	5.29	0.04	2.19	1.27	1.39	2.31	0.16
27	60.77	0.66	12.69	5.10	0.07	2.07	4.84	1.54	2.11	0.14
28	58.24	0.78	15.50	5.73	0.09	2.93	2.82	1.17	2.99	0.16
29	52.32	0.59	15.12	4.57	0.05	4.00	5.10	0.82	2.62	0.11
30	60.46	0.82	14.98	6.89	0.06	2.69	2.04	1.25	2.67	0.16
31	61.47	0.75	12.99	4.52	0.10	2.71	3.58	1.18	2.57	0.18
32	55.08	0.77	18.03	7.26	0.06	3.42	1.14	0.87	3.56	0.16
33	60.67	0.75	15.08	5.56	0.08	2.76	2.22	1.17	2.54	0.17
34	57.67	0.79	14.28	5.08	0.07	2.43	5.19	1.11	2.57	0.15
35	38.94	0.50	9.91	4.12	0.20	2.23	19.68	0.78	2.04	0.07
36	62.42	0.80	14.86	5.94	0.07	2.49	0.83	1.77	2.41	0.15
37	54.99	0.80	15.78	6.70	0.10	3.09	3.68	0.99	3.27	0.16
38	57.48	0.77	13.51	4.96	0.11	2.46	5.15	1.39	2.55	0.17

39	59.33	0.82	14.15	5.53	0.09	2.37	3.11	1.42	2.51	0.14
40	61.20	0.81	14.54	5.42	0.11	2.54	2.48	1.40	2.66	0.17
41	64.19	0.74	13.18	5.37	0.06	2.49	1.50	1.65	2.19	1.99
42	56.60	0.77	14.25	5.26	0.10	3.22	3.72	1.85	2.66	0.17
43	52.11	0.76	15.71	6.40	0.13	3.12	4.97	1.09	3.36	0.18
44	62.39	0.82	14.87	6.06	0.07	2.76	1.09	1.71	2.42	0.15
45	47.64	0.64	12.48	4.93	0.12	2.98	10.68	1.07	2.59	0.07
46	63.42	0.76	13.52	6.17	0.06	2.30	1.17	1.30	2.48	0.13
47	62.22	0.77	14.98	4.14	0.03	2.72	1.04	1.11	2.81	0.14
48	66.34	0.69	12.78	3.26	0.05	2.18	1.89	1.39	2.08	0.12
49	49.63	0.58	10.31	4.40	0.29	4.33	11.15	1.07	0.77	0.10
50	50.25	0.61	12.73	5.17	0.12	5.33	6.87	1.17	1.36	0.07
51	61.08	0.82	14.62	5.88	0.07	2.42	1.74	1.94	0.60	0.04
52	59.59	0.82	15.55	6.11	0.10	2.57	1.78	2.07	0.40	0.04
53	62.16	0.78	13.21	5.29	0.17	2.52	2.61	1.68	0.39	0.05
54	63.53	0.78	14.20	5.25	0.13	2.35	1.92	1.64	0.42	0.05

TRACE ELEMENT VALUES (PPM)												
#	**Sr**	**Ba**	**Zr**	**Y**	**Sc**	**V**	**Cr**	**Ni**	**Cu**	**Zn**	**Nb**	**Be**
1	48	137	331	17.7	7.8	42	29	4	14	23	5	1.2
2	123	476	258	46.5	14.0	54	52	23	27	61	8	2.4
3	125	405	198	31.1	17.8	108	71	28	32	123	12	3.2
4	141	389	233	30.8	15.6	96	62	24	14	85	10	2.7
5	134	344	182	30.9	19.4	102	63	26	28	101	14	3.3
6	284	291	174	28.1	17.0	86	71	28	32	61	9	2.9
7	142	405	147	28.3	19.3	128	86	40	22	130	13	3.5
8	183	487	145	21.9	15.1	112	72		34	117	14	
9	196	247	175	27.0	15.6	99	69	36	27	55	15	3.0
10	329	370	152	29.9	17.1	102	52	27	32	54	18	2.6
11	102	296	151	27.2	18.8	109	77	34	17	73	9	3.1
12	98	339	185	28.1	17.1	100	74	39	30	70	9	3.0
13	165	269	183	27.4	17.7	98	83	44	16	57	12	3.4
14	207	267	163	26.4	15.3	73	66		21	68	12	
15	206	355	208	28.3	14.8	88	66		32	81	13	
16	145	391	176	29.8	17.9	120	78		33	74	14	
17	167	329	176	28.7	14.8	78	61		15	60	13	
18	113	306	386	29.4	10.8	56	44		23	52	11	
19	141	509	223	27.7	14.5	133	61		24	72	11	
20	206	265	237	32.4	12.6	71	51	27	21	59	16	2.1
21	171	114	235	29.6	14.2	124	74	32	95	39	14	2.1
22	176	172	168	28.0	15.2	75	79	38	19	25	14	2.5
23	176	477	187	31.7	13.6	80	55	30	24	64	18	2.2
24	159	390	142	27.7	18.6	121	68	34	22	86	11	3.2
25	232	151	198	30.3	14.7	60	58	24	35	39	15	2.4

26	129	269	370	32.1	12.0	55	50	19	14	61	12	2.2
27	120	271	227	28.8	11.9	66	59	23	22	51	13	2.2
28	202	347	216	29.0	14.3	82	61		28	86	13	
29	653	261	206	37.7	12.4	141	59		27	62	18	
30	288	355	240	29.9	14.9	82	64		20	91	12	
31	283	356	289	31.5	12.4	67	49		27	86	16	
32	255	452	146	26.3	17.9	122	184		29	128	12	
33	648	457	235	27.5	14.0	85	73		23	96	11	
34	179	316	243	31.7	13.1	73	56	23	23	77	16	2.4
35	279	190	149	27.1	10.1	114	36	12	16	18	28	1.6
36	501	423	242	30.9	14.6	95	53	64	27	95	10	2.5
37	244	361	209	29.8	15.1	92	63	32	28	80	15	2.4
38	186	372	293	32.1	12.7	62	101		27	74	15	
39	192	436	268	32.2	13.3	79	68		24	72	12	
40	246	402	262	30.4	13.5	78	54		28	79	12	
41	255	312	280	26.8	12.6	77	49	22	22	71	8	1.9
42	235	392	237	29.6	13.9	72	60		35	83	15	
43	233	369	179	30.0	15.4	98	68		31	90	17	
44	213	425	237	29.0	14.7	101	51	20	26	95	9	2.4
45	418	245	184	24.6	11.6	45	45	18	15	52	20	1.8
46	521	373	245	25.4	12.9	126	54	39	39	68	10	1.9
47	292	343	258	26.0	14.1	137	90	44	22	80	11	2.3
48	1068	337	227	25.3	12.0	88	49	19	21	60	10	1.8
49					9.4	61	42	36	3	28	16	
50					9.8	64	57	40	8	27	18	
51					9.2	64	39	57	12	26	21	
52					10.1	82	50	52	26	19	23	
53					11.8	40	51	45	20	20	20	
54					11.0	34	62	47	24	31	21	

The sample data was generated by three separate ICP-ES analyses between 2003 and 2008, each of which analyzed both major and trace elements. The following tables give the actual values for each of the three ICP-ES analyses, not only for the samples, but for the USGS standards and the internal standards used by the TTU Department of Geosciences ICP-ES lab which were used in the analyses. The loss on ignition (LOI) is also given for each set of major elements, and the total obtained by adding the LOI and wt% values for the major elements.

FIRST ANALYTICAL RUN (MAJOR ELEMENTS IN WT%)												
	SiO2	***TiO2***	***Al2O3***	***Fe2O3***	***MnO***	***MgO***	***CaO***	***Na2O***	***K2O***	***P2O5***	***LOI***	***TOTAL***
SAMPLES												
Marts-1	59.34	0.81	15.08	4.14	0.04	2.51	2.05	1.14	1.52	0.13	12.68	99.44
Marts-2	52.49	0.78	16.06	6.71	0.07	2.59	3.41	1.17	2.32	0.20	14.58	100.39
Marts-3	49.37	0.74	14.29	5.27	0.07	1.85	8.84	1.05	2.35	0.15	16.69	100.67
Neyland-1	53.02	0.87	19.95	7.84	0.06	2.40	0.50	0.98	3.61	0.11	12.31	101.64
Neyland-2	51.88	0.74	16.94	6.93	0.09	2.82	2.71	0.91	2.84	0.16	14.14	100.15
Neyland-3	51.12	0.73	17.52	5.55	0.09	2.67	4.06	0.62	2.96	0.16	14.67	100.16
Patty-1	63.42	0.76	13.52	6.17	0.06	2.30	1.17	1.30	2.48	0.13	8.88	100.19
Patty-2	62.22	0.77	14.98	4.14	0.03	2.72	1.04	1.11	2.81	0.14	9.89	99.86
Patty-3	38.94	0.50	9.91	4.12	0.20	2.23	19.68	0.78	2.04	0.07	21.71	100.18
Patty-4	66.34	0.69	12.78	3.26	0.05	2.18	1.89	1.39	2.08	0.12	9.30	100.09
Patty-5	62.42	0.80	14.86	5.94	0.07	2.49	0.83	1.77	2.41	0.15	7.41	99.16
Patty-6	54.99	0.80	15.78	6.70	0.10	3.09	3.68	0.99	3.27	0.16	11.21	100.77
USGS STANDARDS												
MAG-1	50.25	0.76	16.36	7.27	0.11	3.09	1.41	3.98	3.45	0.15	15.87	86.84
SCO-1	61.99	0.60	13.52	5.12	0.06	2.70	2.57	0.91	2.71	0.19	8.77	90.36
SGR-1	28.17	0.25	6.66	3.34	0.07	4.45	8.45	3.19	1.57	0.28	12.03	56.42
TTU CALIBRATION STANDARDS												
1.5BCM	82.73	1.70	24.02	12.41	0.20	8.79	10.82	6.00	3.23	0.77		150.67
1.5BCM	82.73	1.70	24.02	12.41	0.20	8.79	10.82	6.00	3.23	0.80		150.70
ABA	45.13	2.03	14.51	11.92	0.19	11.42	10.36	3.16	1.41	0.47		100.60
ABA	45.13	2.03	14.51	11.92	0.18	11.42	10.36	3.16	1.41	0.47		100.60
ABA												
BCM	55.15	1.13	16.01	8.27	0.14	5.86	7.21	4.00	2.15	0.43		100.35
BCM	55.15	1.13	16.01	8.27	0.14	5.86	7.21	4.00	2.15	0.46		100.38
BCM												
MHA	60.49	0.84	17.89	5.93	0.10	3.16	6.16	4.33	1.25	0.16		100.31
MHA	60.49	0.84	17.89	5.93	0.10	3.16	6.16	4.33	1.25	0.16		100.31

FIRST ANALYTICAL RUN (TRACE ELEMENTS IN PPM)												
	Sr	***Ba***	***Zr***	***Y***	***Sc***	***V***	***Cr***	***Ni***	***Cu***	***Zn***	***Nb***	***Be***
SAMPLES												
Marts-1	171	114	235	29.6	14.2	124	74	32	95	39	14	2.1
Marts-2	176	172	168	28.0	15.2	75	79	38	19	25	14	2.5
Marts-3	176	477	187	31.7	13.6	80	55	30	24	64	18	2.2
Neyland-1	138	398	146	27.8	19.6	129	87	40	22	133	14	3.5
Neyland-2	178	444	140	21.6	15.5	112	79	37	32	95	14	2.8
Neyland-3	196	247	175	27.0	15.6	99	69	36	27	55	15	3.0
Patty-1	521	373	245	25.4	12.9	126	54	39	39	68	10	1.9
Patty-2	292	343	258	26.0	14.1	137	90	44	22	80	11	2.3
Patty-3	279	190	149	27.1	10.1	114	36	12	16	18	28	1.6
Patty-4	1068	337	227	25.3	12.0	88	49	19	21	60	10	1.8
Patty-5	501	423	242	30.9	14.6	95	53	64	27	95	10	2.5
Patty-6	244	361	209	29.8	15.1	92	63	32	28	80	15	2.4
USGS STANDARDS												
MAG-1	146	497	139	26.0	17.1	126	90	75	31	201	12	2.6
SCO-1	171	575	178	22.5	11.9	117	61	25	30	149	11	1.6
SGR-1	393	301	46	9.9	5.6	116	27	17	57	86	12	1.1
CALIBRATION STANDARDS												
1.5BCM	1091	1344	254	27.5	28.2	192	195	129	81	117	41	2.3
1.5BCM	1091	1344	254	27.5	28.2	192	195	129	81	117	41	2.3
ABA	550	419	170	24.0	27.9	206	362	235	57	95	40	1.3
ABA	550	419	170	24.0	27.9	206	362	235	57	95	40	1.3
ABA					27.9	206	362	235	57	95	40	1.3
BCM	727	896	169	18.3	18.8	128	130	86	54	78	28	1.5
BCM	727	896	169	18.3	18.8	128	130	86	54	78	28	1.5
BCM					18.8	128	130	86	54	78	28	1.5
MHA	566	311	157	15.1	12.8	85	29	24	21	58	10	1.2
MHA	566	311	157	15.1								
RGMT	110	792	239	21.7	5.5	10		3	9	36	9	2.2
RGMT	110	792	239	21.7	5.5	10		2	9	36	9	2.2

SECOND ANALYTICAL RUN (MAJOR ELEMENTS IN WT%)												
	SiO2	***TiO2***	***Al2O3***	***Fe2O3***	***MnO***	***MgO***	***CaO***	***Na2O***	***K2O***	***P2O5***	***LOI***	***TOTAL***
SAMPLES												
CCC-1	58.24	0.78	15.50	5.73	0.09	2.93	2.82	1.17	2.99	0.16	10.23	100.63
CCC-2	52.32	0.59	15.12	4.57	0.05	4.00	5.10	0.82	2.62	0.11	14.61	99.90
CCC-3	60.46	0.82	14.98	6.89	0.06	2.69	2.04	1.25	2.67	0.16	8.44	100.46
HQ-1	55.39	0.78	16.92	7.54	0.07	2.57	0.93	1.86	2.68	0.18	10.54	99.48
HQ-2	57.70	0.76	15.96	5.97	0.07	2.16	2.20	1.71	2.55	0.15	10.44	99.67
HQ-3	55.01	0.85	18.13	6.79	0.07	2.09	2.45	1.29	2.41	0.10	10.42	99.61
HQ-4	53.98	0.77	16.43	6.50	0.08	2.54	3.14	1.68	2.76	0.19	12.32	100.38
HQ-5	65.91	0.68	12.79	3.80	0.08	1.56	3.56	1.68	1.98	0.15	7.74	99.93

HQ-6	57.35	0.79	15.68	6.49	0.07	2.18	2.46	1.67	2.29	0.15	11.45	100.58
Neyland-1	53.21	0.89	20.04	8.15	0.06	2.45	0.55	0.98	3.78	0.12	11.17	101.41
Neyland-2	52.04	0.75	17.49	7.01	0.10	3.00	2.75	0.95	2.93	0.20	13.01	100.22
NSH-1	61.47	0.75	12.99	4.52	0.10	2.71	3.58	1.18	2.57	0.18	9.67	99.71
NSH-2	55.08	0.77	18.03	7.26	0.06	3.42	1.14	0.87	3.56	0.16	10.18	100.52
NSH-3	60.67	0.75	15.08	5.56	0.08	2.76	2.22	1.17	2.54	0.17	9.02	100.01
Patty-3	38.38	0.51	10.14	4.35	0.22	2.20	21.60	0.79	2.02	0.09	21.67	101.96
Patty-4	66.35	0.73	13.07	3.37	0.05	2.20	1.94	1.39	2.08	0.17	9.30	100.64
Patty-7	57.48	0.77	13.51	4.96	0.11	2.46	5.15	1.39	2.55	0.17	11.29	99.85
PRH-1	59.33	0.82	14.15	5.53	0.09	2.37	3.11	1.42	2.51	0.14	10.32	99.80
PRH-2	61.20	0.81	14.54	5.42	0.11	2.54	2.48	1.40	2.66	0.17	8.66	99.99
PRH-3	65.04	0.77	13.45	5.54	0.07	2.45	1.55	1.70	2.27	0.16	6.75	99.75
PRH-4	49.27	0.66	12.70	5.01	0.13	3.23	10.67	1.13	2.66	0.09	8.66	94.22
PSH-1	56.60	0.77	14.25	5.26	0.10	3.22	3.72	1.85	2.66	0.17	11.11	99.71
PSH-2	52.11	0.76	15.71	6.40	0.13	3.12	4.97	1.09	3.36	0.18	11.76	99.58
PSH-3	61.11	0.82	14.54	6.08	0.08	2.69	1.07	1.65	2.38	0.16	8.17	98.75
USGS STANDARDS												
SCO-1	62.16	0.59	13.44	5.11	0.06	2.69	2.62	0.91	2.69	0.22	8.77	99.28
CALIBRATION STANDARDS												
1.5BCM	82.73	1.70	24.02	12.41	0.19	8.79	10.82	6.00	3.23	0.75		150.64
1.5BCM	82.73	1.70	24.02	12.41	0.20	8.79	10.82	6.00	3.23	0.75		150.65
1.5BCM	82.73	1.70	24.02	12.41	0.21	8.79	10.82	6.00	3.23	0.75		150.66
ABA	45.13	2.03	14.51	11.92	0.18	11.42	10.36	3.16	1.41	0.44		100.56
ABA	45.13	2.03	14.51	11.92	0.18	11.42	10.36	3.16	1.41	0.44		100.56
ABA	45.13	2.03	14.51	11.92	0.20	11.42	10.36	3.16	1.41	0.44		100.58
BCM	55.15	1.13	16.01	8.27	0.13	5.86	7.21	4.00	2.15	0.43		100.34
BCM	55.15	1.13	16.01	8.27	0.13	5.86	7.21	4.00	2.15	0.43		100.34
BCM	55.15	1.13	16.01	8.27	0.14	5.86	7.21	4.00	2.15	0.43		100.35
BCM	55.15	1.13	16.01	8.27	0.14	5.86	7.21	4.00	2.15	0.43		100.35
MHA	60.49	0.84	17.89	5.93	0.10	3.16	6.16	4.33	1.25	0.17		100.32
MHA	60.49	0.84	17.89	5.93	0.10	3.16	6.16	4.33	1.25	0.17		100.32
MHA	60.49	0.84	17.89	5.93	0.10	3.16	6.16	4.33	1.25	0.17		100.32
RGMT	73.03	0.28	14.07	1.86	0.04	0.33	1.27	4.52	4.36	0.05		99.81
RGMT	73.03	0.28	14.07	1.86	0.04	0.33	1.27	4.20	4.36	0.05		99.49
RGMT	73.03	0.28	14.07	1.86	0.04	0.33	1.27	4.56	4.36	0.05		99.85

SECOND ANALYTICAL RUN (TRACE ELEMENTS IN PPM)												
	Sr	***Ba***	***Zr***	***Y***	***Sc***	***V***	***Cr***	***Ni***	***Cu***	***Zn***	***Nb***	***Be***
SAMPLES												
CCC-1	202	347	216	29.0	14	82	61		28	86	13	
CCC-2	653	261	206	37.7	12	141	59		27	62	18	
CCC-3	288	355	240	29.9	15	82	64		20	91	12	
HQ-1	207	267	163	26.4	15	73	66		21	68	12	
HQ-2	206	355	208	28.3	15	88	66		32	81	13	

HQ-3	145	391	176	29.8	18	120	78		33	74	14	
HQ-4	167	329	176	28.7	15	78	61		15	60	13	
HQ-5	113	306	386	29.4	11	56	44		23	52	11	
HQ-6	141	509	223	27.7	14	133	61		24	72	11	
Neyland-1	146	409	148	28.9	19	127	85		22	127	12	
Neyland-2	183	487	145	21.9	15	112	72		34	117	14	
NSH-1	283	356	289	31.5	12	67	49		27	86	16	
NSH-2	255	452	146	26.3	18	122	184		29	128	12	
NSH-3	648	457	235	27.5	14	85	73		23	96	11	
Patty-3	295	212	155	27.8	10	116	53		15	40	28	
Patty-4	1064	366	259	25.8	13	89	49		20	72	10	
Patty-7	186	372	293	32.1	13	62	101		27	74	15	
PRH-1	192	436	268	32.2	13	79	68		24	72	12	
PRH-2	246	402	262	30.4	14	78	54		28	79	12	
PRH-3	257	323	278	26.4	13	75	52		21	79	11	
PRH-4	410	245	195	25.0	12	46	57		15	48	20	
PSH-1	235	392	237	29.6	14	72	60		35	83	15	
PSH-2	233	369	179	30.0	15	98	68		31	90	17	
PSH-3	216	435	230	29.4	15	102	54		27	93	10	
USGS SAMPLES												
SCO-1	167	564	184	22.6	12	112	58		25	96	10	
TTU INTERNAL CALIBRATION STANDARDS												
1.5BCM	1091	1344	254	27.5	28	192	195		81	117	41	
1.5BCM	1091	1344	254	27.5	28	192	195		81	117	41	
1.5BCM	1091	1344	254	27.5	28	192	195		81	117	41	
ABA	550	419	170	24.0	28	206	362		57	94	40	
ABA	550	419	170	24.0	28	206	362		57	98	40	
ABA	550	419	170	24.0	28	206	362		57	92	40	
BCM	727	896	169	18.3	19	128	130		54	78	28	
BCM	727	896	169	18.3	19	128	130		54	78	28	
BCM	727	896	169	18.3	19	128	130		54	78	28	
BCM	727	896	169	18.3	19	128	130		54	78	28	
MHA	566	311	157	15.1	13	79	29		21	58	10	
MHA	566	311	157	15.1	13	79	29		21	58	10	
MHA	566	311	157	15.1	13	79	29		21	58	10	
RGMT	110	792	239	21.7	5	10	1		9	34	8	
RGMT	110	792	239	21.7	5	9	0		9	35	8	
RGMT	110	792	239	21.7	5	9	0		9	34	8	

THIRD ANALYTICAL RUN (MAJOR ELEMENTS IN WT%)												
	SiO2	***TiO2***	***Al2O3***	***Fe2O3***	***MnO***	***MgO***	***CaO***	***Na2O***	***K2O***	***P2O5***	***LOI***	***TOTAL***
SAMPLES												
Cedar Hill-1	57.21	0.80	17.48	5.15	0.05	3.58	1.28	0.93	3.21	0.19	9.52	99.40
HQH-1	56.50	0.70	13.73	5.01	0.10	2.07	5.79	1.24	1.81	0.13	12.8	99.90

Meyer's Hill-1	54.54	0.81	16.91	7.20	0.04	3.07	0.91	1.60	2.81	0.20	12.1	100.20
Montford Dam-1	79.54	0.55	7.44	4.73	0.01	0.94	0.78	0.12	0.64	-0.02	5.67	100.39
North Fork-1	44.75	0.69	15.01	5.48	0.19	4.33	7.05	1.33	2.69	0.13	18.7	100.38
OSG-1	58.26	0.87	16.07	8.77	0.06	2.67	1.18	1.17	3.04	0.13	8.1	100.31
OSG-2	63.21	0.81	14.15	7.19	0.03	1.72	0.22	1.43	2.37	0.00	8.05	99.17
Parks Cliffside-1	57.67	0.79	14.28	5.08	0.07	2.43	5.19	1.11	2.57	0.15	10.7	100.06
PRH-3	64.19	0.74	13.18	5.37	0.06	2.49	1.50	1.65	2.19	1.99	6.91	100.28
PSH-3	63.66	0.82	15.19	6.04	0.07	2.83	1.11	1.77	2.46	0.14	7.52	101.61
PSH-4	47.64	0.64	12.48	4.93	0.12	2.98	10.68	1.07	2.59	0.07	16.5	99.70
SCT-1	52.28	0.85	18.53	8.40	0.09	2.55	0.83	1.45	3.05	0.13	11.1	99.22
SCT-2	53.05	0.84	18.22	8.20	0.07	2.55	1.80	1.32	3.13	0.19	11.1	100.45
South Beggs-1	52.63	0.85	17.66	8.93	0.18	3.27	2.37	0.88	3.22	0.11	10.4	100.44
UUH-1	54.45	0.81	15.73	5.72	0.08	2.66	3.99	1.40	1.92	0.22	14.7	101.64
UURR-1	65.59	0.81	13.55	5.29	0.04	2.19	1.27	1.39	2.31	0.16	7.55	100.13
UURR-2	60.77	0.66	12.69	5.10	0.07	2.07	4.84	1.54	2.11	0.14	10	99.98
Zip Cliff-1	56.82	0.90	17.88	6.95	0.03	2.73	0.46	1.71	2.86	0.16	8.68	99.18
Zip Giant Clams-1	55.08	0.78	17.18	6.66	0.09	2.92	1.35	1.54	3.44	0.25	10.1	99.38
USGS STANDARDS												
SCO-1	61.97	0.62	14.39	5.31	0.05	2.78	2.66	0.92	2.73	0.25	8.77	100.45
TTU INTERNAL STANDARDS												
1.5BCM	82.97	1.69	24.08	12.42	0.20	8.79	10.80	5.98	3.22	0.75		150.90
1.5BCM	82.59	1.70	24.09	12.37	0.20	8.75	10.85	5.98	3.24	0.75		150.52
ABA	45.02	2.04	14.54	11.92	0.18	11.38	10.31	3.16	1.42	0.44		100.41
ABA	45.11	2.03	14.48	11.93	0.18	11.37	10.33	3.17	1.41	0.44		100.44
BCM	55.12	1.13	15.94	8.24	0.13	5.89	7.21	4.00	2.14	0.43		100.22
BCM	55.26	1.13	16.03	8.25	0.13	5.86	7.22	3.99	2.15	0.43		100.45
BCM	55.15	1.13	16.05	8.28	0.13	5.87	7.23	3.99	2.16	0.43		100.41
MHA	60.55	0.84	17.91	5.91	0.10	3.15	6.18	4.32	1.25	0.17		100.38
MHA	60.50	0.84	17.86	5.92	0.10	3.15	6.15	4.33	1.25	0.17		100.27
RGMT	72.70	0.28	14.09	1.85	0.04	0.33	1.27	4.19	4.36	0.05		99.16
RGMT	72.89	0.28	14.08	1.85	0.04	0.33	1.27	4.18	4.35	0.05		99.32
RGMT	73.05	0.28	14.04	1.86	0.04	0.33	1.27	4.20	4.37	0.05		99.49

THIRD ANALYTICAL RUN (MAJOR ELEMENTS IN WT%)												
	Sr	***Ba***	***Zr***	***Y***	***Sc***	***V***	***Cr***	***Ni***	***Cu***	***Zn***	***Nb***	***Be***
SAMPLES												
Cedar Hill-1	125	405	198	31.1	17.8	108	71	28.1	32	123	12	3.18
HQH-1	206	265	237	32.4	12.6	70.6	51	26.8	21	59	16	2.12
Meyer's Hill-1	284	291	174	28.1	17	86.5	71	27.5	32	61	9	2.9
Montford Dam-1	48	137	331	17.7	7.8	42.1	29	4.25	14	23	5	1.2
North Fork-1	329	370	152	29.9	17.1	102	52	27	32	54	18	2.56
OSG-1	141	389	233	30.8	15.6	95.9	62	23.7	14	85	10	2.74
OSG-2	123	476	258	46.5	14	53.6	52	22.7	27	61	8	2.38
Parks Cliffside-1	179	316	243	31.7	13.1	72.6	56	23.3	23	77	16	2.38

PRH-3	255	312	280	26.8	12.6	77.1	49	22.3	22	71	8	1.86
PSH-3	209	415	243	28.6	14.4	101	47	20.2	26	97	8	2.36
PSH-4	418	245	184	24.6	11.6	45.3	45	18.1	15	52	20	1.79
SCT-1	102	296	151	27.2	18.8	109	77	34.1	17	73	9	3.12
SCT-2	159	390	142	27.7	18.6	121	68	34.4	22	86	11	3.17
South Beggs-1	134	344	182	30.9	19.4	102	63	25.8	28	101	14	3.33
UUH-1	232	151	198	30.3	14.7	60.3	58	24.5	35	39	15	2.43
UURR-1	129	269	370	32.1	12	55.3	50	18.8	14	61	12	2.23
UURR-2	120	271	227	28.8	11.9	66.3	59	22.8	22	51	13	2.25
Zip Cliff-1	98	339	185	28.1	17.1	100	74	39.2	30	70	9	2.98
Zip Giant Clams-1	165	269	183	27.4	17.7	97.9	83	43.5	16	57	12	3.37
USGS STANDARDS												
SCO-1	173	572	185	23.8	13.2	119	57	16.1	26	109	9	1.79
TTU INTERNAL CALIBRATION STANDARDS												
1.5BCM	1089	1341	254	27.5	28.2	193	195	130	81	117	41	2.3
1.5BCM	1095	1339	255	27.5	28.4	192	194	128	81	117	41	2.31
ABA	547	418	170	24.0	28	205	362	236	57	95	40	1.3
ABA	552	417	170	24.1	27.9	207	361	236	57	95	40	1.3
BCM	724	896	170	18.2	18.8	129	130	85.8	54	78	28	1.51
BCM	729	892	169	18.3	18.8	128	130	85.7	54	78	28	1.5
BCM	729	894	169	18.3	18.8	128	130	86.2	54	78	28	1.51
MHA	563	313	157	15.1	12.8	78.9	29	24.1	21	58	10	1.2
MHA	567	312	156	15.1	12.8	78.8	29	23.9	21	58	10	1.2
RGMT	110	790	238	21.7	5.87	10.9	0.9	1.05	7.5	36	9	2.2
RGMT	110	790	239	21.8	5.9	10.9	0.3	0.51	7.5	36	9	2.21
RGMT	110	789	239	21.8	5.88	10.9	0.7	2.9	8.7	36	9	2.2

The following two tables give the values for the North American Shale Composite given by Condie et al. (1993), which were used in the multivariate analyses.

NORTH AMERICAN SHALE COMPOSITE VALUES: MAJOR ELEMENTS (WT%) SOURCE: CONDIE ET AL. (1993)									
SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5
64.8	0.7	16.9	5.67		2.86	3.63	1.14	3.97	0.13

NORTH AMERICAN SHALE COMPOSITE VALUES: TRACE ELEMENTS (PPM) SOURCE: CONDIE ET AL. (1993)											
Sr	Ba	Zr	Y	Sc	V	Cr	Ni	Cu	Zn	Nb	Be
142	636	200	35	15	130	125	58			13	

APPENDIX 3

INVENTORY OF VERTEBRATE FOSSILS FROM THE DOCKUM GROUP (UPPER TRIASSIC) OF SOUTHERN GARZA COUNTY

The following inventory is based almost entirely on material from the Museum of Texas Tech (MOTT) collection, with the exception of some aetosaur from the Post Quarry in the Dallas Museum of Natural History (DMNH). Some of the DMNH material was examined by the author, but descriptions of material not seen is in quotation marks and taken from Long and Murry's (1995) appendices. The specimens are listed by locality first, higher taxon second, alpha taxon third. "Citations and notes" contains citations for material which has been published, or is soon to be, and also identifies type material, and any additional comments on the material deemed worthy of mention. Due to the high volume of material still being collected by Bill Mueller and Doug Cunningham, the inventory is already somewhat out of date, and also does not include material which is not (yet) diagnostic beyond being Vertebrata *incertae sedis*, Tetrapoda *incertae sedis*, or Amniota *incertase sedis*.

SITE	SPECIMEN #	HIGHER TAXON	ALPHA TAXON	ELEMENT(S)	CITATIONS & NOTES
MOTT 3928 (Eastern Garza) Boren Ranch sandstone/beds					
NA	TTU P-12785	Parasuchia	*Incertae sedis*	Small cervical vertebra centrum	
MOTT 3867 (OS Ranch) Boren Ranch sandstone/beds					
NA	TTU P-11053	Osteichthyes	*Incertae sedis*	Fragmentary scales and bones	
NA	TTU P-10722	Metoposauridae	*Incertae sedis*	Large centrum, badly weathered	*Metoposaurus* or *Koskinonodon*
NA	TTU P-10723	Metoposauridae	*Incertae sedis*	Limb bone fragments	*Metoposaurus* or *Koskinonodon*
NA	TTU P-10724	Metoposauridae	*Incertae sedis*	Proximal end of rib	*Metoposaurus* or *Koskinonodon*
NA	TTU P-10766	Metoposauridae	*Incertae sedis*	Fragment of skull roof	*Metoposaurus* or *Koskinonodon*
NA	TTU P-11295	Metoposauridae	*Incertae sedis*	Partial skull	*Metoposaurus* or *Koskinonodon*
NA	NA	Metoposauridae	*Incertae sedis*	Articular region of a large mandible	*Metoposaurus* or *Koskinonodon*, un-numbered, in drawer A, cabinet 70 (J2)

Site 1	TTU P-10404	Dicynodontia	*Incertae sedis*	Large right scapula	Mueller and Chatterjee, 2007, in prep
Site 1	TTU P-11705	Parasuchia	*Incertae sedis*	Osteoderm	
NA	TTU P-11708	Parasuchia	*Incertae sedis*	Large partial ungal	
Site 2	TTU P-11706	Parasuchia	*Paleorhinus* sp.	Skull (part of anterior left side of skull including most of snout, part of external nares and anterobital fenestra) and both mandibles	
MOTT 3873 (OS Ranch East) Boren Ranch sandstone/beds					
NA	TTU P-11698	Metoposauridae	*Incertae sedis*	Large occipital condyle	*Metoposaurus* or *Koskinonodon*
MOTT 3872 (OS Flat Road) Boren Ranch sandstone/beds					
NA	TTU P-9605	Shuvosauridae	*Incertae sedis*	Large edentulous right maxilla	Lehane, 2005, fig. 38
MOTT 3910 (OS Road Side) Boren Ranch sandstone/beds					
NA	TTU P-11849	Parasuchia	*Incertae sedis*	Modest sized right premaxilla	
NA	TTU P-11849	Metoposauridae	*Incertae sedis*	Partial palate	
MOTT 3702 (OS Ranch Fish) Boren Ranch sandstone/beds?					
NA	TTU P-10361	Palaeoniscidae	*Turseodus dolorensis*	Partial skull and scales	On display, locality has not been relocated
NA	TTU P-10725	Parasuchia	*Incertae sedis*	Scapulocoracoid (part of left scapular blade and scapular glenoid)	Black preservation
MOTT 3704 (OS Ranch Giants) Boren Ranch sandstone/beds?					
	TTU P-11522	Parasuchia	*Incertae sedis*	Skull (fragmentary, unprepared, but nicely preserved)	
NA	TTU P-11523	Parasuchia	*Incertae sedis*	Mandible (fragments of a massive jaw)	Skull remains uncollected
NA	TTU P-9622	Parasuchia	*Incertae sedis*	Five fragmentary, fairly large osteoderms	
MOTT 3890 (Lake Alan Henry-Cedar Hill) Boren Ranch sandstone/beds					
NA	TTU P-11422	Parasuchia	*Paleorhinus scurriensis*	Skull (part of skull roof preserving part of right orbit, external nares, antorbital fenestra)	
MOTT 3869 (Boren/Neyland Quarry) Lower unit of the Cooper Canyon Formation					
Site 6	TTU P-10504	Osteichthyes	*Incertae sedis*	Possible skull bone	
Site 1	TTU P-10873	Osteichthyes	*Incertae sedis*	Tiny verrtebra	
Site 20	TTU P-?	Metoposauridae	*Incertae sedis*	Tiny fragment of mandible	
Site 6	TTU P-10488	Metoposauridae	*Incertae sedis*	Large vertebra	*Metoposaurus* or *Koskinonodon*
Site 24	TTU P-10489	Metoposauridae	*Incertae sedis*	Medium size axis centrum	

Site 8	TTU P-10547	Metoposauridae	*Incertae sedis*	Large metoposaur tooth, badly weathered	*Metoposaurus* or *Koskinonodon*
Site 19	TTU P-10549	Metoposauridae	*Incertae sedis*	Nearly complete right clavicle	*Metoposaurus* or *Koskinonodon*
Site 9	TTU P-10556	Metoposauridae	*Incertae sedis*	Incomplete interclavicle	*Metoposaurus* or *Koskinonodon*
Site 6	TTU P-10649	Metoposauridae	*Incertae sedis*	Tooth	
Site 11	TTU P-10694	Metoposauridae	*Incertae sedis*	Tiny incomplete clavicle	
NA	TTU P-10768	Metoposauridae	*Incertae sedis*	Partial skull	*Metoposaurus* or *Koskinonodon*
Site 1	TTU P-10864	Metoposauridae	*Incertae sedis*	Two small incomplete caudal vertebrae	
NA	TTU P-11043	Metoposauridae	*Incertae sedis*	Incomplete right clavicle	*Metoposaurus* or *Koskinonodon*
Site 24	TTU P-11149	Metoposauridae	*Incertae sedis*	Miscellaneous fragments of various sizes (vertebrae, pectoral and pelvic fragments, etc…)	Several un-numbered bags from same site in drawer assumed to belong to specimen
Site 24	TTU P-11152	Metoposauridae	*Incertae sedis*	Skull fragments	
Site 15	TTU P-11300	Metoposauridae	*Incertae sedis*	Tiny fragment of tooth row	
Site 24	TTU P-11321	Metoposauridae	*Incertae sedis*	Illium fragment	
Site 24	TTU P-11322	Metoposauridae	*Incertae sedis*	Illium fragment	
NA	TTU P-11663	Metoposauridae	*Incertae sedis*	Small ornamented fragment, element identification uncertain	
Site 20	TTU P-11675	Metoposauridae	*Incertae sedis*	Tiny jaw fragment	
NA	TTU P-11687	Metoposauridae	*Incertae sedis*	Large complete atlas, beautifully preserved	*Metoposaurus* or *Koskinonodon*
Site 24	TTU P-12387	Metoposauridae	*Incertae sedis*	Small partial limb bone	
Site 24	TTU P-12528	Metoposauridae	*Incertae sedis*	Tiny centrum	
NA	TTU P-9424	Metoposauridae	*Incertae sedis*	Large nearly complete interclavicel and both clavicles	*Metoposaurus* or *Koskinonodon*
NA	TTU P-9607	Metoposauridae	*Incertae sedis*	Partial braincase	Associated with *"Ischigualastia"* phytosaur mandible
Site 6	TTU P-10530	Metoposauridae	*Metoposaurus bakeri*	Large complete skull	Houle and Mueller, 2005
Site 8	TTU P-11046	Metoposauridae	*Metoposaurus bakeri*	Large nearly complete skull	
Site 24	TTU P-10568	Metoposauridae	*Incertae sedis*	Small partial skull	
Site 23	TTU P-10402	Dicynodontia	Gen. et sp. nov.	Incomplete, disarticulated skull	Mueller and Chatterjee, 2007, in prep

Site 17	TTU P-9421	Dicynodontia	Gen. et sp. nov.?	Nearly complete mandible	Mueller and Chatterjee, 2007, in prep; Lehman and Chatterjee, 2005 (Fig. 12)
Site 18	TTU P-10407	Dicynodontia	*Incertae sedis*	Partial tusk	Mueller and Chatterjee, in prep
Site 17	TTU P-10450	Dicynodontia	*Incertae sedis*	Basisphenoid	Mueller and Chatterjee, in prep
Site 34	TTU P-10751	Dicynodontia	*Incertae sedis*	Proximal end of large radius	May go with TTU P-11150; Mueller and Chatterjee, in prep
Site 34	TTU P-10752	Dicynodontia	*Incertae sedis*	Partial squamosal	Mueller and Chatterjee, in prep
Site 34	TTU P-11150	Dicynodontia	*Incertae sedis*	Distal end of large radius	May go with TTU P-10750; Mueller and Chatterjee, in prep
NA	TTU P-10753	Dicynodontia?	*Incertae sedis*	Partial vertebra	Mueller and Chatterjee
Site 34	TTU P-11292	Dicynodontia?	*Incertae sedis*	Squamosal(?) fragments	Mueller and Chatterjee
NA	TTU P-9487	Sphenodontidae	*Incertae sedis*	Probable pterygoid preserving two rows of teeth of differing size	Nick Fraser, personal communication
NA	TTU P-10346	Protorosauria	*Malerisaurus* sp.	Cervical vertebra	Bill Mueller, pers. comm.
NA	TTU P-10347	Protorosauria	*Malerisaurus* sp.	Cervical vertebra	Bill Mueller
Site 4	TTU P-10482	Protorosauria	*Malerisaurus* sp.	Unprepared skeleton, including jaw fragments	Bill Mueller
NA	TTU P-10553	Protorosauria	*Malerisaurus* sp.	One tibia, one proximal tibia, two distal humeri, one fragment	Bill Mueller
NA	TTU P-10563	Protorosauria	*Malerisaurus* sp.	Complete femur	Bill Mueller
NA	TTU P-10565	Protorosauria	*Malerisaurus* sp.	One proximal humerus, three distal humeri	Bill Mueller
NA	TTU P-10566	Protorosauria	*Malerisaurus* sp.	Dorsal vertebrae	Bill Mueller
NA	TTU P-10567	Protorosauria	*Malerisaurus* sp.	Complete femur	Bill Mueller
Site 4	TTU P-11334	Protorosauria	*Malerisaurus* sp.	Three distal femora	Bill Mueller
Site 4	TTU P-11335	Protorosauria	*Malerisaurus* sp.	Distal femur	Bill Mueller
Site 1	TTU P-11340	Protorosauria	*Malerisaurus* sp.	Several proximal and distal femora	Bill Mueller
Site 5	TTU P-11688	Protorosauria	*Malerisaurus* sp.	Tiny proximal femur	Bill Mueller
Site 4	TTU P-11887	Protorosauria	*Malerisaurus* sp.	Proximal and distal ends of femur	Bill Mueller
Site 13	TTU P-12139	Protorosauria	*Malerisaurus* sp.	Femur	Bill Mueller
Site 1	TTU P-12437	Protorosauria	*Malerisaurus* sp.	Proximal femur	Bill Mueller
Site 5	TTU P-12450	Protorosauria	*Malerisaurus* sp.	Proximal and distal ends of humerus	Bill Mueller
Site 1	TTU P-124536	Protorosauria	*Malerisaurus* sp.	Proximal femur	Bill Mueller
Site 1	TTU P-12500	Protorosauria	*Malerisaurus* sp.	Proximal femur	Bill Mueller
Site 4	TTU P-12504	Protorosauria	*Malerisaurus* sp.	Proximal femur	Bill Mueller

Site 4	TTU P-10843	Drepanosauridae	*Incertae sedis*	Incomplete tail "claw"?	Mueller and Chatterjee, in prep
Site 1	TTU P-10430	Trilophosauria	cf. *Trilophosaurus*	Jaw fragment with teeth	
Site 4	TTU P-10673	Trilophosauria	cf. *Trilophosaurus*	Fifth metatarsal	
Site 4	TTU P-12401	Trilophosauria	*Trilophosaurus buettneri*	Dentary with teeth	
NA	TTU P-9495	Trilophosauria	*Trilophosaurus buettneri*	Jaw fragment with teeth, cusps not well-preserved	
Site 1b	TTU P-10413	Trilophosauria	*Trilophosaurus dornorum*	Maxilla with teeth	Mueller and Parker, 2006 (Fig. 5B)
Site 3	TTU P-10582	Trilophosauria	*Trilophosaurus dornorum*	Jaw fragment with teeth	Mueller and Parker, 2006
Site 3	TTU P-10583	Trilophosauria	*Trilophosaurus dornorum*	Jaw fragment with teeth	Mueller and Parker, 2006
Site 12	TTU P-10586	Trilophosauria	*Trilophosaurus dornorum*	Dentaries with teeth	Mueller and Parker, 2006
Site 12	TTU P-10587	Trilophosauria	*Trilophosaurus dornorum*	Jaw fragment with teeth	
Site 12	TTU P-10405	Trilophosauria	*Trilophosaurus jacobsi*	Jaw fragment with teeth	
Site 1	TTU P-10411	Trilophosauria	*Trilophosaurus jacobsi*	Single tooth	
Site 4	TTU P-10418	Trilophosauria	*Trilophosaurus jacobsi*	Single tooth	
Site 2	TTU P-10422	Trilophosauria	*Trilophosaurus jacobsi*	Jaw fragment with teeth	
Site 1	TTU P-10425	Trilophosauria	*Trilophosaurus jacobsi*	Jaw fragment with teeth	
Site 4	TTU P-10431	Trilophosauria	*Trilophosaurus jacobsi*	Partial skull, badly preserved	
Site 4	TTU P-10531	Trilophosauria	*Trilophosaurus jacobsi*	Jaw fragments with teeth	
NA	TTU P-9496	Trilophosauria	*Trilophosaurus jacobsi*	Jaw fragments with teeth	
Site 3	TTU P-9618	Trilophosauria	*Trilophosaurus jacobsi*	Jaw fragment with teeth	
Site 1	TTU P-10424	Trilophosauria	*Trilophosaurus jacobsi?*	Jaw fragment with teeth	
Site 2	TTU P-10427	Trilophosauria	*Trilophosaurus jacobsi?*	Badly preserved jaw fragment with teeth	
Site 3	TTU P-10581	Trilophosauria	*Trilophosaurus jacobsi*?	Badly preserved jaw fragments with teeth	
Site 4	TTU P-10584	Trilophosauria	*Trilophosaurus jacobsi?*	Badly preserved jaw and teeth fragments	
Site 12	TTU P-10589	Trilophosauria	*Trilophosaurus jacobsi*?	Astragalus	
Site I	TTU P-10412	Trilophosauria	*Trilophosaurus* new species A	Dentary with teeth	Bill Mueller, in prep
Site 5	TTU P-10585	Trilophosauria	*Trilophosaurus* new species A	Maxilla with teeth	Bill Mueller, in prep

Site 5b	TTU P-10408	Trilophosauria	*Trilophosaurus* new species B	Three dentary fragments with teeth	Bill Mueller, in prep
Site 4	TTU P-10428	Trilophosauria	*Trilophosaurus* new species B	Jaw fragment with teeth	Bill Mueller, in prep
Site 4	TTU P-10709	Trilophosauria	*Trilophosaurus* new species B	Jaw fragment with teeth	Bill Mueller, in prep
Site 4	TTU P-10965	Trilophosauria	*Trilophosaurus* new species B	Jaw fragment with teeth	Bill Mueller, in prep
Site 4	TTU P-?	Trilophosauria	*Trilophosaurus* sp.	Large proximal humerus and small distal humerus	
Site 4	TTU P-?	Trilophosauria	*Trilophosaurus* sp.	Several proximal and distal humerus fragments	
	TTU P-?	Trilophosauria	*Trilophosaurus* sp.	Large second metatarsal	
Site 12	TTU P-10416	Trilophosauria	*Trilophosaurus* sp.	Jaw fragment	
Site 2	TTU P-10426	Trilophosauria	*Trilophosaurus* sp.	Tooth	
Site 1	TTU P-10429	Trilophosauria	*Trilophosaurus* sp.	Jaw fragment	
Site 12	TTU P-10440	Trilophosauria	*Trilophosaurus* sp.	Jaw and teeth fragments	
Site 3	TTU P-10579	Trilophosauria	*Trilophosaurus* sp.	Distal quadrate	
Site 4	TTU P-10580	Trilophosauria	*Trilophosaurus* sp.	Distal quadrate	
Site 12	TTU P-10588	Trilophosauria	*Trilophosaurus* sp.	Jaw fragment with teeth	
Site 4	TTU P-10590	Trilophosauria	*Trilophosaurus* sp.	Proximal fifth metatarsal	
NA	TTU P-10616	Trilophosauria	*Trilophosaurus* sp.	Large anterior cervical vertebra	
NA	TTU P-10617	Trilophosauria	*Trilophosaurus* sp.	Large anterior cervical vertebra	
NA	TTU P-10618	Trilophosauria	*Trilophosaurus* sp.		
NA	TTU P-10619	Trilophosauria	*Trilophosaurus* sp.	Caudal vertebra	
NA	TTU P-10620	Trilophosauria	*Trilophosaurus* sp.	Caudal vertebra	
NA	TTU P-10621	Trilophosauria	*Trilophosaurus* sp.	Caudal vertebra	
NA	TTU P-10622	Trilophosauria	*Trilophosaurus* sp.	Caudal vertebra	
NA	TTU P-10623	Trilophosauria	*Trilophosaurus* sp.	Caudal vertebra	
NA	TTU P-10624	Trilophosauria	*Trilophosaurus* sp.	Caudal vertebra	
NA	TTU P-10625	Trilophosauria	*Trilophosaurus* sp.	Caudal vertebra	
Site 1	TTU P-10626	Trilophosauria	*Trilophosaurus* sp.	Caudal vertebra	
NA	TTU P-10627	Trilophosauria	*Trilophosaurus* sp.	Nearly complete humerus	
NA	TTU P-10628	Trilophosauria	*Trilophosaurus* sp.	Small poximal humerus	

NA	TTU P-10629	Trilophosauria	*Trilophosaurus* sp.	Three distal humeri	
Site 5	TTU P-10656	Trilophosauria	*Trilophosaurus* sp.	Tiny cervical vertebra	
Site 4	TTU P-10811	Trilophosauria	*Trilophosaurus* sp.	Astragalus	
NA	TTU P-10876	Trilophosauria	*Trilophosaurus* sp.	Large ungal	
NA	TTU P-10879	Trilophosauria	*Trilophosaurus* sp.	Jaw fragment with teeth	
NA	TTU P-10900	Trilophosauria	*Trilophosaurus* sp.	Anterior dentary with symphysis	
NA	TTU P-9488	Trilophosauria	*Trilophosaurus* sp.	Jaw fragment with teeth	
NA	TTU P-9500	Trilophosauria	*Trilophosaurus* sp.	Jaw fragment with teeth	
NA	TTU P-11518	Archosauriformes	cf. *Doswellia*	Incomplete osteoderm	
Site 5b	TTU P-10409	Parasuchia	*Incertae sedis*	Skull fragments, including partial prootic and quadrate	
NA	TTU P-10410	Parasuchia	*Incertae sedis*	Right basipterygoid process and part of parabasisphenoid of a very large phytosaur	
Site 5c	TTU P-10434	Parasuchia	*Incertae sedis*	Almost complete neural arch	
Site 5c	TTU P-10435	Parasuchia	*Incertae sedis*	Fragmentary neural arch	
Site 11	TTU P-10481	Parasuchia	*Incertae sedis*	Incomplete interclavicle	
Site 6	TTU P-10506	Parasuchia	*Incertae sedis*	Beatuful maxillary tooth	
Site 4	TTU P-10511	Parasuchia	*Incertae sedis*	Tiny maxillary tooth	
Site 11	TTU P-10597	Parasuchia	*Incertae sedis*	Large incomplete osteoderm	
Site 6	TTU P-10599	Parasuchia	*Incertae sedis*	Large incomplete osteoderm	
Site 4	TTU P-10633	Parasuchia	*Incertae sedis*	Left quadrate	
Site 4b	TTU P-10634	Parasuchia	*Incertae sedis*	Skull fragment	
Site 6	TTU P-10635	Parasuchia	*Incertae sedis*	Possible sacral vertebra	
Site 14	TTU P-10636	Parasuchia	*Incertae sedis*	Cervical vertebra centrum, neural arch absent, strong ventral keel	
NA	TTU P-10637	Parasuchia	*Incertae sedis*	Two partial basicrania with occitial condyles and basal tubera	
Site 10	TTU P-10638	Parasuchia	*Incertae sedis*	Vertebra centrum, lacking neural arch	

Site 16	TTU P-10639	Parasuchia	*Incertae sedis*	Caudal vertebra centrum, partial neural arch attached	
NA	TTU P-10640	Parasuchia	*Incertae sedis*	Vertebra centrum, probably sacral	
Site 11	TTU P-10661	Parasuchia	*Incertae sedis*	Two tiny premaxillary teeth	
Site 26	TTU P-10682	Parasuchia	*Incertae sedis*	Astragalus	
Site 5e	TTU P-10757	Parasuchia	*Incertae sedis*	Left astragalus	
Site 1	TTU P-10880	Parasuchia	*Incertae sedis*	Small ungal	
Site 5	TTU P-11886	Parasuchia	*Incertae sedis*	Modest sized dorsal vertebra	
Site 9	TTU P-12427	Parasuchia	*Incertae sedis*	Teeth	
Site 8	TTU P-12454	Parasuchia	*Incertae sedis*	Tooth	
Site 9	TTU P-12512	Parasuchia	*Incertae sedis*	Teeth	
NA	TTU P-9422	Parasuchia	*Incertae sedis*	Incomplete right maxilla and almost complete right mandible, beautiful preservation	
NA	TTU P-9427	Parasuchia	*Incertae sedis*	Left and right posterior mandibles, left more complete	Edler, 1999 described posterior mandible as partial dicynodont skull referrable to "Ischigualastia"
Site 16	TTU P-9423	Parasuchia	*Paleorhinus* cf. *P. sawini*	Nearly complete skull, incomplete mandible, partial postcranial skeleton	
NA	TTU P-10423	Suchia	*Revueltosaurus callenderi*	Isolated tooth and crown	
Site 5	TTU P-11750	Aetosauria	cf. *Stagonolepis*?	Almost complete anterior caudal paramedian and associated lateral osteoderm	
Site 18	TTU P-11595	Aetosauria	*Incertae sedis*	Fragment of a paramedian osteoderm	
Site 1A	TTU P-12447	Aetosauria	*Incertae sedis*	Fragment of boss or lateral spike	
Site 22	TTU P-10406	Aetosauria	*Incertae sedis*	Fragmentary osteoderms, possible skull fragment, non-aetosaur tooth	
NA	TTU P-10747	Aetosauria	*Incertae sedis*	Partial paramedian osteoderm	
Site 5c	TTU P-11148	Aetosauria	*Incertae sedis*	Incomplete paramedian osteoderm	
NA	TTU P-10444	Rauisuchidae	*Incertae sedis*	Tooth	
NA	TTU P-10512	Rauisuchidae	*Incertae sedis*	Tooth	
Site 6	TTU P-10555	Shuvosauridae	*Incertae sedis*	Partial centrum	Jeremiah Kokes, in prep

Site 1	TTU P-10837	Shuvosauridae	*Incertae sedis*	Astragalus	Jeremian Kokes, in prep
NA	TTU P-10209	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10210	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002); TTU P-10210 through TTU P-101216 form an articulated series of drosal vertebrae and associated rib fragments
NA	TTU P-10211	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002); TTU P-10210 through TTU P-101216 form an articulated series of drosal vertebrae and associated rib fragments
NA	TTU P-10212	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002); TTU P-10210 through TTU P-101216 form an articulated series of drosal vertebrae and associated rib fragments
NA	TTU P-10213	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002); TTU P-10210 through TTU P-101216 form an articulated series of drosal vertebrae and associated rib fragments
NA	TTU P-10214	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002); TTU P-10210 through TTU P-101216 form an articulated series of drosal vertebrae and associated rib fragments
NA	TTU P-10215	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002); TTU P-10210 through TTU P-101216 form an articulated series of drosal vertebrae and associated rib fragments
NA	TTU P-10216	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002); TTU P-10210 through TTU P-101216 form an articulated series of drosal vertebrae and associated rib fragments
NA	TTU P-10217	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10345	Pterosauromorpha?	*"Procoelosaurus"* sp.	Caudal vertebra	
Site 6	TTU P-10668	Pterosauromorpha?	*"Procoelosaurus"* sp.	Badly preserved vertebra	
Site 4	TTU P-11323	Pterosauromorpha?	*"Procoelosaurus"* sp.	Cervical vertebra	
Site 5c	TTU P-12037	Pterosauromorpha?	*"Procoelosaurus"* sp.	Caudal vertebra	TTU P-12037 through TTU P-12040 are associated
Site 5c	TTU P-12038	Pterosauromorpha?	*"Procoelosaurus"* sp.	Caudal vertebra	TTU P-12037 through TTU P-12040 are associated

Site 5c	TTU P-12039	Pterosauromorpha?	*"Procoelosaurus"* sp.	Caudal vertebra	TTU P-12037 through TTU P-12040 are associated
Site 5c	TTU P-12040	Pterosauromorpha?	*"Procoelosaurus"* sp.	Caudal vertebra	TTU P-12037 through TTU P-12040 are associated
Site 1a	TTU P-10091	Pterosauromorpha?	*"Pteromimus longicollis"*	Cervical vertebra	Atanassov (2002)
Site 5c	TTU P-10096	Pterosauromorpha?	*"Pteromimus longicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10331	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10332	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10333	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10334	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10335	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10336	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10337	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
Site 5c	TTU P-10338	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10344	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10348	Pterosauromorpha?	cf. *"Procoelosaurus"*	Cervical vertebra	
Site 4	TTU P-10349	Pterosauromorpha?	cf. *"Procoelosaurus"*	Cervical vertebra	
Site 4	TTU P-10350	Pterosauromorpha?	cf. *"Procoelosaurus"*	Cervical vertebra	
Site 4	TTU P-10351	Pterosauromorpha?	cf. *"Procoelosaurus"*	Cervical vertebra	
Site 4	TTU P-10352	Pterosauromorpha?	cf. *"Procoelosaurus"*	Cervical vertebra	
	TTU P-10546	Dinosauromorpha	*Dromomeron* sp.	Tibia	
Site 1	TTU P-11186	Dinosauromorpha	*Dromomeron* sp.	Distal femur	
MOTT 3614 (Rocker A Oil Field) Lower unit of the Cooper Canyon Formation?					
NA	TTU P-9209	Aetosauria	*Typothorax coccinarum*	Two partial paramedian osteoderms	Small, 1989 (Pl. 4J)
NA	TTU P-9228	Aetosauria	Desmatosuchinae *incertae sedis*	Two non-emarginate lateral horns	
MOTT 3881 (Meyer's Hill) Lower unit of the Cooper Canyon Formation					
NA	TTU P-10421	Dicynodontia	*Incertae sedis*	Large left humerus	
MOTT 3624 (Post Quarry) Lower unit of the Cooper Canyon Formation					
NA	TTU P-9216	Metoposauridae	*Apachesaurus gregorii*	Skull and mandible	Davidow-Henry, 1989 (Fig.1, pl. 4). Lost on loan, whereabouts unknown, natural mold in collections
NA	TTU P-9168	Temnospondyli	*Rileymillerus cosgriffi*	Skull and mandible	Bolt and Chatterjee, 2000, holotype

NA	TTU P-9170	Temnospondyli	*Rileymillerus cosgriffi*	Postcranial material	
NA	TTU P-10826	Trithelodontidae	*Incertae sedis*	Tooth	
NA	TTU P-9020	Trithelodontidae	*Incertae sedis*	Partial mandible with teeth	Chatterjee, 1982, holotype of "*Pachygenelus milleri*"
NA	TTU P-9245	Trithelodontidae	*Incertae sedis*	Partial mandible with teeth	
NA	TTU P-9472	Sphenodontidae	cf. *Clevosaurus*	Premaxilla with broken teeth, additional discrete tooth under maxillary facet similar to Cromhall clevosaurs	Nick Fraser, personal communication
NA	TTU P-9473	Sphenodontidae	*incertae sedis*	Mandible	Nick Fraser, personal communication
NA	TTU P-11277	Sphenosuchia	*incertae sedis*	Distal femur	
NA	TTU P-11443	Sphenosuchia	*incertae sedis*	Femur	
NA	TTU P-11444	Sphenosuchia	*incertae sedis*	Femur	
NA	TTU P-9466	Sphenosuchia	*incertae sedis*	Premaxilla	
NA	TTU P-11338	Protorosauria	*Malerisaurus* sp.	Cervical vertebra	
NA	TTU P-11237	Drepanosauridae	*Incertae sedis*	Five caudal vertebrae, one cervical vertebra	
NA	TTU P-9604	Drepanosauridae	*Incertae sedis*	Nearly complete scapulocoracoid	
NA	TTU P-9606	Drepanosauridae	*Incertae sedis*	Fragment of scapulocoracoid with glenoid	
NA	TTU P-9201	Drepanosauridae?	*Protoavis texensis* (in part)	Cervical vertebrae	
NA	TTU-P10698	Trilophosauria	cf. *Trilophosaurus*	Tiny tricuspid tooth	
NA	TTU P-9497	Trilophosauria	*Trilophosaurus dornorum*	Tooth	Mueller and Parker, 2006
NA	TTU P-10600	Trilophosauria	*Trilophosaurus* sp.	Small radius	
NA	TTU P-9231	Parasuchia	*Incertae sedis*	left humerus, right ulna, proximal end of left ulna	
NA	TTU P-9236	Parasuchia	*Incertae sedis*	Beautiful, almost complete right scapulocoracoid of a fairly large phytosaur	
NA	TTU P-9234	Parasuchia	*Leptosuchus* cf. *L. crosbiensis*	Skull (mostly complete, needs extensive repreparation)	
NA	DMNH 9894	Aetosauria	*Paratypothorax* sp.	Incomplete lateral osteoderm	Long and Murry, 1995
NA	DMNH 9896	Aetosauria	*Paratypothorax* sp.	Fragment of a paramedian osteoderm	Long and Murry, 1995

NA	DMNH 9900	Aetosauria	*Paratypothorax* sp.	"Paramedian plate fragment"	Long and Murry, 1995
NA	DMNH 9914	Aetosauria	*Paratypothorax* sp.	"Distal caudal paramedian plate"	Long and Murry, 1995 (Fig. 113F-H)
NA	DMNH 9919	Aetosauria	*Paratypothorax* sp.	"Three fragments of paramedian plates"	Long and Murry, 1995
NA	DMNH 9921	Aetosauria	*Paratypothorax* sp.	"Lateral plate fragments"	Long and Murry, 1995
NA	DMNH 9922	Aetosauria	*Paratypothorax* sp.	"Two lateral plates"	Long and Murry, 1995
NA	DMNH 9927	Aetosauria	*Paratypothorax* sp.	"Large series of bosses from dorsal and caudal paramedian plates"	Long and Murry, 1995
NA	DMNH 9928	Aetosauria	*Paratypothorax* sp.	"Lateral plates"	Long and Murry, 1995
NA	DMNH 9931	Aetosauria	*Paratypothorax* sp.	Lateral end of a left paramedian osteoderm	Long and Murry, 1995
NA	DMNH 9934	Aetosauria	*Paratypothorax* sp.	"Paramedian plate in two pieces, one includes boss"	Long and Murry, 1995
NA	DMNH 9939	Aetosauria	*Paratypothorax* sp.	Massive, incomplete pelvis with two sacral vertebrae	Long and Murry, 1995 (Fig. 116)
NA	DMNH 9942	Aetosauria	*Paratypothorax* sp.	Block containing at least six dorsal paramedian osteoderms and several lateral osteoderms, some almost articulated, ribs, and appendicular elements	Long and Murry, 1995 (Fig. 113A-E)
NA	DMNH 9986	Aetosauria	*Paratypothorax* sp.	"Paramedian plate fragment with base of boss"	Long and Murry, 1995
NA	TTU P-11599	Aetosauria	*Paratypothorax* sp.	Incomplete dorsal paramedian osteoderms	
NA	TTU P-12540	Aetosauria	*Paratypothorax* sp.	Numerous incomplete associated paramedian and lateral osteoderms, originally partially articulated and intact.	Found near *Paratypothorax* material that is part of TTU P-9416, and may belong to the same individual.
NA	TTU P-9169	Aetosauria	*Paratypothorax* sp.	Complete dorsal paramedian osteoderm	Small (1985; 1989b, Pl.5H); Long and Murry (1995) identified as *Desmatosuchus;* two osteoderm fragments in box probably go to *Typothorax* specimen TTUP-9214.
NA	TTU P-9215	Aetosauria	*Paratypothorax* sp.	Incomplete dorsal paramedian osteoderm, lateral ostoderm horn, chevron, osteoderm fragments and possible skull elements	Small (1989; Pl. 5G) identified lateral horn identified as mandible

NA	TTU P-9416 (in part)	Aetosauria	*Paratypothorax* sp.	Excellent vertebrae from the cervical through caudal series for *Desmatosuchus,* but also an excellent scapulocoraocid, probably *Desmatosuchus*, and *Paratypothorax* verts and a gracile fibula with a big trochanter, probably *Paratypothoprax.*	
NA	TTU P-9214	Aetosauria	*Typothorax* sp.	Partial skeleton including braincase, dentary, several vertebrae, appendicular material, and numerous osteoderms probably representing most of the carapace.	Small, 1985, 1989 (Pl. 4K-L, J described at TTU P-9208) ; Martz, 2002 (numerous figures)
NA	TTU P-9420 (in part)	Aetosauria	Aetosaurinae *incertae sedis*	Two dorsal paramedian osteoderms	
NA	DMNH 1160-8	Aetosauria	*Desmatosuchus smalli*	Lateral spike	
NA	DMNH 9889	Aetosauria	*Desmatosuchus smalli*	"Various armor plate fragments"	Long and Murry (1995)
NA	DMNH 9890	Aetosauria	*Desmatosuchus smalli*	"Anterior caudal vertebra"	Long and Murry (1995)
NA	DMNH 9893	Aetosauria	*Desmatosuchus smalli*	"Incomplete dorsal paramedian plate exhibiting complete lateral articular surface"	Long and Murry (1995)
NA	DMNH 9906	Aetosauria	*Desmatosuchus smalli*	"First caudal vertebra missing neural spine"	Long and Murry (1995)
NA	DMNH 9909	Aetosauria	*Desmatosuchus smalli*	"incomplete large lateral horn"	Long and Murry (1995)
NA	DMNH 9910	Aetosauria	*Desmatosuchus smalli*	"Nearly complete strongly recurved pectoral spike"	Long and Murry (1995)
NA	DMNH 9913	Aetosauria	*Desmatosuchus smalli*	"Mid-caudal vertebra"	Long and Murry (1995)
NA	DMNH 9939	Aetosauria	*Desmatosuchus smalli*	"Sacrum with complete first sacral rib, second sacral rib unattached, from enormous individual"	Long and Murry (1995)
NA	DMNH 9940	Aetosauria	*Desmatosuchus smalli*	Several incomplete paramedian osteoderms, lateral osteoderm fragment	Long and Murry (1995)
NA	DMNH 9941	Aetosauria	*Desmatosuchus smalli*	"Nearly complete anterior caudal paramedian plate"	Long and Murry (1995)
NA	DMNH 9998	Aetosauria	*Desmatosuchus smalli*	"Incomplete posterior cervical lateral spike"	Long and Murry (1995)

NA	TTU P-10083	Aetosauria	*Desmatosuchus smalli*	Excellent right humerus and ulna, incomplete lateral osteoderm.	Small (1985; 1989b, Pl. 5E); Long and Murry (1995); formerly TTU P-9170
NA	TTU P-9023	Aetosauria	*Desmatosuchus smalli*	Excellent skull lacking most of snout, incomplete left and right mandibles, several incomplete paramedian and lateral osteoderms.	Small (1985; 1989b, Pl. 5F; 2002, Fig. 1C); Long and Murry (1995)
NA	TTU P-9024	Aetosauria	*Desmatosuchus smalli*	Almost complete skull, complete mandible, extensive paramedian and lateral osteoderms, badly eroded dorsal vertebra, some good caudal vertebrae, complete right scapulocoracoid, partial pelvis, complete left humerus, complete right femur, partial left femur, two complete right tibias of almost identical size that may be small to be associated with the rest of the material, a possible large metapodial	Holotype of *Desmatosuchus smalli* (Parker, 2005, Figs. 2A-B, 3A-D, 5A-B); Small (1985; 1989b, Pl. 5A, C-D, I; 2002, Figs. 1A-B, 8); Long and Murry, 1995
NA	TTU P-9025	Aetosauria	*Desmatosuchus smalli*	Partial skull	Small (1985, 1989b, 2002)
NA	TTU P-9204	Aetosauria	*Desmatosuchus smalli*	Extensive osteoderm material, mostly fragmentary, ribs, probable interclavicle, a partial dorsal paramedian ostedoerms looks like the anomalous paramedian of TTU P-9420	Small (1989b)
NA	TTU P-9207	Aetosauria	*Desmatosuchus smalli*	Incomplete skull	
NA	TTU P-9225	Aetosauria	*Desmatosuchus smalli*	Proximal humerus	
NA	TTU P-9226	Aetosauria	*Desmatosuchus smalli*	Four incomplete lateral osteoderms, two rib fragments	
NA	TTU P-9229	Aetosauria	*Desmatosuchus smalli*	Extensive osteoderm material including some excellent dorsal paramedians, other postcranial material mostly fragmentary.	Small (1989b)

NA	TTU P-9416 (in part)	Aetosauria	*Desmatosuchus smalli*	Excellent vertebrae from the cervical through caudal series for *Desmatosuchus*, but also an excellent scapulocoraocid	
NA	TTU P-9419	Aetosauria	*Desmatosuchus smalli*	Fragmentary osteoderms, some extremely tantalizing postcranial material including vertebrae, appendicular material, and a partial pelvis with fused sacrals	A *Shuvosaurus* femur is kept with this material, possible *Shuvosaurus* vertebrae as well.
NA	TTU P-9420 (in part)	Aetosauria	*Desmatosuchus smalli*	Mostly complete, disarticulated skull, several cervcial vertebrae, and lateral osteoderms.	Small (2002, Fig. 9)
NA	TTU P-9205	Aetosauria	*Incertae sedis*	Nearly complete axis	
NA	TTU P-9206	Aetosauria	*Incertae sedis*	Partial basicranium	
NA	TTU P-9227	Aetosauria	*Incertae sedis*	Metapodials and phalanges of a large aetosaur	
NA	TTU P-9171	Aetosauria	*insertae sedis*	Very small proximal ulna	Small (1985, 1989b); Long and Murry (1995) all referred to *Desmatosuchus*
NA	TTU P-9000	Rauisuchidae	*Postosuchus kirkpatricki*	Excellent skull and postcranial skeleton	Chatterjee, 1985, holotype; Long and Murry, 1995; Weinbaum, 2002, 2007
NA	TTU P-9002	Rauisuchidae	*Postosuchus kirkpatricki*	Excellent skull and postcranial skeleton	Chatterjee, 1985, paratype; Long and Murry, 1995; Weinbaum, 2002, 2007
NA	TTU P-10082	Saurischia	*Incertae sedis*	Right illium and pubis	Lehane, 2005, text fig. 26 identified as *Shuvosaurus;* Nesbitt and Chatterjee, in prep; Lehman and Chatterjee, 2005 (p. 345 fig. 12G), identified as *Coelophysis.*
NA	TTU P-10969	Shuvosauridae	*Shuvosaurus inexpectus*	Right quadrate	Lehane, 2005
NA	TTU P-11045	Shuvosauridae	*Shuvosaurus inexpectus*	Scapula	Lehane, 2005
NA	TTU P-9001	Shuvosauridae	*Shuvosaurus inexpectus*	Excellent postcranial skeleton	Chatterjee, 1985, paratype of *Postosuchus kirkpatricki*; Long and Murry, 1995, holotype of *Chatterjea elegans*; Weinbaum, 2002
NA	TTU P-9003	Shuvosauridae	*Shuvosaurus inexpectus*	Postcranial material	Chatterjee, 1985, paratype of *Postosuchus kirkpatricki;* Long and Murry, 1995

NA	TTU P-9004	Shuvosauridae	*Shuvosaurus inexpectus*	Postcranial material	Chatterjee, 1985, paratype of *Postosuchus kirkpatricki;* Long and Murry, 1995
NA	TTU P-9005	Shuvosauridae	*Shuvosaurus inexpectus*	Postcranial material	Chatterjee, 1985, paratype of *Postosuchus kirkpatricki;* Long and Murry, 1995
NA	TTU P-9006	Shuvosauridae	*Shuvosaurus inexpectus*	Postcranial material	Chatterjee, 1985, paratype of *Postosuchus kirkpatricki;* Long and Murry, 1995
NA	TTU P-9007	Shuvosauridae	*Shuvosaurus inexpectus*	Postcranial material	Chatterjee, 1985, paratype of *Postosuchus kirkpatricki;* Long and Murry, 1995
NA	TTU P-9008	Shuvosauridae	*Shuvosaurus inexpectus*	Postcranial material	Chatterjee, 1985, paratype of *Postosuchus kirkpatricki;* Long and Murry, 1995
NA	TTU P-9009	Shuvosauridae	*Shuvosaurus inexpectus*	Postcranial material	Chatterjee, 1985, paratype of *Postosuchus kirkpatricki;* Long and Murry, 1995
NA	TTU P-9010	Shuvosauridae	*Shuvosaurus inexpectus*	Postcranial material	Chatterjee, 1985, paratype of *Postosuchus kirkpatricki;* Long and Murry, 1995
NA	TTU P-9011	Shuvosauridae	*Shuvosaurus inexpectus*	Postcranial material	Chatterjee, 1985, paratype of *Postosuchus kirkpatricki;* Long and Murry, 1995
NA	TTU P-9021 (in part)	Shuvosauridae	*Shuvosaurus inexpectus*	Posterior mandible	Chatterjee, 1993, part of holotype of *Technosaurus smalli;* Irmis et al. (2007)
NA	TTU P-9235	Shuvosauridae	*Shuvosaurus inexpectus*	Vertebrae	Jeremiah Kokes, in prep
NA	TTU P-9280	Shuvosauridae	*Shuvosaurus inexpectus*	Disarticulated elements comprising most of the skull and mandible, dubiously associated postcrania	Chatterjee, 1993, holotype; Lehane (2005)
NA	TTU P-9281	Shuvosauridae	*Shuvosaurus inexpectus*	Left squamosal and left palantine	Chatterjee, 1993, paratype; Lehane, 2005
NA	TTU P-9282	Shuvosauridae	*Shuvosaurus inexpectus*	Partial skull, including braincase	Chatterjee, 1993, paratype; Lehane, 2005
NA	TTU P-10110	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Partial skeleton including partial right maxilla, partial left dentary, two sacral vertebrae, a right illium, right ischium, left ischium, and almost complete right hindlimb	Atanassov (2002), holotype
NA	TTU P-10111	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Cervical vertebra	Atanassov (2002)

NA	TTU P-10112	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10113	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10114	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10115	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10116	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10117	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10118	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10119	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10120	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10121	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10122	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10123	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Sacral vertebra	Atanassov (2002)
NA	TTU P-10125	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10126	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10127	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10128	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10129	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10130	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10131	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10132	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10133	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Sacral vertebra	Atanassov (2002)
NA	TTU P-10134	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10135	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10136	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10137	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Cervical vertebra	Atanassov (2002)

NA	TTU P-10138	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Sacral vertebra	Atanassov (2002)
NA	TTU P-10139	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10140	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10141	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10142	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10143	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10144	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10145	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10146	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10147	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10148	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10149	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10150	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10151	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10152	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10153	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10154	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10156	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10157	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10158	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10159	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Sacral vertebra	Atanassov (2002)
NA	TTU P-10160	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Sacral vertebra	Atanassov (2002)
NA	TTU P-10161	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10162	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10163	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10164	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)

NA	TTU P-10165	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10166	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10167	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10168	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10169	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10170	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10171	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10172	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10173	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10174	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10175	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10176	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10177	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10178	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10179	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10180	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10181	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10182	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10183	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10184	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10186	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10187	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10188	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10189	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10190	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10191	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)

NA	TTU P-10192	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10193	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10194	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10195	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10196	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10197	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10198	Pterosauromorpha?	*"Procoelosaurus brevicollis"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10085	Pterosauromorpha?	*"Pteromimus longicollis"*	Partial skull with two cervical vertebrae and an unidentified element	Atanassov (2002), holotype
NA	TTU P-10086	Pterosauromorpha?	*"Pteromimus longicollis"*	Left vomer	Atanassov (2002)
NA	TTU P-10087	Pterosauromorpha?	*"Pteromimus longicollis"*	Left pterygoid	Atanassov (2002)
NA	TTU P-10088	Pterosauromorpha?	*"Pteromimus longicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10089	Pterosauromorpha?	*"Pteromimus longicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10090	Pterosauromorpha?	*"Pteromimus longicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10092	Pterosauromorpha?	*"Pteromimus longicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10093	Pterosauromorpha?	*"Pteromimus longicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10094	Pterosauromorpha?	*"Pteromimus longicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-10095	Pterosauromorpha?	*"Pteromimus longicollis"*	Cervical vertebra	Atanassov (2002)
NA	TTU P-9489	Pterosauromorpha?	*"Pteromimus longicollis"*	Partial left maxilla	Atanassov (2002)
NA	TTU P-9490	Pterosauromorpha?	*"Pteromimus longicollis"*	Partial right maxilla	Atanassov (2002)
NA	TTU P-10124	Pterosauromorpha?	cf. *"Procoelosaurus"*	Sacral vertebra	
NA	TTU P-10155	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10185	Pterosauromorpha?	cf. "*Procoelosaurus*"	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10218	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10219	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	Atanassov (2002)
NA	TTU P-10220	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10221	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10222	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	Atanassov (2002)
NA	TTU P-10223	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	Atanassov (2002)

NA	TTU P-10288	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10289	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10290	Pterosauromorpha?	cf. *"Procoelosaurus"*	Sacral vertebra	
NA	TTU P-10291	Pterosauromorpha?	cf. *"Procoelosaurus"*	Sacral vertebra	
NA	TTU P-10292	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10293	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10294	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10295	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10296	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10297	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10298	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10299	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10300	Pterosauromorpha?	cf. *"Procoelosaurus"*	Cervical vertebra	
NA	TTU P-10301	Pterosauromorpha?	cf. *"Procoelosaurus"*	Vertebra fragment	
NA	TTU P-10302	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10303	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10304	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10305	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10306	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10307	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10308	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10309	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10310	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10311	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10312	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10313	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10314	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10315	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10316	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10317	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10318	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	

NA	TTU P-10319	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10320	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10321	Pterosauromorpha?	cf. *"Procoelosaurus"*	Sacral vertebra	
NA	TTU P-10322	Pterosauromorpha?	cf. *"Procoelosaurus"*	Vertebra fragment	
NA	TTU P-10323	Pterosauromorpha?	cf. *"Procoelosaurus"*	Spine table	
NA	TTU P-10324	Pterosauromorpha?	cf. *"Procoelosaurus"*	Spine table	
NA	TTU P-10325	Pterosauromorpha?	cf. *"Procoelosaurus"*	Spine table	
NA	TTU P-10326	Pterosauromorpha?	cf. *"Procoelosaurus"*	Spine table	
NA	TTU P-10327	Pterosauromorpha?	cf. *"Procoelosaurus"*	Spine table	
NA	TTU P-10328	Pterosauromorpha?	cf. *"Procoelosaurus"*	Spine table	
NA	TTU P-10329	Pterosauromorpha?	cf. *"Procoelosaurus"*	Spine table	
NA	TTU P-10330	Pterosauromorpha?	cf. *"Procoelosaurus"*	Spine table	
NA	TTU P-10339	Pterosauromorpha?	cf. *"Procoelosaurus"*	Caudal vertebra	
NA	TTU P-10340	Pterosauromorpha?	cf. *"Procoelosaurus"*	Dorsal vertebra	
NA	TTU P-10341	Pterosauromorpha?	cf. *"Procoelosaurus"*	Spine table	
NA	TTU P-10342	Pterosauromorpha?	cf. *"Procoelosaurus"*	Spine table	
NA	TTU P-10343	Pterosauromorpha?	cf. *"Pteromimus"*	Cervical vertebra	
NA	TTU P-11127	Dinosauriformes	*Incertae sedis*	Tibia	Nesbitt and Chatterjee, in prep; In pieces, but complete; basal to Dinosauria
NA	TTU P-9021 (in part)	Dinosauriformes	*Technosaurus smalli*	Premaxilla and partial mandible with teeth	Chatterjee, 1984, holotype; Irmis et al., 2006, 2007 (Fig. 9)
NA	TTU P-10071	Theropoda	Coelophysoidea *incertae sedis*	Right illium	Lehane, 2005 referred to *Shuvosaurus;* Lehman and Chatterjee, 2005 (p. 345, fig. 12F), identified as *Coelophysis;* Nesbitt and Chatterjee, in prep
NA	TTU P-11044	Theropoda	*Incertae sedis*	Left tibia	Lehane, 2005 identified as *Shuvosaurus;* Nesbitt and Chatterjee, in prep
NA	TTU P-9200 (in part)	Theropoda	*Protoavis texensis*	Braincase and femur	Chatterjee, 1991, 1999; holotype of *Protoavis texensis*, Witmer, 1997, 2001; Hutchinson, 2001; Irmis et al., 2007
NA	TTU P-9201 (in part)	Theropoda	*Protoavis texensis*	Astragalus and calcaneum	Chatterjee, 1991, 1999; *Protoavis texensis*; Paul, 1988; Chatterjee, 1999; Irmis et al., 2007

MOTT 3705 (OS Ranch Brazos) Upper Cooper Canyon Formation					
NA	TTU P-11524	Poposauridae	*Poposaurus sp.*	Badly preserved vertebra and postacetabular process of illium	
MOTT 3878 (Lott Hill) upper unit of the Cooper Canyon Formation					
NA	TTU P-10447	Trilophosauria	*Trilophosaurus dornorum*	Maxilla with teeth	Mueller and Parker, 2006
NA	TTU P-9609	Aetosauria	*incertae sedis*	Large boss from an osteoderm	
NA	TTU P-11601	Shuvosauridae	*Incertae sedis*	Calcaneum	Jeremiah Kokes, in prep
MOTT 3882 (UU Sand Creek) middle unit of the Cooper Canyon Formation					
NA	DMNS 20491	Procolophonidae	*Libognathus sheddi*	Left dentary with teeth, part of coronoid	Small, 1997, holotype
NA	TTU P-10449	Aetosauria	cf. *Rioarribasuchus*	Excellent assemblage of paramedian and lateral osteoderms, with associated ribs and a chevron.	
NA	TTU P-10777	Pterosauromorpha?	cf. *"Procoelosaurus"*	Tiny vertebra	
MOTT 3883 (UU RR Flats) middle unit of the Cooper Canyon Formation					
NA	TTU P-11858	Aetosauria	cf. *Rioarribasuchus?*	Partial paramedian osteoderm with boss	Possibly cf. *Rioarribasuchus*
NA	TTU P-10448	Aetosauria	*Incertae sedis*	Fragmentary osteoderms, unossified vertebra centra, and limb elements of a very small aetosaur	Possibly juvenile *Typothorax*
NA	TTU P-11564	Aetosauria	*Incertae sedis*	Fragments of a probable lateral osteoderm	
MOTT 3903 (Big Red Mud Metoposaur) middle unit of the Cooper Canyon Formation					
NA	TTU P-?	Aetosauria	*Typothorax* sp.	Fragmentary dorsal paramedians	
MOTT 3896 (Big Hill Road) middle? unit of the Cooper Canyon Formation					
NA	TTU P-12110	Parasuchia	*Incertae sedis*	Premaxilla and maxilla	
MOTT 3908 (K.W. Flats) upper unit of the Cooper Canyon Formation					
NA	TTU P-11583	Parasuchia	*Incertae sedis*	Fragmentary femur	
MOTT 3909 (Squeak Site) upper unit of the Cooper Canyon Formation					
NA	TTU P-11584	Parasuchia	*Incertae sedis*	Miscellaneous material, including an osteoderm and a spine table	

MOTT 3892 (Headquarters Site) middle unit of the Cooper Canyon Formation					
Site 4	TTU P-10812	Drepanosauridae	*Incertae sedis*	Fragmentary cervical vertebra	Mueller and Chatterjee, in prep
Site 4	TTU P-10813	Drepanosauridae	*Incertae sedis*	Posterior cervical vertebra?	Mueller and Chatterjee
Site 2	TTU P-10814	Drepanosauridae	*Incertae sedis*	Cervical vertebra	Mueller and Chatterjee
Site 4	TTU P-10815	Drepanosauridae	*Incertae sedis*	Posterior cervical vertebra	Mueller and Chatterjee
NA	TTU P-10817	Drepanosauridae	*Incertae sedis*	Cervical vertebra	Mueller and Chatterjee
NA	TTU P-10889	Drepanosauridae	*Incertae sedis*	Large ungal	Mueller and Chatterjee
NA	TTU P-10894	Drepanosauridae	*Incertae sedis*	Tail "claw"	Mueller and Chatterjee
Site 2	TTU P-10896	Drepanosauridae	*Incertae sedis*	Tiny tail "claw"	Mueller and Chatterjee
NA	TTU P-10898	Drepanosauridae	*Incertae sedis*	Left illium	Mueller and Chatterjee
Site 2	TTU P-11155	Drepanosauridae	*Incertae sedis*	Vertebra fragment	Mueller and Chatterjee
Site 2	TTU P-11156	Drepanosauridae	*Incertae sedis*	Crushed cervical vertebra	Mueller and Chatterjee
NA	TTU P-12108	Aetosauria	*Typothorax coccinarum*	Partial paramedian osteoderm	
Site 6	TTU P-11664	Aetosauria	Aetosaurinae *incertae sedis*	Fragment of a lateral osteoderm	
Site 1	TTU P-11223	Parasuchia	*Incertae sedis*	Ungal and distal metapodial?	
Site 1	TTU P-11854	Parasuchia	*Incertae sedis*	Left illium	
Site 1	TTU P-11855	Parasuchia	*Incertae sedis*	Two sacral verebrae centra and caudal vertebrae centra with neural arch missing, cervical vertebra	
Site 1	TTU P-11856	Parasuchia	*Incertae sedis*	Small left femur	
NA	TTU P-11880	Parasuchia	*Pseudopalatus buceros/P. pristinus*	Partial squamosal	
Site 1	TTU P-11857	Aetosauria	*Typothorax coccinarum*	Partial paramedian osteoderm	
Site 1	TTU P-11865	Shuvosauridae	*Incertae sedis*	Vertebra centra	Jeremiah Kokes, in prep
Site 1	TTU P-10836	Pterosauromorpha?	cf. *"Procoelosaurus"*	Vertebra	
MOTT 3898 (Headquarters South) middle unit of the Cooper Canyon Formation					
Site 4	TTU P-11440	Osteichthyes	*Incertae sedis*	Tiny vertebrae	
NA	TTU P-10895	Drepanosauridae	cf. *Drepanosaurus*	Large ungal	Mueller and Chatterjee
NA	TTU P-10816	Drepanosauridae	*Incertae sedis*	Cervical vertebra	Mueller and Chatterjee
Site 4	TTU P-10822	Drepanosauridae	*Incertae sedis*	Vertebra fragment	Mueller and Chatterjee
NA	TTU P-10823	Drepanosauridae	*Incertae sedis*	Cervical vertebra	Mueller and Chatterjee
Site 4	TTU P-10834	Drepanosauridae	*Incertae sedis*	Vertebra fragment	Mueller and Chatterjee
Site 4	TTU P-10884	Drepanosauridae	*Incertae sedis*	Vertebra condyle	Mueller and Chatterjee
NA	TTU P-10885	Drepanosauridae	*Incertae sedis*	Fragmentary cervical vertebra?	Mueller and Chatterjee

Site 1A	TTU P-10886	Drepanosauridae	*Incertae sedis*	Vertebra fragment	Mueller and Chatterjee
Site 4	TTU P-10887	Drepanosauridae	*Incertae sedis*	Cervical vertebra	Mueller and Chatterjee
NA	TTU P-10888	Drepanosauridae	*Incertae sedis*	Posterior cervical vertebra?	Mueller and Chatterjee
Site 4	TTU P-10890	Drepanosauridae	*Incertae sedis*	Tiny tail "claw"?	Mueller and Chatterjee
NA	TTU P-10899	Drepanosauridae	*Incertae sedis*	Fragment of scapulocoracoid?	Mueller and Chatterjee
Site 4	TTU P-10902	Drepanosauridae	*Incertae sedis*	Cervical vertebra?	Mueller and Chatterjee
Site 4	TTU P-10904	Drepanosauridae	*Incertae sedis*	Fragmentary cervical vertebra	Mueller and Chatterjee
Site 4	TTU P-10905	Drepanosauridae	*Incertae sedis*	Vertebra fragment	Mueller and Chatterjee
Site 4	TTU P-10906	Drepanosauridae	*Incertae sedis*	Vertebra fragment	Mueller and Chatterjee
Site 4	TTU P-10907	Drepanosauridae	*Incertae sedis*	Cervical vertebra	Mueller and Chatterjee
NA	TTU P-10908	Drepanosauridae	*Incertae sedis*	Cervical vertebra?	Mueller and Chatterjee
Site 4	TTU P-10909	Drepanosauridae	*Incertae sedis*	Vertebra condyle	Mueller and Chatterjee
Site 4	TTU P-10910	Drepanosauridae	*Incertae sedis*	Vertebra fragment	Mueller and Chatterjee
Site 4	TTU P-10928	Drepanosauridae	*Incertae sedis*	Tail "claw"	Mueller and Chatterjee
Site 4	TTU P-10929	Drepanosauridae	*Incertae sedis*	Vertebra fragment	Mueller and Chatterjee
Site 4	TTU P-10931	Drepanosauridae	*Incertae sedis*	Vertebra fragment	Mueller and Chatterjee
Site 4	TTU P-10933	Drepanosauridae	*Incertae sedis*	Tiny tail "claw"?	Mueller and Chatterjee
Site 4	TTU P-10963	Drepanosauridae	*Incertae sedis*	Vertebra fragment	Mueller and Chatterjee
Site 4	TTU P-10964	Drepanosauridae	*Incertae sedis*	Vertebra fragment	Mueller and Chatterjee
Site 4	TTU P-10966	Drepanosauridae	*Incertae sedis*	Fragmentary cervical vertebra?	Mueller and Chatterjee
Site 4	TTU P-10976	Drepanosauridae	*Incertae sedis*	Cervical vertebra	Mueller and Chatterjee
Site 4	TTU P-10978	Drepanosauridae	*Incertae sedis*	Posterior cervical vertebra?	Mueller and Chatterjee
Site 4	TTU P-10979	Drepanosauridae	*Incertae sedis*	Posterior cervical vertebra?	Mueller and Chatterjee
Site 4	TTU P-11134	Drepanosauridae	*Incertae sedis*	Large ungal	Mueller and Chatterjee
Site 4	TTU P-11154	Drepanosauridae	*Incertae sedis*	Cervical vertebra	Mueller and Chatterjee, in prep
Site 4	TTU P-11214	Parasuchia	*Incertae sedis*	Very small teeth	
Site 1	TTU P-10927	Sphenosuchia	*Incertae sedis*	Complete skull and semi-articulated postcranial skeleton	
Site 2	TTU P-11279	Sphenosuchia	*Incertae sedis*	Distal tibia	
Site 4	TTU P-11623	Sphenosuchia	*Incertae sedis*	Maxilla	
Site 1c	TTU P-11414	Shuvosauridae	*Incertae sedis*	Proximal femur	Jeremiah Kokes, in prep
Site 1	TTU P-10866	Dinosauromorpha	*Dromomeron* sp.	Distal femur	Sterling Nesbitt, pers. comm.

Site 1	TTU P-11282	Dinosauromorpha	*Dromomeron* sp.	Proximal femur	Sterling Nesbitt, pers. comm.
Site 1	TTU P-11877	Dinosauromorpha	*Dromomeron* sp.	Proximal femur	Sterling Nesbitt, pers. comm..\
MOTT 3899 (Headquarters NW) middle unit of the Cooper Canyon Formation					
NA	TTU P-12546	Aetosauria	Paratypothoracisini *incertae sedis*	Lateral end of a paramedian osteoderm	
NA	TTU P-11175	Saurischia	*Incertae sedis*	Tibia	
MOTT 3900 (Headquarters North) middle unit of the Cooper Canyon Formation					
NA	TTU P-11337	Protorosauria	*Malerisaurus* sp.	Proximal femur	
MOTT 3901 (Green Tooth Arroyo) middle unit of the Cooper Canyon Formation					
Site 2	TTU P-11304	Metoposauridae	*Incertae sedis*	Small clavicle	
NA	TTU P-10939	Parasuchia	*Incertae sedis*	Proximal tibia	
MOTT 3634 (Lott Kirkpatrick) upper unit of the Cooper Canyon Formation					
NA	TTU P-102	Parasuchia	*Pseudopalatus buceros/ P. pristinus*	Partial skull	
NA	TTU P-11895	Parasuchia	*Pseudopalatus buceros/P. pristinus*	Right squamosal	
NA	TTU P-10072	Theropoda	*Incertae sedis*	Several articulated cervical and dorsal vertebrae, incomplete pubis, proximal end of left femur, left distal tibia, left astragalus	Nesbitt and Chatterjee, in prep; Lehane, 2005, text fig. 27-28 identified as *Shuvosaurus;* Lehman and Chatterjee, 2005 (p. 345, fig. 12H-I), identified as *Coelophysis.*
MOTT 3635 (Lott-Kirkpatrick) upper unit of the Cooper Canyon Formation					
NA	TTU P-11058	Parasuchia	*Incertae sedis*	Paired premaxillae	
MOTT 3921 (Problematic Hill) upper unit of the Cooper Canyon Formation					
NA	TTU P-11883	Parasuchia	*Incertae sedis*	Partial quadrate	
NA	TTU P-11885	Aetosauria	Paratypothoracisini *incertae sedis*	Incomplete lateral osteoderm	
MOTT 3874 (Simpson Ranch) upper unit of the Cooper Canyon Formation					
NA	TTU P-10068	Procolophonidae	*Libognathus sheddi*	Antorbital portion of skull	Mueller and Chatterjee, 2003, in review
NA	TTU P-10069	Procolophonidae	*Libognathus sheddi*	Right dentary with teeth, part of coronoid	Mueller and Chatterjee, 2003, in review
NA	TTU P-10081	Procolophonidae	*Libognathus sheddi*	Left maxilla and associated premaxilla with teeth, part of ectopterygoid	Mueller and Chatterjee, 2003, in review
NA	TTU P-10523	Procolophonidae	*Libognathus sheddi*	Part of quadratojugal	Mueller and Chatterjee, 2003, in review
NA	TTU P-10524	Procolophonidae	*Libognathus sheddi?*	Distal femur	Mueller and Chatterjee, 2003, in review
NA	TTU P-10525	Procolophonidae	*Libognathus sheddi?*	Partial vertebra	Mueller and Chatterjee, 2003, in review
NA	TTU P-11151	Procolophonidae	*Libognathus sheddi?*	Distal humerus	Mueller and Chatterjee, 2003, in review

MOTT 3631 (Macy Ranch) upper unit of Cooper Canyon Formation					
NA	TTU P-9425	Parasuchia	*Pseudopalatus ("Macysuchus")* sp.	Partial skull and articulated skeleton	McQuilkin, 1998; "*Macysuchus brevirostris*"; Christina Chavez, in prep
NA	TTU P-12122	Parasuchia	*Incertae sedis*	Osteoderms	
NA	TTU P-12508	Parasuchia	*Incertae sedis*	Left femur	
MOTT 3924 ("Macy Ranch") upper unit of Cooper Canyon Formation					
NA	TTU P-12543	Parasuchia	*Incertae sedis*	Sacral rib	
MOTT 3925 (Macy Ranch Debbie) upper unit of Cooper Canyon Fomation					
NA	TTU P-10767	Parasuchia	*Incertae sedis*	Vertebra	
NA	TTU P-12547	Aetosauria	*Paratypothorax* sp.	Two paramedian osteoderms, a partial lateral osteoderm, and a massive femur	
MOTT 3926 (Macy Ranch 3926) upper unit of Cooper Canyon Formation					
	TTU P-12124	Parasuchia	*Incertae sedis*	Premaxilla	
MOTT 3870 (Patricia Site) upper unit of Cooper Canyon Formation					
Site 1a	TTU P-10721	Osteichthyes	*Incertae sedis*	Mass of scales and other bones	
NA	TTU P-10761	Metoposauridae	*Incertae sedis*	Large partial interclavicle and vertebra centrum	*Metoposaurus* or *Koskinonodon*
NA	TTU P-10078	Parasuchia	*Incertae sedis*	Crested snout fragment	Probably *Pseudopalatus*
Site 1c	TTU P-10762	Parasuchia	*Incertae sedis*	Left femur, relatively poor prservation, found as float	
Site 1c	TTU P-10763	Parasuchia	*Incertae sedis*	Complete right femur	
Site 1a	TTU P-10764	Parasuchia	*Incertae sedis*	Complete left humerus	
Site 2	TTU P-10765	Parasuchia	*Incertae sedis*	Complete right humerus, collected as float	
Site 4	TTU P-10769	Parasuchia	*Incertae sedis*	Fibula	
Site 2b	TTU P-10869	Parasuchia	*Incertae sedis*	Huge complete ungal	
NA	TTU P-10883	Parasuchia	*Incertae sedis*	Left illium, pubis, ischium	Probably *Pseudopalatus*
Site 8	TTU P-11059	Parasuchia	*Incertae sedis*	Complete left humerus, in decent condition	
Site 2	TTU P-11153	Parasuchia	*Incertae sedis*	Partial calcaneum	
Site 5	TTU P-11208	Parasuchia	*Incertae sedis*	Large complete right femur	
Site 3	TTU P-11535	Parasuchia	*Incertae sedis*	Osteoderm	
Site 1a	TTU P-11554	Parasuchia	*Incertae sedis*	Largely complete postcranial skeleton, unfortunately did not survive collection intact	Probably *Pseudopalatus*
Site 1c	TTU P-11619	Parasuchia	*Incertae sedis*	Scapulocoracoid	

Site 4	TTU P-11719	Parasuchia	*Incertae sedis*	Right fifth metatarsal	
Site 4	TTU P-11720	Parasuchia	*Incertae sedis*	Right metatarsal	
Site 1	TTU P-11741	Parasuchia	*Incertae sedis*	Incomplete dorsal vertebra	
NA	TTU P-11742	Parasuchia	*Incertae sedis*	Complete cervical vertebra	
Site 2	TTU P-11743	Parasuchia	*Incertae sedis*	Left illium and proxial pubis	
Site 4	TTU P-11744	Parasuchia	*Incertae sedis*	Left radius	
Site 1	TTU P-11853	Parasuchia	*Incertae sedis*	Two proximal humeri, left and right	
Site 2	TTU P-11879	Parasuchia	*Incertae sedis*	Pelvic girdle, nearly complete right illium and proximal pubis	
Site 2	TTU P-11894	Parasuchia	*Incertae sedis*	Phalanx	
NA	TTU P-12125	Parasuchia	*Incertae sedis*	Basioccipital	
NA	TTU P-12444	Parasuchia	*Incertae sedis*	Radius	
Site 2	TTU P-9627	Parasuchia	*Incertae sedis*	Right humerus, collected as float	
Site 2	TTU P-9628	Parasuchia	*Incertae sedis*	Complete left humerus	
NA	TTU P-11423	Parasuchia	*Pseudopalatus ("Macysuchus")* sp.	Nearly complete skull	"Spike", crested morph
Site 1	TTU P-10075	Parasuchia	*Pseudopalatus buceros/ P. pristinus*	Posterior part of skull	"Shorty"
Site 3	TTU P-10076	Parasuchia	*Pseudopalatus* nov. sp.	Nearly complete skull	Hungerbühler et al., 2003, in review, holotype; "Papa John", non-crested morph
Site 1	TTU P-10077	Parasuchia	*Pseudopalatus* nov. sp.	Nearly complete skull	Hungerbühler et al., 2003, in review; "Andy", crested morph
Site 1	TTU P-10074	Parasuchia	*Pseudopalatus* sp.	Nearly complete skull	Hungerbühler et al., in review; "Patty", non-crested morph
Site 2	TTU P-10070	Aetosauria	*Typothorax coccinarum*	Two nearly complete anterior dorsal paramedian osteoderms, nearly complete lateral osteoderm, nearly complete scapulocoracoid.	Martz, 2002
Site 1	TTU P-11587	Aetosauria	*Typothorax coccinarum*	Incomplete lateral osteoderm	
Site 3	TTU P-11588	Aetosauria	*Typothorax coccinarum*	Incomplete appendicular osteoderm	Resembles appendicular osteoderms from Canjilon Quarry
Site 2	TTU P-11591	Aetosauria	*Typothorax coccinarum*	Complete lateral osteoderm	
Site 2	TTU P-11592	Aetosauria	*Typothorax coccinarum*	Incomplete lateral osteoderm	
Site 2	TTU P-11536	Aetosauria	*Incertae sedis*	Proximal humerus	

Site 1C	TTU P-11586	Aetosauria	*Incertae sedis*	Partial paramedian osteoderm	Possibly *Typothorax*
Site 2	TTU P-11589	Aetosauria	*Incertae sedis*	Incomplete cervical vertebra	Almost identical to cervical vertebra of TTU P-9214 only larger, probably *Typothorax*.
Site 2	TTU P-11590	Aetosauria	*Incertae sedis*	Badly weathered proximal right femur	Probably *Typothorax coccinarum*
Site 1c	TTU P-11593	Aetosauria	*Incertae sedis*	Badly crushed distal left femur	Probably *Typothorax coccinarum*
Site 4	TTU P-11612	Rauisuchidae	*Incertae sedis*	Left tibia	
Site 1	TTU P-11686	Rauisuchidae	*Incertae sedis*	Left tibia	
Site 2	TTU P-9626	Rauisuchidae	*Incertae sedis*	Right ectopterygoid	
Site 3a	TTU P-10783	Shuvosauridae	*Incertae sedis*	Beautiful complete right femur, partial right tibia, associated phalanx	Jeremiah Kokes, in prep
NA	TTU P-10534	Theropoda	*Incertae sedis*	Tibia	Cunningham et al., 2002 identified as ornithischian, "TTUP un-numbered" of Irmis et al., 2007
MOTT 3880 (Patty East) upper unit of Cooper Canyon Formation					
Site 5	TTU P-11158	Metoposauridae	*Incertae sedis*	Incomplete skull roof, large metoposaur	*Metoposaurus* or *Koskinonodon*
Site 5	TTU P-11415	Parasuchia	*Incertae sedis*	Left illium	
Site 6	TTU P-11878	Parasuchia	*Incertae sedis*	Snout of a large phytosaur skull	Probably *Pseudopalatus*
Site 2	TTU P-10868	Aetosauria	*Incertae sedis*	Complete astragalus	Probably *Typothorax*
MOTT 3884 (Far East) upper unit of Cooper Canyon Formation					
NA	TTU P-11890	Parasuchia	*Incertae sedis*	Large distal radius	
MOTT 3885 (Bauchier-Crenshaw) upper unit of Cooper Canyon Formtion					
NA	TTU P-11567	Aetosauria	*Typothorax coccinarum*	Fragmentary paramedian osteoderms	A phytosaur osteoderm and several other bone fragments are included with the specimen.
MOTT 3891 (Caterpillar Canyon) upper unit of Cooper Canyon Formation					
NA	NA	Parasuchia	*Incertae sedis*	Most of a large left humerus	
MOTT 3895 (Audad Bluff) upper unit of Canyon Formation					
NA	TTU P-11891	Aetosauria	*Typothorax coccinarum*	Partial paramedian osteoderm	
NA	TTU P-10775	Metoposauridae	*Incertae sedis*	Large vertebra centrum	*Metoposaurus* or *Koskinonodon*
NA	TTU P-11893	Parasuchia	*Incertae sedis*	Left ulna	
MOTT 3913 (Rchard's skull) upper unit of Cooper Canyon Formation					
NA	TTU P-11707	Parasuchia	*Incertae sedis*	Skull, only crested snout recovered	Probably *Pseudopalatus*
MOTT 3920 (Sandstone Alley) upper unit of Cooper Canyon Formation					
NA	TTU P-11897	Parasuchia	*Incertae sedis*	Very large partial skull	

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**Note on the references: For a few particular individuals who have senior authored an extremely large number of papers, papers with multiple authors are listed sequentially rather than strictly alphabetically.*

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Fig. 2.3. Correlated measured sections from the Dockum Group of southern Garza County, with stratigraphic levels of vertebrate localities and mudstone samples indicated. The sections are ordered approximately southwest (left) to northeast (right), but are spaced evenly rather than to any kind of horizontal scale, and do not fall along a single transect, so this figure should be interpreted only as a very crude generalized cross section roughly parallel to the dip of the base of the Dockum Group. Individual sections are figured and described in Appendix A.

Fig. 2.4. Composite lithostratigraphic sections, geologic maps, and geologic cross sections, for southern Garza County, West Texas: a, composite lithostratigraphic section for southern Garza County; b, simplified color-coded composite lithostratigraphic section and key giving symbols and descriptions of units; c, geologic map of southern Garza County, most ground cover not shown to expose concealed contacts, Quaternary contacts (and some Cretaceous contacts) modified after Barnes et al. (1993, 1994); d, map showing path of cross sections across southern Garza County, names of localities and well logs given in Figs. 1.5 and 1.6; e, cross section A-A'; f, cross section B-B'; g, cross section C-C'; h, cross section D-D'.

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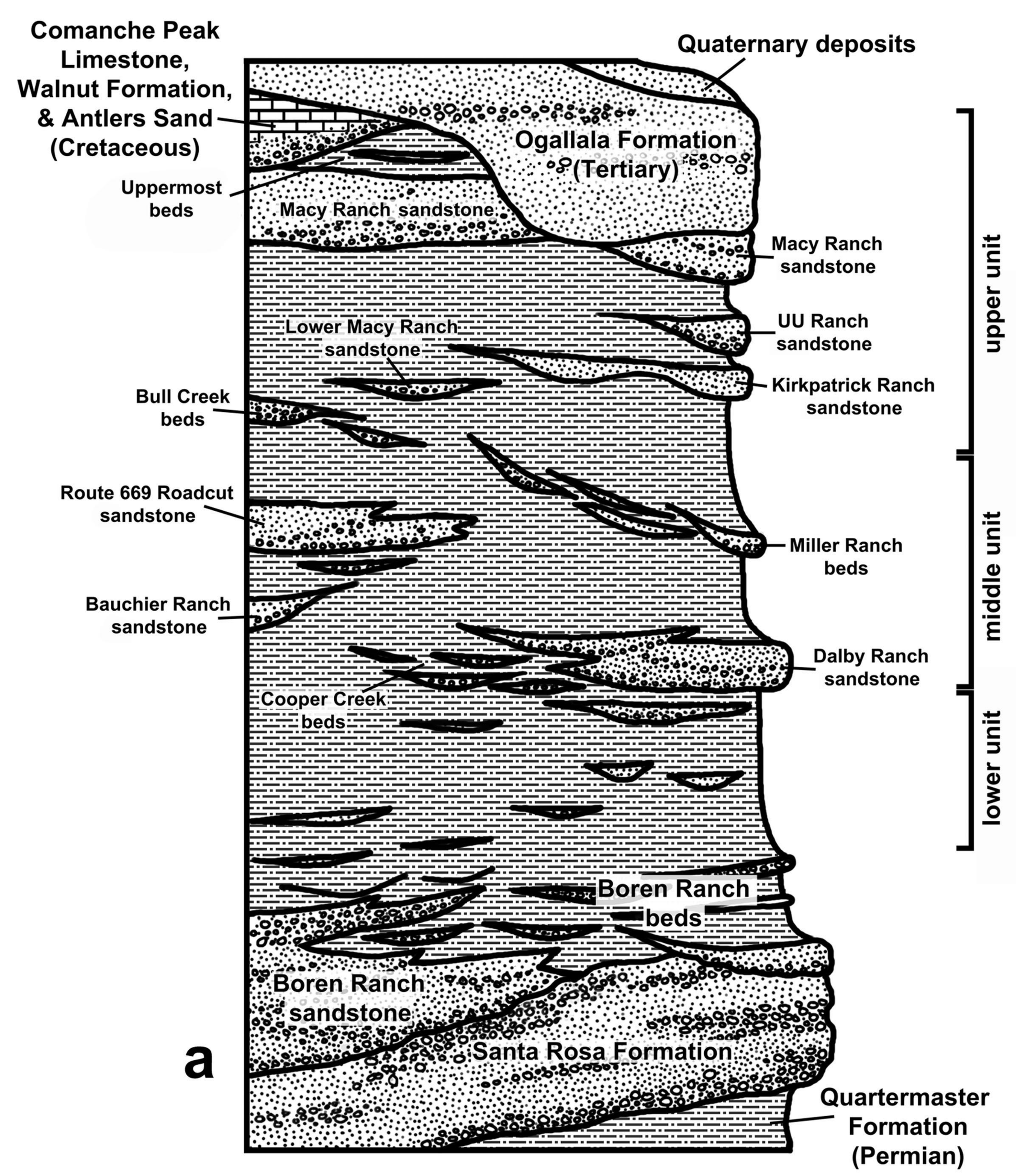

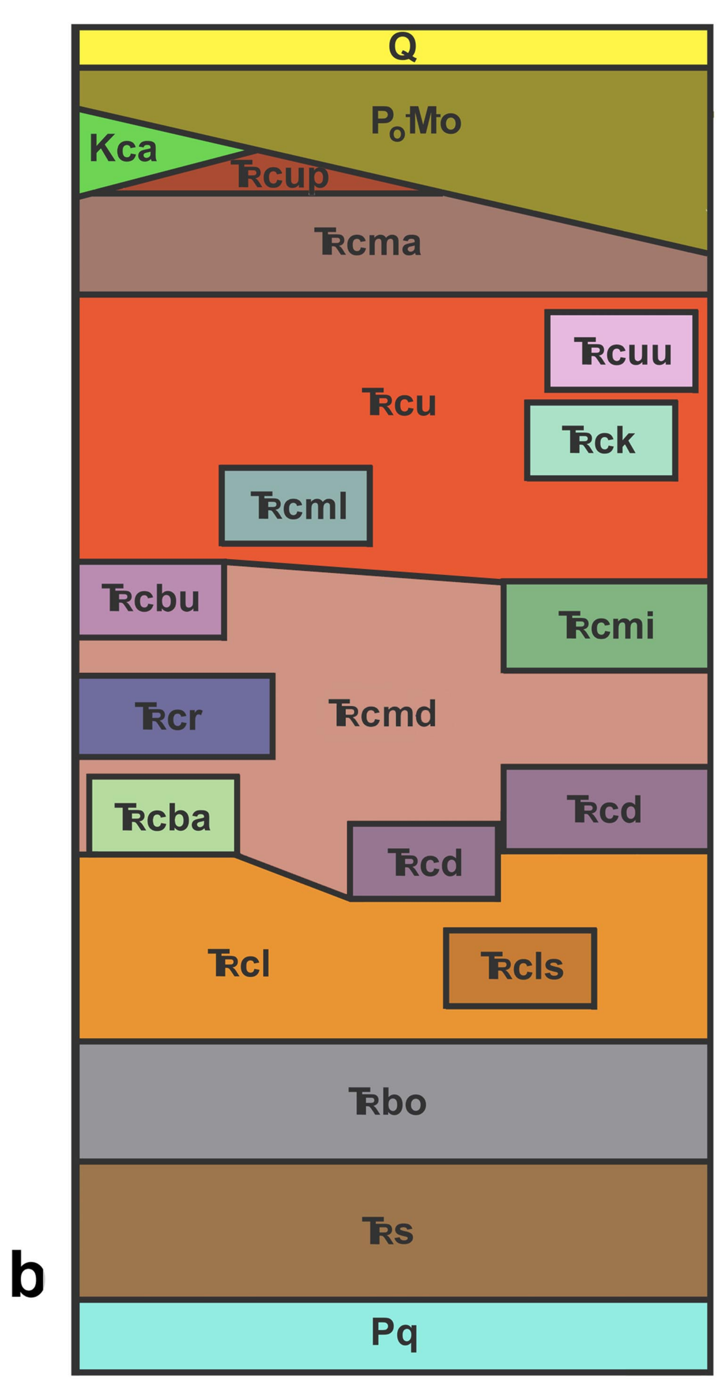

Q, undifferentiated Quaternary: fluvial and aeolian deposits; gravel, sand, silt, and soil.

P_oM_o, Ogallala Formation (Miocene-Pliocene): fluvial gravel, sand, and mud, capped by caliche.

Kca, undivided Comache Peak Limestone, Walnut Formation, and Antlers Sand (Lower Cretaceous): marine limestone, shale, and marl, and fluvial sandstone, siltstone, and conglomerate.

TRcup, uppermost beds of the upper unit of the Cooper Canyon Formation (Upper Triassic): fluvial overbank mudstone, reddish with drab-colored reduction mottling, interbedded sandstone and conglomerate.

TRcma, Macy Ranch sandstone of the upper unit of the Cooper Canyon Formation (Upper Triassic): amalgamated meandering channel sandstone (highly micaceous) and conglomerate (intrabasinal) with minor interbedded mudstone, all drab-colored, locally with abundant vertebrate fossils, plant material, and concretions.

TRcuu, UU Ranch sandstone of the upper unit of the Cooper Canyon Formation (Upper Triassic): amalgamated meandering fluvial channel sandstone (highly micaceous) and conglomerate (intrabasinal) with minor interbedded mudstone, all drab-colored.

TRck, Kirkpatrick Ranch sandstone of the upper unit of the Cooper Canyon Formation (Upper Triassic): fluvial channel sandstone (highly micaceous) and conglomerate (intrabasinal) with minor interbedded mudstone, all reddish-brown.

TRcml, Lower Macy Ranch sandstone of the upper unit of the Cooper Canyon Formation (Upper Triassic): meandering fluvial channel sandstone (highly micaceous) and conglomerate (intrabasinal) with minor interbedded mudstone, all drab-colored.

TRcu, overbank deposits and un-mapped sandstones and conglomerates in the upper unit of the Cooper Canyon Formation (Upper Triassic): Reddish-brown fluvial overbank mudstones with drab-colored reduction mottling and pedogenic carbonate nodules, with interbedded small channel and sheetflood sandstones and conglomerates, locally with abundant vertebrate fossils and unionid bivalves.

TRcbu, Bull Creek beds of the middle unit of the Cooper Canyon Formation (Upper Triassic): amalgamated and single-story bedload-dominated fluvial channel sandstone (highly micaceous) and conglomerate (intrabasinal), mostly reddish-brown, in closely associated but discontinuous lenses within reddish overbank mudstone.

TRcmi, Miller Ranch sandstone of the middle unit of the Cooper Canyon Formation (Upper Triassic): reddish and drab-colored meandering and bedload-dominated fluvial channel sandstone (highly micaceous) and conglomerate (intrabasinal) in closely associated but discontinuous lenses within reddish overbank mudstone, locally with abundant unionid bivalves.

TRcr, Route 669 Roadcut sandstone of the middle unit of the Cooper Canyon Formation (Upper Triassic): amalgamated meandering fluvial channel sandstone (micaceous) and conglomerate (intrabasinal) with minor interbedded mudstone, drab-colored.

TRcba, Bauchier Ranch sandstone of the middle unit of the Cooper Canyon Formation (Upper Triassic): drab-colored fluvial channel sandstone and conglomerate (all highly siliceous), locally with massive spherical concretions.

TRcd, undifferentiated Dalby Ranch sandstone and Cooper Creek beds of the middle unit of the Cooper Canyon Formation (Upper Triassic): amalgamated meandering fluvial channel sandstone (mighly micaceous) and conglomerate (intrabasinal) with minor interbedded mudstone, all drab-colored (Dalby Ranch sandstone) and reddish-brown and drab-colored bedload-dominated fluvial channel sandstone and conglomerate in closely associated but discontinuous lenses within reddish overbank mudstone (Cooper Creek beds).

TRcmd, overbank deposits and un-mapped sandstones and conglomerates in the middle unit of the Cooper Canyon Formation (Upper Triassic): Reddish fluvial overbank mudstones with drab-colored reduction mottling and, pedogenic carbonate nodules, with interbedded small channel and sheetflood sandstones and conglomerates, locally with abundant vertebrate fossils and unionid bivalves.

TRcl, lower unit of the Cooper Canyon Formation (Upper Triassic): Reddish and orangeish fluvial overbank mudstones with drab-colored reduction mottling and interbedded sandstones (micaceous) and conglomerates (intrabasinal) in highly discontinuous lenses and ribbons, with small lacustrine basins in the lower part of the unit, locally with abundant vertebrate fossils, unionid bivalves, and petrified wood.

TRcls, channel deposits in the lower unit of the Cooper Canyon Formation (Upper Triassic): Fluvial channel sandstone and conglomerate in discontinuous but locally distinctive and traceable lenses and ribbons.

TRbo, Boren Ranch sandstone and Boren Ranch beds (Upper Triassic): amalgamated meandering fluvial channel sandstone (micaceous) and conglomerate (intrabasinal) with minor interbedded mudstone (Boren Ranch sandstone) and complexly interbedded fluvial and lacustrine sandstone, conglomerate, and mudstone (Boren Ranch beds), locally with abundant vertebrate fossils and petrified wood.

TRs, Santa Rosa Sandstone (Upper Triassic): bedload-dominated fluvial channel sandstone and conglomerate (all highly siliceous) with minor interbedded mudstone.

Pq, Quartermaster Formation (Permian): Tidal flat and sabkha mudstone, sandstone, evaporite, and dolomite, mostly reddish.

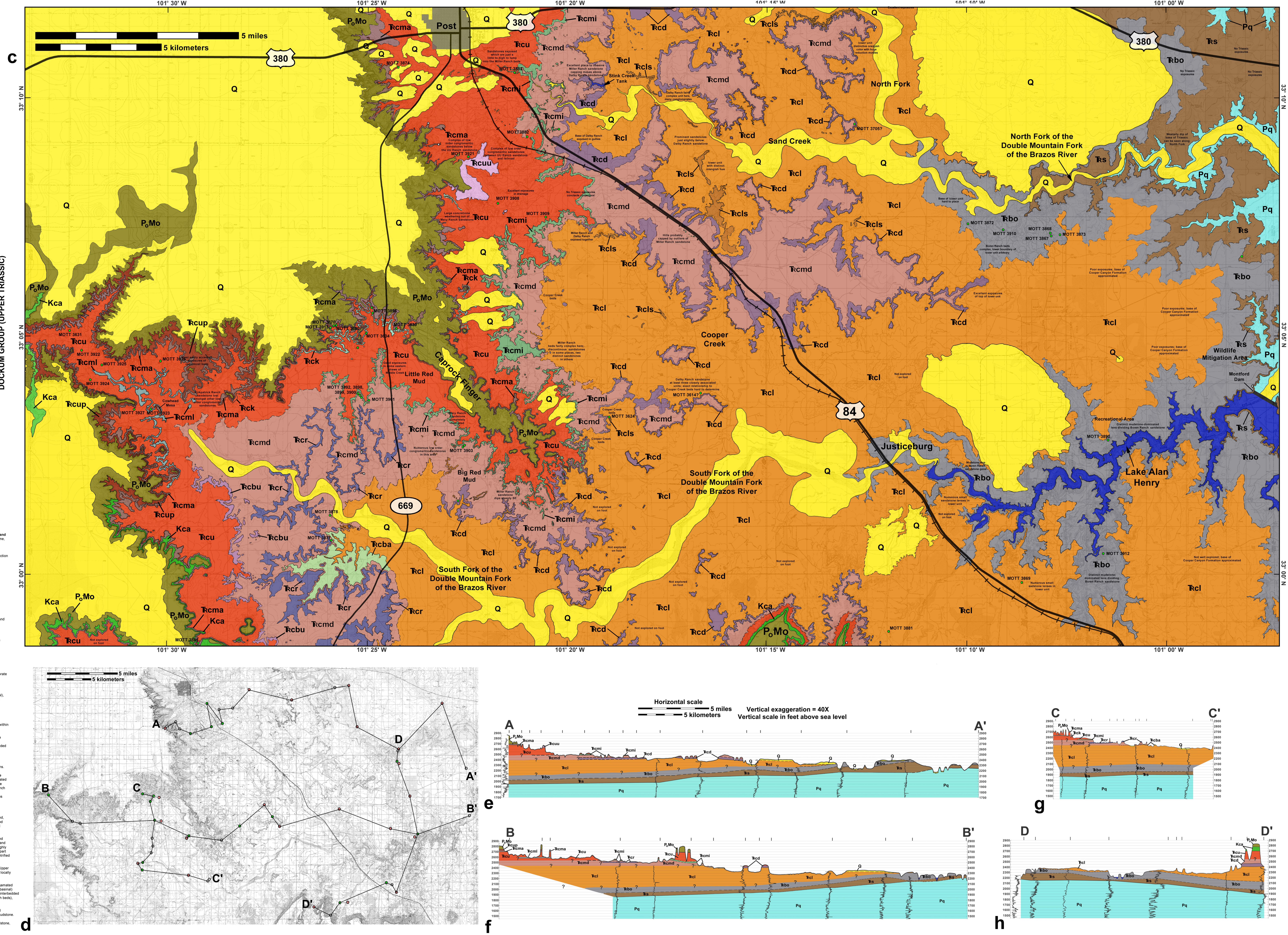

Fig. 6.1. Biostratigraphic range chart for the Dockum Group of southern Garza County. Horizontal bars represent the stratigraphic levels of particular localities, "X"s represent occurrences of taxa at those localities, vertical black bars the known ranges for those taxa, vertical gray bars possible range extentions based on uncertain occurrences, gray boxes are composite ranges for several taxa of particular interest as a group, from left to right: the genus *Paleorhinus*, the genus *Pseudopalatus*, and dinosauromorphs.