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Stratigraphy of the Permian-Triassic boundary in southeastern New Mexico and west Texas

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STRATIGRAPHY OF THE PERMIAN-TRIASSIC BOUNDARY IN SOUTHEASTERN NEW MEXICO AND WEST TEXAS

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Abstract _____ At the Permian-Triassic boundary everywhere in west Texas and southeastern New Mexico, Upper Permian (late Ochoan = Changxingian), or older Guadalupian strata are overlain by Upper Triassic (late Carnian = Tuvalian) strata. The youngest Upper Permian strata are the Quartermaster Formation (= Pierce Canyon red beds = Dewey Lake Formation); the Late Permian age of the Quartermaster is verified by invertebrate fossils, magnetostratigraphy and K-Ar ages. Vertebrate fossils document the late Carnian age of overlying Triassic strata of the Santa Rosa Formation and Camp Springs Member of the Dockum Formation. No Lower or Middle Triassic strata are present in southeastern New Mexico and west Texas. The Permian-Triassic boundary in this area thus is a major unconformity that encompasses at least 25 million years. Because the Permian-Triassic boundary in southeastern New Mexico and west Texas is bracketed by nonmarine siliciclastic red beds, it has often been incorrectly placed. Upper Permian Strata are distinguished by being brick-red, not variegated, texturally and mineralogically relatively mature, ripple-laminar to laminar and unfossiliferous, whereas Upper Triassic strata are grayish red, variegated texturally and mineralogically relatively immature, trough-crossbedded and fossiliferous. We describe 12 reference points in southeastern New Mexico and west Texas where the Permian-Triassic boundary is well exposed.

INTRODUCTION

Upper Permian and Triassic strata are exposed intermittently and have an extensive subsurface distribution across the southern High Plains of west Texas and eastern New Mexico (Fig. **I).** The Upper Permian strata were the basis of the Ochoan Series (Stage) of Adams et al. (1939; also see Adams, 1944) and are mostly evaporites capped by a relatively thin sequence of nonmarine red beds. The overlying Triassic strata—traditionally termed Dockum Group (Formation)—are also nonmarine red beds. Because nonmarine red beds bracket the Permian-Triassic boundary on the southern High Plains, some confusion exists over the nature and placement of that boundary. This article attempts to eliminate this confusion by reviewing the age relationships of Ochoan strata, reviewing the age of the Triassic strata that overlie Ochoan strata, and describing the stratigraphy of the Permian-Triassic contact (disconformity) in southeastern New Mexico and west Texas.

LATE PERMIAN–TRIASSIC TIME SCALE

International agreement has not been achieved on many details of the Permian and Triassic time scales, so we briefly explain our usage. We follow Glenister et al.'s (1992) recent proposal of the Guadalupian

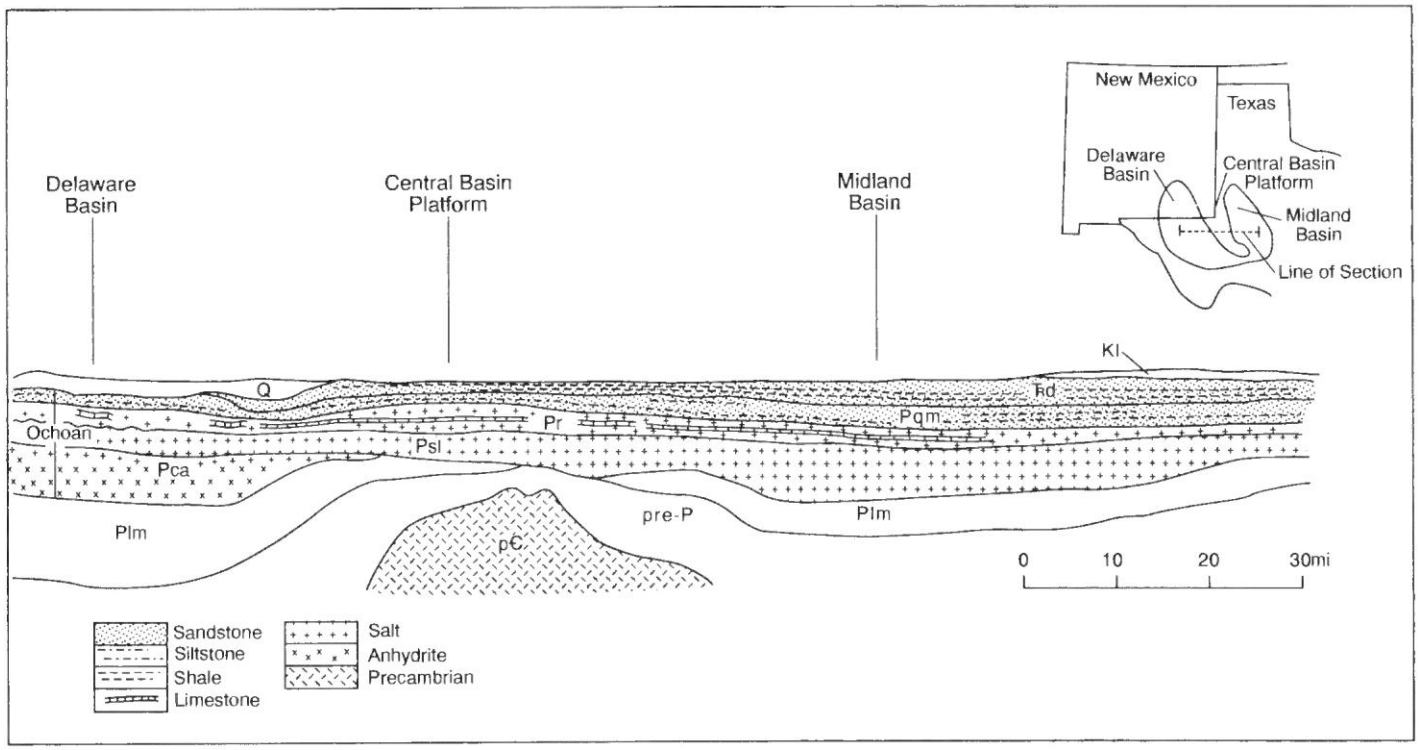


FIGURE 1. Generalized cross section through Delaware and Midland basins showing regional extent of Ochoan strata; PC = Precambrian, pre-P = pre-Permian rocks, Plm = Lower and middle Permian rocks, Pcz = Castile Formation, Psl = Salado Formation, Pr = Rustler Formation, Pqm = Quartermaster Formation, Trd = Dockum Formation, Kl = Lower Cretaceous rocks and Q = Quaternary deposits (modified from King, 1942).

as a standard for Middle Permian time. The youngest stage of the Middle Permian, the Capitanian, thus encompasses the strata immediately underlying Ochoan strata in west Texas and southeastern New Mexico—the Lamar Limestone Member of the Bell Canyon Formation and its equivalent and, the Tansill Formation of the Artesia Group (Glenister et al., 1992).

The Upper Permian is divided into two stages, either the Dzhulfian and Dorashamian of Transcaucasia or the Longtanian and Changxingian of southeastern China (Waterhouse, 1976; Yang et al., 1986). We use the Chinese stage names here, as did Harland et al. (1989), although as explained below, correlation of Ochoan strata with Late Permian marine stages is largely problematic. It is important to note that the Tatarian Stage of Nikitin (1887) is based on nonmarine red beds in the Russian Cisurals and does not provide a suitable international standard for the Late Permian (e.g., Lozovsky, 1991). Therefore, use of Tatarian on Permian time scales (e.g., Van Eysinga, 1983; Palmer, 1983) should be avoided.

The numerical age of the Permian-Triassic boundary has long been poorly constrained. However, Claoue-Long et al. (1991) recently reported a fission-track age on zircons in a bentonite at Meishan in southeastern China of 251.2 ± 3.4 Ma. This bentonite is immediately below early Induan marine strata with the ammonite *Otoceras?* overlain by strata containing the conodont *Hindeodus parvus.* Either taxon has been argued to mark the base of the Triassic (Yin et al., 1986; Tozer, 1988), so the bentonite closely approximates the Permian-Triassic boundary, to which we assign a numerical age of 251 Ma (Fig. 2).

No Lower Triassic strata are present in southeastern New Mexico or west Texas, despite some claims to the contrary, so this part of the Triassic time scale is not of great importance here. Middle Triassic (Anisian) strata, the Anton Chico Member of the Moenkopi Formation, are present in east-central New Mexico (Guadalupe, Quay and De Baca Counties) and crop out as far southeast as Bull Gap in Lincoln County (T9S, R8E: Lucas, 1991). However, no Middle Triassic strata are present in southeastern New Mexico or west Texas, despite various statements in the literature (see below). The oldest Triassic strata in this area are of Late Triassic (late Carnian) age, about 225 Ma.

OCHOAN STRATA

General stratigraphy

The name Ochoan Series (taken from the Ochoa Post Office in T24S, R34E, Lea County, New Mexico) was given by Adams et. al. (1939) to the fourth and uppermost regional division of the Permian. The series, which includes all post-Guadalupian and pre-Triassic rocks in southeastern New Mexico and west Texas, consists largely of evaporites and fine-grained elastics. It may attain thicknesses in excess of 1212 m in the subsurface.

Four subdivisions were recognized by Adams (1935) as follows: lower Castile Formation, upper Castile Formation, Rustler Formation and Dewey Lake Redbeds (Formation). Shortly thereafter the upper Castile was renamed the Salado Formation by Lang (1935). The Salado includes an anhydrite bed that previously had been considered part of the lower Castile. Nonetheless, the Castile as currently defined is dominantly anhydrite (and calcite), whereas the Salado is dominantly halite.

Areal extents of the Castile and Salado differ considerably. The Castile is restricted to the Delaware basin, whereas the overlying Salado is present in both the Delaware and Midland basins (Figs. 1 and 3). Apparently the central basin platform became slightly negative during Salado time, which then permitted evaporite deposition to extend eastward into the Midland basin and thus encompass most of the Permian basin.

The main area of Castile-Salado outcrop is the gypsum plain, extending from south of Carlsbad, New Mexico southward into Culberson County, Texas, an area that includes the western part of the Delaware basin. In this area the Castile consists of alternating laminae of calcium sulfate and calcite, in a sequence as much as 600 m thick near the center of the basin. The laminae are commonly microfolded (Kirkland and Evans, 1980), a feature that may locally be seen in outcrop. Dissolution features are also common, the result of removal of underlying salt. The formation is most noted for the limestone masses which stand out in bold relief on the gypsum plain to form "castiles." A secondary origin of these limestone masses was proposed by Kirkland and Evans (1980). Their hypothesis is that sulfate-reducing bacteria obtained energy by using sulfate ions to oxidize hydrocarbons that migrated updip. The calcium ions resulting from the dissolution of anhydrite reacted with bicarbonate and carbonate to form calcite.

The Salado Formation, due to the preponderance of salt, has poor outcrops so thickness and other data are entirely from the subsurface.

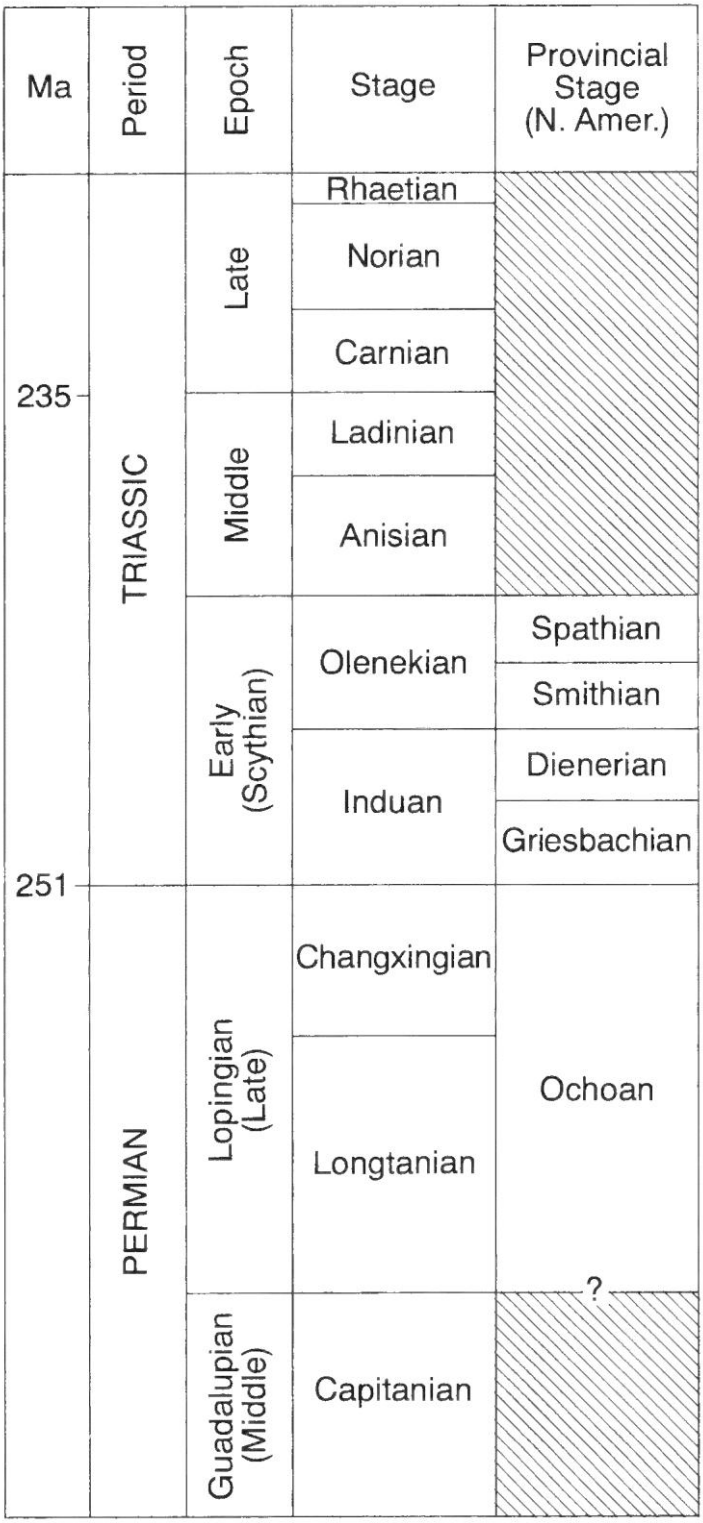


FIGURE 2. Middle Permian to Late Triassic time scale employed in this paper.

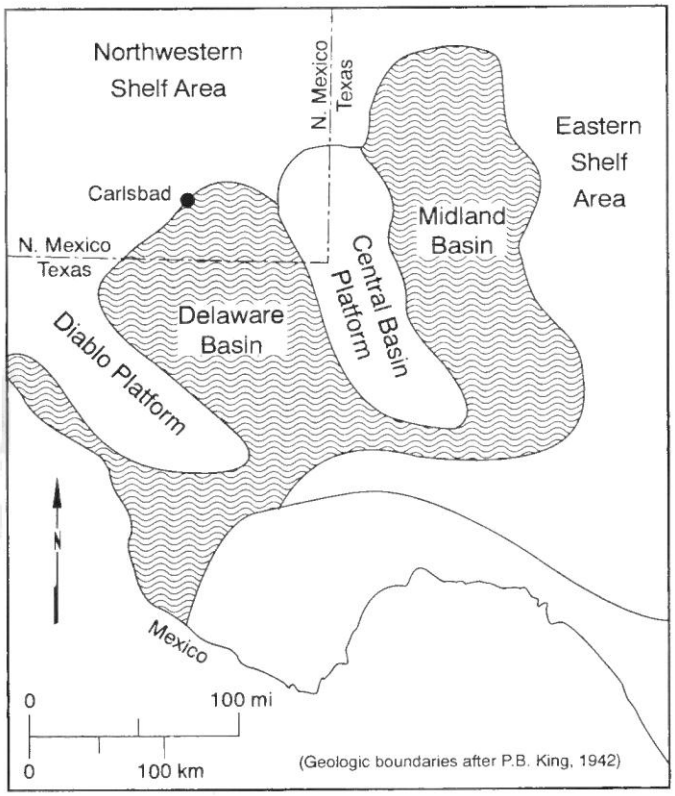


FIGURE 3. Geographic relationship of Delaware and Midland basins, southeastern New Mexico and west Texas.

Indications are that it is as much as 600 m thick in the Delaware basin, thinning northward and northeastward into the Texas Panhandle (Lang, 1937, p. 885). Adams (1969) reported that the unit was nearly 84% halite or argillaceous halite and only 12% sulfate. Clastic units have been noted, however. For example, in Lea County, New Mexico, a distinctive, fine-grained, orangish-red sand approximately 3 m thick occurs in the upper part of the Salado. This sand was designated the Vaca Triste Member by Adams (1944). While not widely recognized, the Vaca Triste does represent near-shore deposition during a regression or low stand in a restricted marine basin. Other members of the Salado have economic significance. Vast quantities of potassium (potash) have been produced from the McNutt potash zone (Fig. 4) since mining commenced there in 1934 (Austin and Barker, 1990).

The closely related Castile and Salado Formations are part of a marine evaporite sequence deposited in the Permian basin during Late Permian (Ochoan) time. Preservation of the thin laminae in the Castile, studied by Anderson and Kirkland (1966), suggests that deposition was in relatively deep water, well below wave base and took about 200300,000 years (Anderson, 1982). Other workers concur that the basin was initially deep (Lang, 1935; Adams, 1944; King, 1947). The anomalous thickness of latest Permian strata in an area that otherwise has very little paleotopography is an enigma. How did a basin form so quickly and then stabilize in a comparatively aseismic region? Elam (1992) proposed a rifting origin for the various structural elements in the Permian basin, but with a restrictive definition of the term rifting. He envisions it as crustal dilation above a thermal bubble and would not relate Permian basin genesis to the drifting apart of discrete crustal plates.

A thick brecciated zone up to 46 m thick was noted by Madsen and Raup (1988) at the top of the Castile Formation. The breccia consists of massive anhydrite and apparently owed its origin to pre-Salado removal of halite, particularly along the western margin of the Delaware basin. This may indicate some eastward tilting of the basin, placing the western side in a position vulnerable to erosion while the subsidence and tectonic adjustments to the east permitted the subsequent Salado evaporite basin to extend across the central-basin platform and into the Midland basin. Others have recognized salt dissolution and an angular unconformity between the Castile and Salado Formations in the northern part of the Delaware basin (Adams, 1944; Anderson, 1981).

The Rustler Formation, named by Richardson (1904) for exposures in the Rustler Hills, Culberson County, Texas, is present in both the Delaware and Midland basins, although thinner in the latter. In the Delaware basin the unit is 60 to 150 m thick and in the western part rests with angular unconformity on the Salado Formation (Adams, 1935). The Rustler consists of anhydrite, red silty shales and magnesian limestone (Lang, 1935). The anhydrite generally forms the thickest unit in the subsurface, but has numerous sandy, lenticular red-bed partings.

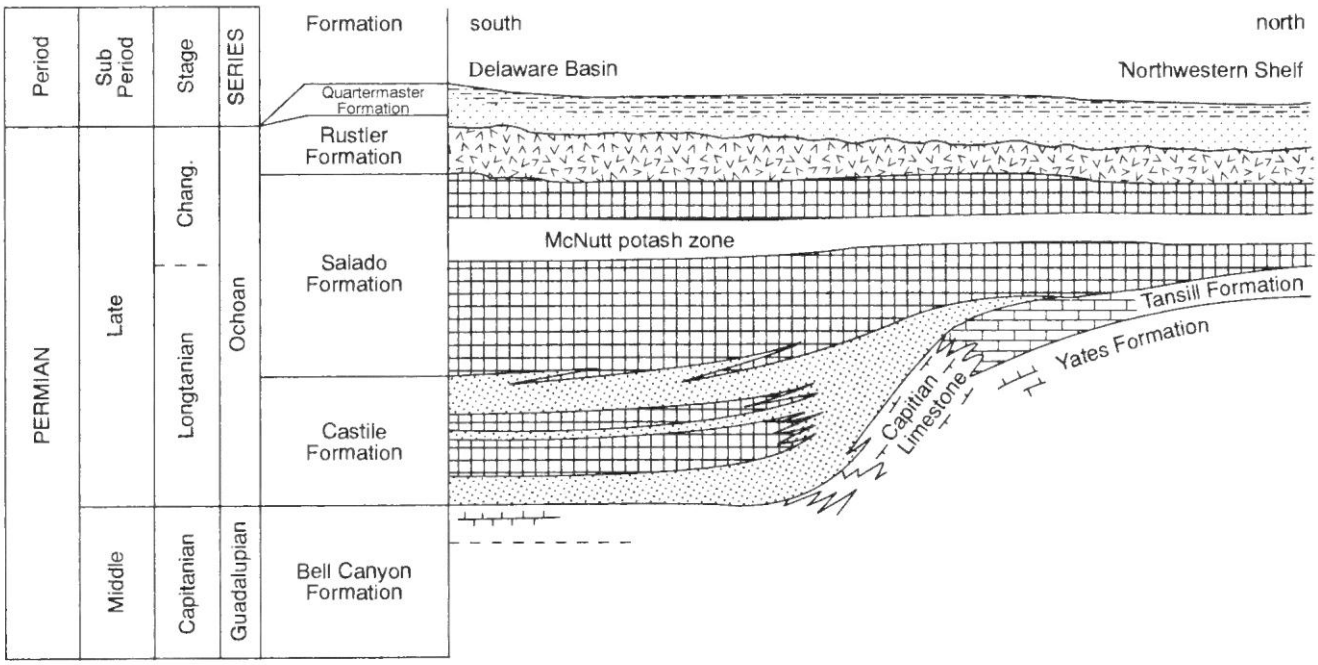


FIGURE 4. Generalized structure-stratigraphic section of Upper Permian rocks in Delaware basin, showing position of McNutt potash zone (modified from Austin, 1978).

The magnesian limestones, or dolomites, are commonly less than 9 m thick, but are porous and locally form good aquifers (Adams, 1935). They extend across the Delaware basin and eastward, well into the Midland basin where they form good marker beds (Fig. 1). In terms of depositional environments the Rustler represents the last episode of chemical deposition in the Permian basin.

Macrofossils from the Rustler Formation, principally brachiopods, support a Late Permian age assignment (Walter, 1953). Conodonts indicate a Changxingian age (Croft, 1978; Wardlaw and Grant, 1992).

Final stage of Ochoan Series

The final stage of Ochoan depositional history is represented by a relatively thin sequence of red to reddish-orange fine-grained sandstone, siltstone and shale, similar to that of the much older Artesia Group. The basal few meters of the unit, particularly in the southern portion of the Permian basin, are marked by a zone of frosted quartz sand grains, somewhat coarser than other sandy intervals in the unit (Adams, 1935). These strata were designated (Lang, 1935) the "Pierce Canyon Redbeds" from exposures in Pierce Canyon, southeast of Loving in Eddy County, New Mexico. The exposures, however, were very limited and the type section of the formation was described from well cuttings in a test hole 56 km to the southeast in Loving County, Texas. The subsurface thickness was established as 106 m from this well. Adams (1935) accepted the name Pierce Canyon Redbeds for these youngest Permian strata, but discounted their correlation with the youngest Permian strata in Oklahoma and the Texas Panhandle, which had been designated the Quartermaster by Gould (1902). Adams recognized Quartermaster through the Panhandle, but southward into the northern Midland basin he incorrectly correlated it with the Yates Sand of the Whitehorse (Artesia) Group. Adams thus considered the Quartermaster to be much older than the youngest Permian rocks of the southern basins, for which he preferred to use the name Pierce Canyon Redbeds.

In their discussion of Permian stratigraphy in the Midland basin, Page and Adams (1940) introduced the name Dewey Lake Formation for the youngest strata of the Ochoan series. They discarded the name Pierce Canyon because it had been established, to their satisfaction, that the red beds exposed in Pierce Canyon were of the Gatuňa Formation of Plio-Pleistocene age. The Dewey Lake Formation was named from a subsurface section, the Penn-Habenstreit No. 1, a cable-tool well (dry hole) in Glasscock County, Texas; Dewey Lake is a nearby alkali lake.

Aside from the revelation that the Pierce Canyon outcrop was in reality that of the Gatuňa Formation, the unit had also been included with the overlying Upper Triassic Dockum Group (Formation). Lang (1937) implied in his discussion of the Pecos Valley that the top of the Permian was the top of the Rustler. Morgan (1942) presented a cross section in which he included the Pierce Canyon Formation in the Dockum. Subsequent work, however, beginning with that of Bates (1942), used the name Dewey Lake for these strata and correctly included them in the Permian Ochoan series. The overlying Dockum has a conglomerate at or near the base, resting unconformably on Permian strata (Lucas and Anderson, 1992). The Dockum also has a much less mature lithology, both texturally and mineralogically.

The U.S. Geological Survey eventually recommended that the name Pierce Canyon be abandoned (Keroher, 1966) and that Dewey Lake be used instead across the Permian basin. Most published accounts followed that recommendation, but both names would subsequently appear informally. One of the most recent usages of Pierce Canyon Formation was by Fracasso and Kolker (1985), who described and dated volcanic ash beds in the Quartermaster (= Dewey Lake) Formation (see below).

With the Pierce Canyon name gone, the nomenclature for latest Ochoan rocks now consisted of Dewey Lake in the Permian basin (both Delaware and Midland basins) and the Quartermaster to the north in the Texas Panhandle and into Oklahoma. Miller (1966) recognized that the Quartermaster and Dewey Lake Formation have "essentially identical mineral assemblages" and occupy the same stratigraphic position. Based on our own observations of these units, both in the field and in the laboratory, we agree with Miller's conclusions. In an effort to simplify the nomenclature and add to the understanding of regional correlations we suggest one name be used for these strata. The name Quartermaster (Gould, 1902) has precedence over Dewey Lake (Page and Adams, 1940) and we thus recommend that Dewey Lake be abandoned in favor of the name Quartermaster Formation.

It must be noted that Miller (1966), while correctly assuming the regional correlations, proceeded to pick the Permo-Triassic boundary incorrectly at Maroon Cliffs in sec. 1, T21 S, R29E, Eddy County, New Mexico (see Lucas and Anderson, 1992, this volume), and also gave an incorrect lithologic description of Permian rocks at this locality because he had the top of the Ochoan (Pierce Canyon) placed too high in this section. Thus his description of high feldspar content in Permian rocks is in error.

Age of Quartermaster Formation

Several workers, most recently Schiel (1988), have questioned a Late Permian age assignment for the Quartermaster (= Dewey Lake) Formation, suggesting that it is of Triassic age. The only chronologically significant fossils known from the Quartermaster Formation are three mollusc taxa from Briscoe County, *Texas—Naticopsis transversus* (Beede), *Schizodus oklahomensis* Beede and *Myalina acutirostris* Newell and Burma—that suggest a Permian age (Roth et al., 1941). Furthermore, magnetostratigraphy of the Quartermaster Formation in Palo Duro Canyon, Texas, suggests correlation with the Illawara magnetozone at the end of the Kiaman superchron (Molina-Garza et al., 1989). This indicates a Late Permian age.

Finally, in an attempt to settle the lingering issue of the age of the formation, Fracasso and Kolker (1985) sampled and dated a volcanic ash bed in the Quartermaster Formation. The ash bed lies 4 to 20 m above the base of the formation in Caprock Canyon State Park, Texas. K-Ar dates of 251 ±4 and 261 ±9 Ma were obtained by Fracasso and Kolker. These values are well within the range of the Late Permian. Also, at the sample locality the Upper Triassic Dockum Formation rests unconformably on the Quartermaster. A thin pebbly zone which we correlate with the Camp Springs Member marks the base of the Dockum. Therefore, we accept the radiometric age dates of Fracasso and Kolker (1985), recognize a Permian-Triassic boundary at approximately 251 Ma and assert that the isotopic dates, lithology, magnetostratigraphy, regional stratigraphic relationships and faunal evidence thoroughly discount the possibility of an Early to Middle Triassic age for the Quartermaster Formation.

TRIASSIC STRATA

Triassic strata in southeastern New Mexico and west Texas pertain to the Chinle Group of Lucas (1993). In southeastern New Mexico, the basal unit of the Chinle Group is the Santa Rosa Formation, whereas in west Texas it is the Camp Springs Member of the Dockum Formation (Lucas and Anderson, 1992, 1993 and this volume).

In east-central New Mexico, the Santa Rosa Formation consists of, in ascending order, the Tecolotito, Los Esteros and Tres Lagunas Members. The medial, mudstone-dominated Los Esteros Member contains fossil plants and vertebrates that indicate a late Carnian age (Ash, 1988; Hunt and Lucas, 1988). In west Texas (Randall, Scurry and Crosby Counties) the Camp Springs Member of the Dockum Formation produced the phytosaur *Paleorhinus*, indicative of a late Carnian age (Hunt and Lucas, 1991). These fossils thus establish the age of the oldest Triassic strata in southeastern New Mexico and west Texas as Late Triassic (late Carnian). On the Harland et al. (1989) numerical time scale this is about 225 Ma.

Claims that older (Early or Middle Triassic strata) are present in west Texas cannot be substantiated. McGowen et al. (1979, 1983; also see Johns and Granata, 1987) claimed, based on King (1935), that the Bissett Formation in the Glass Mountains is of Early Triassic age. However, the fossils on which King (1935) based this age determination have long been known to have been misidentified (Langston, 1974). The presence of the dinosaur *Iguanodon* in the Bissett Formation indicates that it is of Early Cretaceous (Neocomian) age (Langston, 1974).

May (1987), May and Lehman (1989) and Lehman (1992) claimed

to have identified an eolianite immediately below the Dockum Formation in the Floyd-Randall Counties outcrop belt that is possibly equivalent to the Middle Triassic (Anisian) Anton Chico Member of the Moenkopi Formation in east-central New Mexico. We have examined this "eolianite" at three localities—Wayside Crossing in Armstrong County, on the Silverton Highway in Briscoe County and at Quitaque Peaks in Floyd County. At the latter locality the "eolianite" contains golf-ball-sized mudballs and clearly is not an eolianite. Instead it is a fluvial sandstone in the upper Quartermaster Formation similar to those documented in the Quartermaster Formation elsewhere by Schiel (1988).

There is no evidence of Early or Middle Triassic strata in west Texas. Claims of a "gradational" contact between the Permian and Triassic in the subsurface of west Texas (McGowen et al., 1979) cannot be substantiated. The Permian-Triassic contact in west Texas is a profound unconformity that represents part of Late Permian time, all of the Early' Middle Triassic and part of the Late Triassic, a hiatus of at least 25 million years.

PERMIAN-TRIASSIC BOUNDARY
Criteria

The Permian-Triassic boundary in southeastern New Mexico and west Texas is bracketed by nonmarine, siliciclastic red beds. Fossils are sparse in these strata and available literature makes it clear that many previous workers had difficulty in correctly identifying the Permian-Triassic boundary. To aid in its identification, we describe in detail 12 surface reference points in southeastern New Mexico and west Texas where the Permian-Triassic boundary is well exposed (Fig. 5). Before doing so, we present general criteria for distinguishing Upper Permian from Upper Triassic strata in this region. These criteria are based on color, texture, mineralogy, bedforms and fossils.

1. Color—Upper Permian strata of the Quartermaster Formation are characteristically moderate reddish brown (10 R 4/6), commonly called "brick-red" or "orange-red" with some grayish green/yellowish gray reduction mottles. No color variegation is evident. In contrast, Upper Triassic strata are *variegated* grayish red, grayish green, yellowish brown and grayish red to purple.

2. Texture—Upper Permian sandstones are very fine- to fine-grained, relatively well sorted and rounded. Most Upper Permian strata are siltstones or silty sandstones. In contrast, Upper Triassic sandstones are fine to coarse grained, poorly to moderately sorted and subangular to subrounded. Conglomerates with extrabasinal siliceous clasts of quartzite and chert are characteristic of basal Upper Triassic strata, but are absent in Upper Permian strata.

3. Mineralogy—Upper Permian sandstones are quartzarenites or slightly micaceous quartzarenites and are frequently gypsiferous. Upper Triassic sandstones are generally micaceous litharenites and are not gypsiferous.

4. Bedforms—Upper Permian sandstones are typically ripple-laminar, laminar or massive and form laterally persistent, repetitive (cyclic) beds. Trough crossbeds are present in some beds. In contrast, the dominant bedform of Upper Triassic sandstones is trough crossbedding characterized by lenticular beds.

5. Fossils—With one exception (Roth et al., 1941), no fossils other than nondescript *Skolithos-like* burrows are known from the Upper Permian red beds. In contrast, Upper Triassic strata often contain fossils of petrified wood (either silicified or iron oxidized), unionid bivalves, bone fragments, whole bones and coprolites.

In summary, Upper Permian strata are brick-red, not variegated, texturally and mineralogically relatively mature, ripple-laminar to laminar and unfossiliferous, whereas Upper Triassic strata are grayish red, variegated, texturally and mineralogically relatively immature, troughcrossbedded and fossiliferous.

Reference points

The following reference points for the Permian-Triassic boundary encompass all of west Texas and southeastern New Mexico (Fig. 5). In east-central New Mexico, Middle Triassic strata of the Anton Chico Member of the Moenkopi Formation disconformably overlie Middle Permian (Guadalupian) strata of the Artesia Group (Lucas and Hunt, 1987, 1989; Lucas and Hayden, 1988). This Permian-Triassic boundary is present in San Miguel, Guadalupe, De Baca and Lincoln Counties and has already been well described by Lucas and Hayden (1988) and Lucas (1991).

Trujillo Camp, Oldham County, Texas

The Permian-Triassic boundary is exposed at the lectostratotype section of the Trujillo Member of the Dockum Formation designated by Lucas and Anderson (1993) near Trujillo Camp, Oldham County, Texas (Trujillo Camp, Texas, 1966 7.5-minute quadrangle; UTM 3923770N, 692485E, zone 13). Here the uppermost dolomitic limestone ledge of the Quartermaster Formation (Alibates dolomite of Gould, 1907 and subsequent authors) is overlain by 6.2 m of laminar and ripple-laminar, very fine-grained micaceous and gypsiferous moderately reddish brown (10 R 4/6) quartz sandstone that forms the top of Quartermaster Formation (Figs. 5, 6A). The base of the Upper Triassic is 0.2 m of color mottled (brown, red, gray and yellow) silty mudstone. These mottled strata are overlain by 2.1 m of pale red trough-crossbedded micaceous sandstone. These two units are here assigned to the Tecovas Formation, following Gould (1907), thus suggesting that the Camp Springs Member is not present at Trujillo Camp. The overlying Trujillo Formation, here at its type section (Lucas and Anderson, 1993), is 13.7 m thick and mostly trough-crossbedded limestone, siltstone-pebble conglomerate, and very fine-grained subarkosic and litharenitic sandstone.

East Amarillo Creek, Potter County, Texas

On the eastern bank of East Amarillo Creek, just south of its confluence with the Canadian River, the Permian-Triassic boundary is well exposed (Puente, Texas, 1953 7.5-minute quadrangle; UTM 3928200N, 2338850E, zone 14). Here the "Alibates Dolomite Bed" (stratigraphically highest dolomite in the Quartermaster Formation) is overlain by 12.1 m of mostly laminar and ripple laminar siltstone and very fine-grained gypsiferous quartzose sandstone. Dominant colors are moderate reddish orange (10 R 6/6) and moderate reddish brown (10 R 4/6) with minor light greenish gray (5 GY 8/I) and light olive gray (5 Y 6/1) mottling and color banding.

The base of the Triassic Dockum Formation is a very fine-grained quartzose silty sandstone that is 1.3 m thick (Fig. 6B). This sandstone is extensively color mottled grayish red (10 R 4/2), light olive gray (5 Y 6/I) and dark yellowish orange (10 YR 6/6). It is overlain by dusky yellow (5 Y 6/4) smectitic mudstone. The basal "mottled strata" represent a paleoweathering profile common at the base of the Chinle Group to the west in New Mexico and on the Colorado Plateau (Stewart et al., 1972; Lucas et al., 1990). We assign these sandy strata to the Camp Springs Member and the overlying mudstones to the Tecovas Member of the Dockum Formation.

Palo Duro Canyon, Randall County, Texas

The Permian-Triassic boundary is well exposed in Palo Duro Canyon in and immediately around the State Park. A typical exposure (Fig. 6C) is the *Paleorhinus* locality documented by Hunt and Lucas (1991) just north of the Park boundary (UTM 3874800N, 256850E, zone 14). The top of the Quartermaster Formation here is a 1 m-thick, laminar, moderately reddish brown (10 R 4/6) silty mudstone underlain by interbedded light brown (5 YR 8/2) gypsiferous and micaceous very fine-grained sandstones and siltstones. The base of the Dockum Formation is 1.4 m of trough-crossbedded silica-and clay-pebble conglomerate that produced the *Paleorhinus* skull described by Hunt and Lucas (1991). This skull thus demonstrates a late Carnian (Tuvalian) age for the basal Dockum, here identified as Camp Springs Member, at Palo Duro Canyon. Mottled (red, orange, green, gray) smectitic mudstone of the Tecovas Member overlies the Camp Springs Member at Palo Duro Canyon (Fig. 6C).

Wayside Crossing, Armstrong County, Texas

The east-facing cut of Texas Highway 284 just south of Wayside Crossing exposes the Permian-Triassic boundary (Pleasant Creek, Texas,

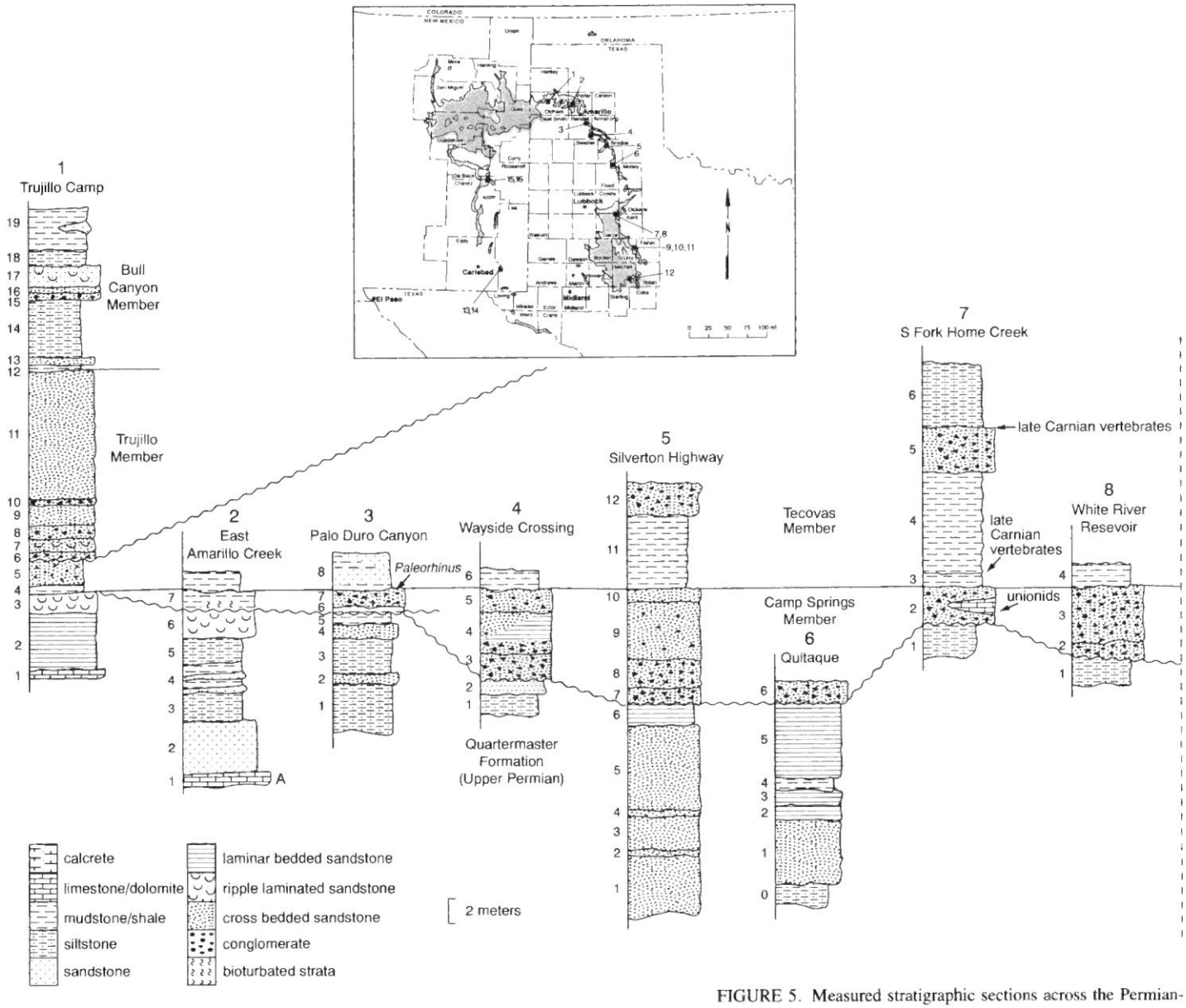


FIGURE 5. Measured stratigraphic sections across the Permian-

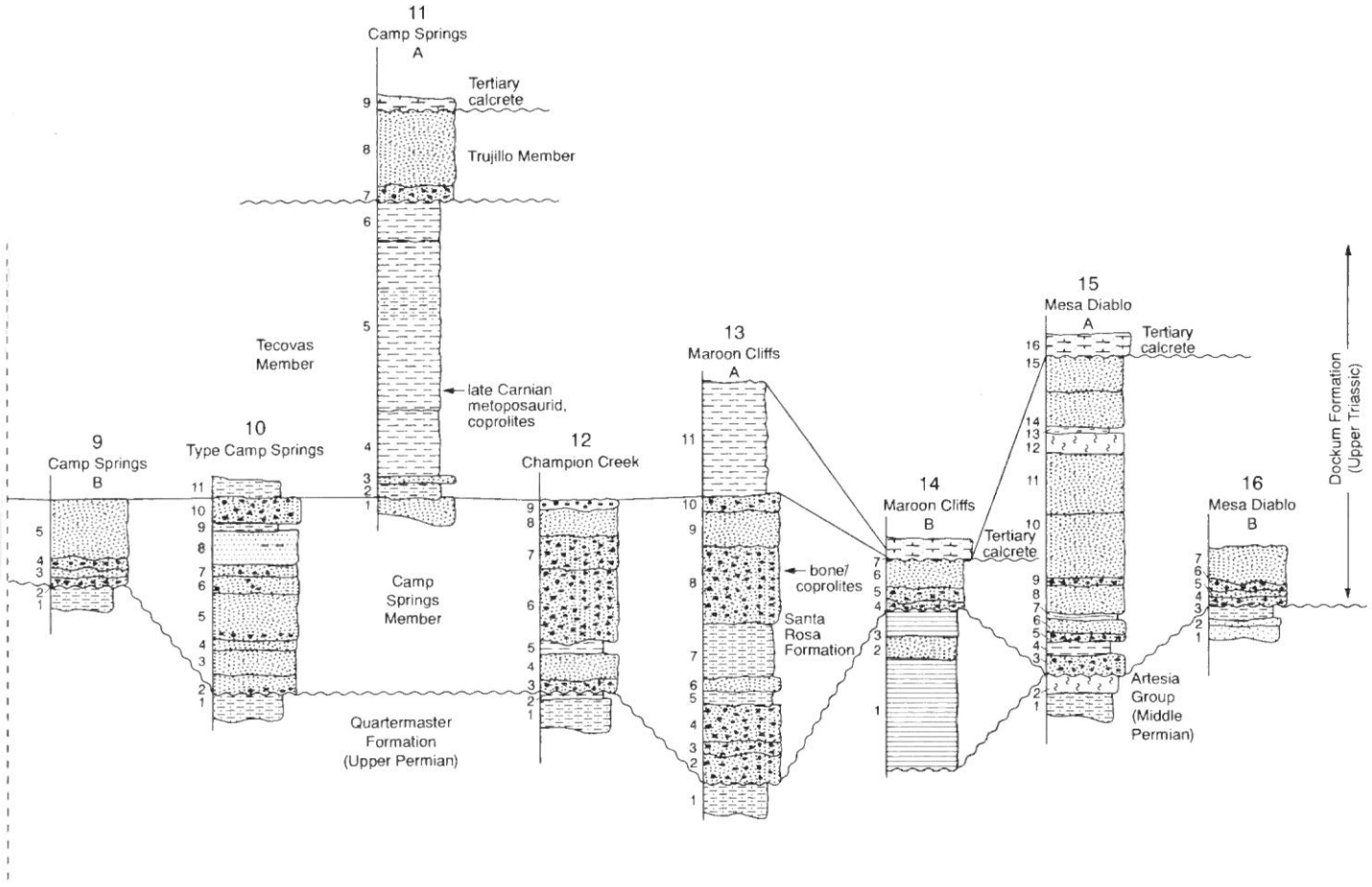
1963, 7.5—minute quadrangle; UTM 3853940N, 277150E, zone 14). The Camp Springs Member here is a 5.5 m thick trough-crossbedded sandstone and conglomerate, overlain by a moderate reddish brown (10 **R** 4/6) to grayish red (10 R 4/2) smectitic mudstone at the base of the Tecovas Member. Sandstones of the Camp Springs Member are fine to coarse-grained, grayish orange pink (10 **R** 8/2) to white (N 9) quartzarenites. Conglomerates contain not only siliceous clasts (mostly quartzite) but also rip-up clasts of underlying siltstones of the Quartermaster Formation. The uppermost bed of the Quartermaster Formation is a 0.8 m-thick sandstone that is moderately reddish orange (10 R 6/6) very fine-grained, subrounded, well sorted and quartzose. It rests on gypsiferous siltstone that is color banded moderate reddish orange (10 R 6/6) and yellowish gray (5 Y 8/1).

Silverton Highway, Briscoe County, Texas

The Permian-Triassic boundary is well exposed on the south side of Texas Highway 256 just south of Mexican Creek (Lake Theo, Texas, 1967, 7.5—minute quadrangle; UTM 3816380N, 308170E, zone 14). The top of the Quartermaster Formation is 1.5 m of laminar, moderately reddish brown (10 R 4/6), very fine-grained gypsiferous sandstone above trough crossbedded brown-to-orange micaceous sandstone.

The Camp Springs Member at the base of the Dockum is 9.3 m of trough crossbedded silica- and mud-pebble conglomerate and sandstone that is mostly yellowish gray (5 Y 8/1) and pinkish gray (5 YR 8/1). Variegated (grayish red and light greenish gray) smectitic mudstone of the Tecovas Member overlies the Camp Springs Member.

May (1988; also see May and Lehman, 1989) interpreted the trough-crossbedded sandstones of the upper part of the Quartermaster Formation at this section (our units 1-5, Fig. 5) as an "eolian unit" of Triassic age, possibly equivalent to strata of the Moenkopi Formation. Similar strata also are present in the upper Quartermaster Formation at Wayside Crossing (Fig. 5, section 4) and Quitaque (Fig. 5, section 6; Fig. 6D-E) and May (1988) also assigned them to this "eolian unit." His basis for such an interpretation was solely that "the predominant sedimentary structure is large scale trough cross-bedding (80 to 110 centimeters thick) indicative of aeolian [sic] deposition" (May, 1988, p 24). However, these sandstones have mineralogy and texture characteristic of Quartermaster sandstones and closely resemble fluvial Quartermaster sandstones described by Schiel (1988) at Maroon Cliffs in southeastern New Mexico. We thus feel quite certain that the "eolian unit" of May (1988) is part of the Permian Quartermaster Formation.



Triassic boundary in west Texas and southeastern New Mexico.

Quitaque Peaks, Floyd County, Texas

Immediately northwest of the intersection of Texas Highways 97 and 1065, the Permian-Triassic boundary section crops out (Quitaque Peaks, Texas, 1967, 7.5-minute quadrangle; UTM 3788350N, 309890E, zone 14). The base of the Triassic Dockum Formation, the Camp Springs Member, is a 1.4 m-thick trough crossbedded grayish orange-pink (10 R 8/2) to pale red (10 **R** 6/2), silica-pebble conglomerate with a "granitic" matrix (micaceous arkose of biotite grains in a microcline/quartz groundmass) (Fig. 6F). The underlying top bed of the Quartermaster Formation is 6 m of finely laminar moderately reddish brown (10 R 4/6) very fine grained micaceous sandstone (Fig. 6D).

May (1988) badly miscorrelated this section (his Floyd County FC-2 section); he identified the conglomerate we recognize as the base of the Camp Springs as the base of the Trujillo Member of the Dockum Formation. Our units 2-5 (Fig. 5, section 6), which are moderately reddish brown (10 R 4/6), gypsiferous laminar sandstones characteristic of the Quartermaster Formation, were assigned by May (1988) to the Tecovas Member and he identified our unit **I** as his "eolian unit." This miscorrelation in part led Lehman (1992) to erroneously conclude that the Camp Springs and Trujillo Members of the Dockum Formation are the same unit, a conclusion readily refuted by biostratigraphy (Lucas and Anderson, 1993).

Home Creek, Crosby County, Texas

Along the southern tributary of Home Creek, low-lying badlands expose the Permian-Triassic boundary (Kalgary, Texas, 1966, 7.5-minute quadrangle; UTM 3701730N; 298800E, zone 14). The uppermost unit of the Permian Quartermaster Formation is a grayish orange-pink (5 YR 7/2) to light brown (5 YR 6/4), laminar, calcareous siltstone exposed in the creek bank. The overlying Camp Springs Member of the Dockum Formation is 2.8 m thick and contains algal stromatolites and unionid bivalves (NMMNH locality 1313) in a grayish pink (5 R 8/2) and very pale orange (10 YR 8/2) lens of limestone. The dominant lithology of the Camp Springs Member, however, is trough crossbedded limestone and siltstone-pebble conglomerate with a matrix of very fine-to medium-grained, poorly sorted, subrounded-subangular, quartzose, slightly micaceous sandstone that is dusky yellow (5 Y 6/4) and weathers light olive gray (5 Y 6/1). Overlying, mudstone-dominated strata of the Tecovas Formation are smectitic mudstones that are mostly grayish red (10 R 4/2) to dark reddish brown (10 R 3/4) but are mottled yellowish gray (5 Y 6/4). These Tecovas strata form the low badlands at the head

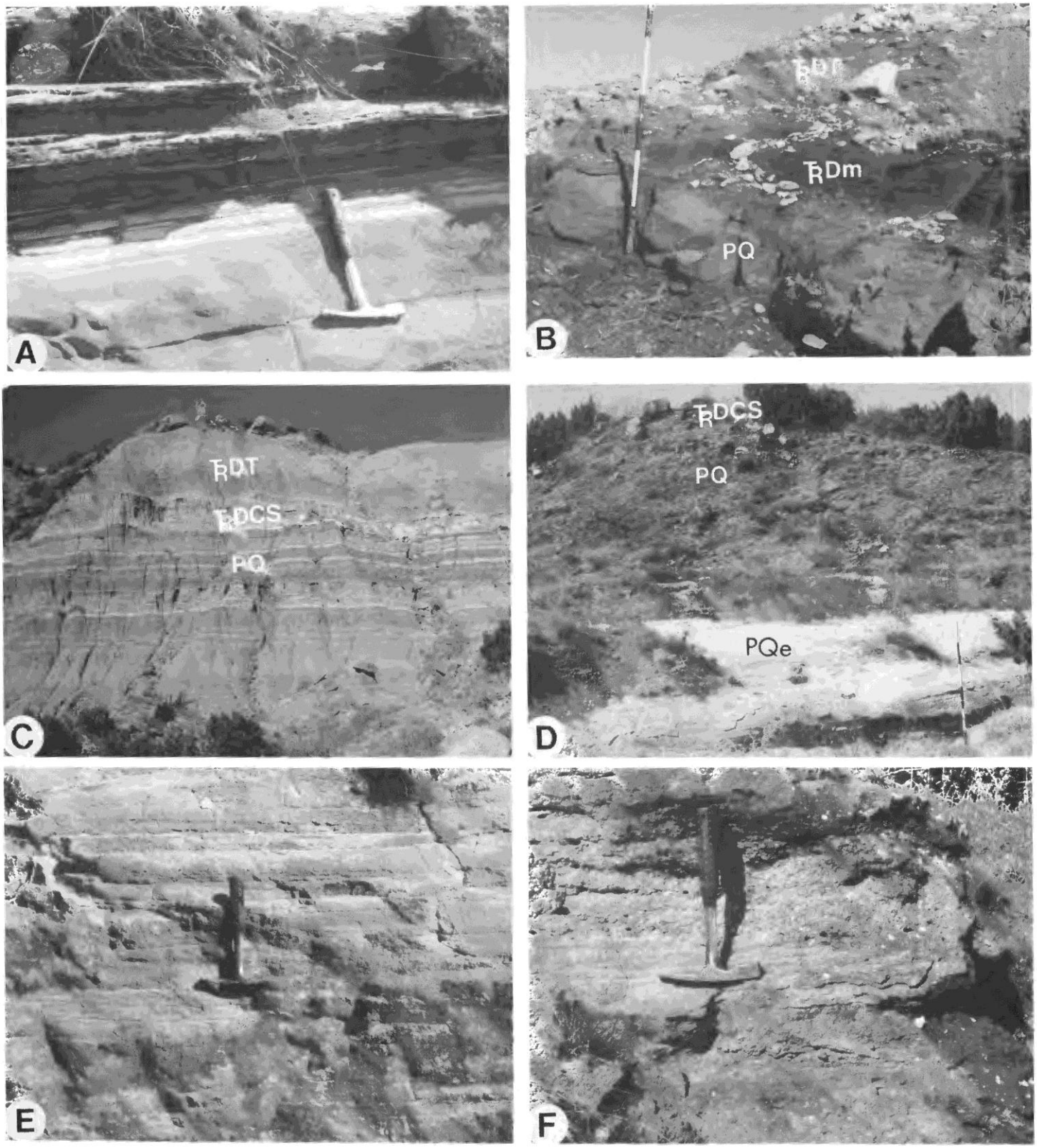


FIGURE 6. Photographs of selected outcrops of the Permian-Triassic boundary in west Texas. A, uppermost sandstones of the Upper Permian Quartermaster Formation at Trujillo Camp, Oldham County, Texas (reference point 1). B, the Permian-Triassic boundary on East Amarillo Creek, Potter County, Texas (reference point 2) where Upper Permian Quartermaster Formation (PQ) is overlain by mottled strata (TRDm) at the base of the Tecovas Member of the Dockum Formation (TRDT). C, the Permian-Triassic boundary in Palo Duro Canyon, Randall County, Texas (reference point 3) where the Upper Permian Quartermaster Formation (PQ) is overlain by a thin, light-colored interval dominated by sandstone and conglomerate assigned to the Camp Springs Member of the Dockum Formation (TRDCS), overlain, in turn, by the Tecovas Member (TRDT). D–F, the Permian-Triassic boundary at Quitaque Peaks, Floyd County, Texas (reference point 6) where the "Triassic eolianite" (PQe) of May (1988) and May and Lehman (1989) is overlain by uppermost Quartermaster strata (PQ) they erroneously identified as Tecovas Member of Dockum Formation, capped by Camp Springs Member (TRDCS) strata they incorrectly assigned to the Trujillo Member. The so-called "Triassic eolianite" actually is a typical laminar to shallow trough-crossbedded sandstone. Silica-pebble conglomerate (F) characterizes the Camp Springs Member at this locality.

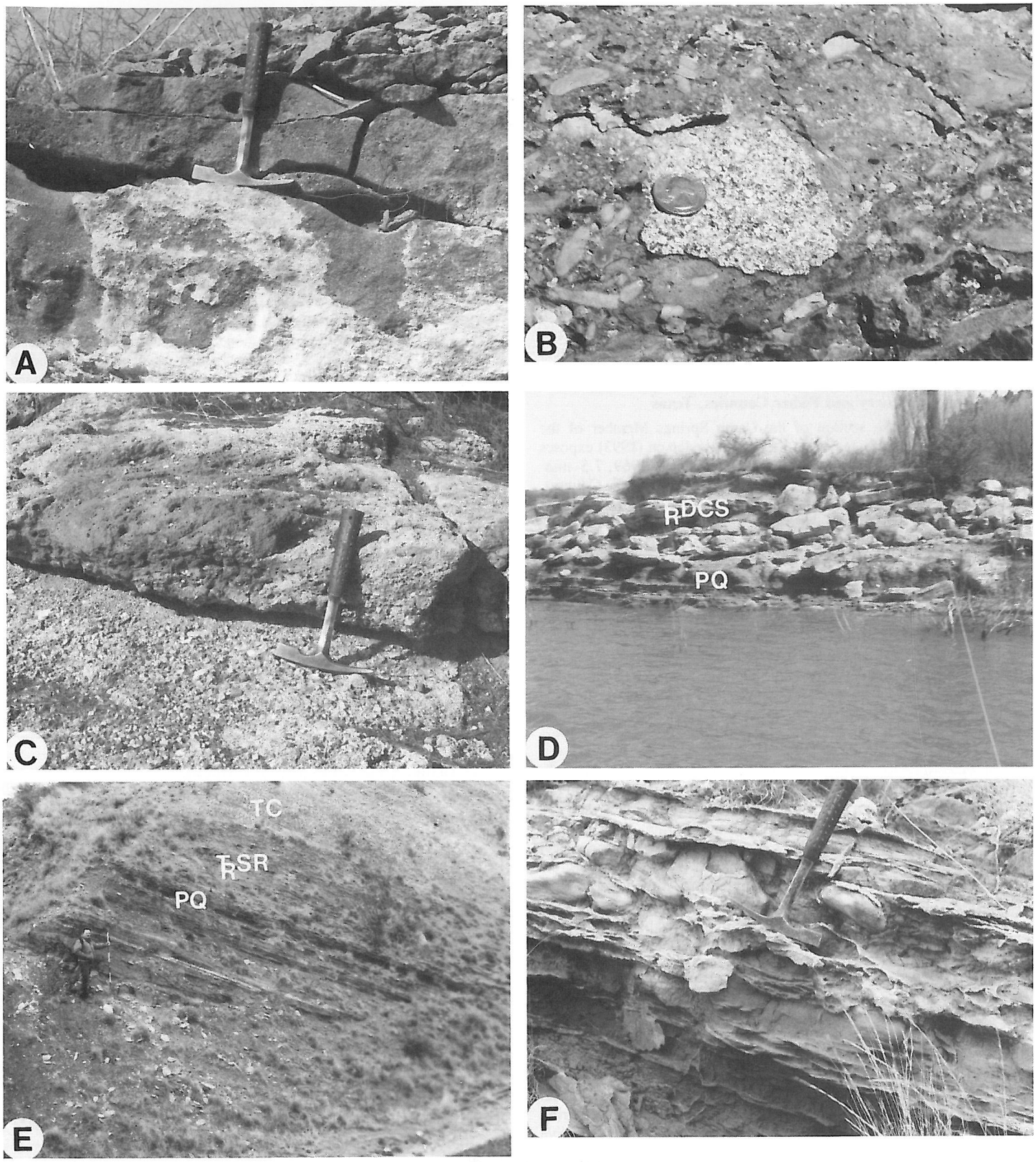


FIGURE 7. Photographs of selected outcrops of the Permian-Triassic boundary in West Texas and southeastern New Mexico. A, characteristic trough-crossbedded conglomerate of the Camp Springs Member of the Dockum Formation near Camp Springs, Scurry County, Texas (reference point 10). B, granite clast in Camp Springs Member conglomerate near Camp Springs in Fisher County, Texas (reference point 9). C, silica-pebble conglomerate of Camp Springs Member on southern shore of White River Reservoir, Crosby County, Texas (reference point 8). D, Upper Permian Quartermaster Formation (PQ) overlain by Camp Springs Member of Dockum Formation (TRDCS) on the southeastern shore of Champion Creek Lake, Mitchell County, Texas (reference point 12). E–F, Upper Permian Quartermaster Formation (PQ) overlain by Upper Triassic Santa Rosa Formation (TRSR) overlain, in turn, by Tertiary calcrete (TC) north of Maroon Cliffs in Eddy County, New Mexico (reference point 14). The basal conglomerate of the Santa Rosa Formation (F) contains hammer-head-size clasts of Quartermaster sandstone.

of the south fork of Home Creek and produce fossil vertebrates and ostracods of late Carnian age (Murry, 1986, 1989; Kietzke and Lucas, 1991; Lucas and Luo, 1993).

White River Reservoir, Crosby County, Texas

Along the southeastern shore of White River Reservoir, the Permian-Triassic boundary is well exposed (Smith Tank, Texas, 1962, 7.5-minute quadrangle; UTM 3704340N, 306670E, zone 14 and vicinity). Here the Camp Springs Member is about 5.5 m of clast-supported silica-pebble conglomerate (Fig. 7C). Trough crossbedding is the dominant bedform and most clasts are gray, pink, orange and white quartzite up to 2.5 cm in diameter. Silicified wood and oxidized plant stem impressions are common. These Camp Springs strata are remarkably similar to basal silica-pebble conglomerates of the Santa Rosa Formation in Lincoln County, New Mexico (Lucas, 1991), the Shinarump Formation on the Colorado Plateau (Stewart et al., 1972) and the Gartra Formation in northeastern Utah and adjacent parts of Idaho and Wyoming (McCormick and Picard, 1969a, b). At White River Reservoir, the top of the Upper Permian Quartermaster Formation is moderately reddish-brown (10 R 4/6), sandy siltstone.

Camp Springs, Scurry and Fisher Counties, Texas

The lectostratotype section of the Camp Springs Member of the Dockum Formation designated by Lucas and Anderson (1993) exposes the Permian-Triassic boundary (Camp Springs, Texas, 1969, 7.5–minute quadrangle; UTM 3629620N, 344120E, zone 14, Scurry County). The escarpment to the northeast also well exposes the boundary (UTM 3630610N, 345320E, zone 14, Fisher County).

At this section in Fisher County (Fig. 5, section 9), 6.0 m (minimum thickness) of Camp Springs Member are exposed above pale yellowish brown (10 YR 6/2) sandy micaceous siltstone at the top of the Quartermaster Formation. Camp Springs sandstones and conglomerates are trough crossbedded and range from yellowish gray (5 Y 8/1) and pinkish gray (5 YR 8/1) unweathered, to dark yellowish brown (10 YR 4/2) weathered. Sandstone and conglomerate matrices are granitic in composition—micaceous and feldspathic with minor quartz. Indeed, at least one 15 cm-diameter clast of coarse microcline granite is present in the basal conglomerate of the Camp Springs Member (Fig. 7B). Other clasts are mostly siltstone rip-ups of the underlying Quartermaster Formation.

The lectostratotype section of the Camp Springs Member (Fig. 5, section 10) displays the upper and lower contacts of the unit. The top of the Quartermaster Formation is a moderately yellowish brown (10 YR 5/4) siltstone overlain by 13.3 m of Camp Springs conglomerate and sandstone (similar to lithologies of the Fisher County section just described: Fig. 7A). Muddy, moderately brown (5 YR 4/4) sandstone of the Tecovas Member overlies the Camp Springs Member at its type section.

A section just southwest of the village of Camp Springs in Scurry County is critical to understanding the regional correlation of the Camp Springs Member (Fig. 5, section 11; located on the Inadale NW, Texas, 1969, 7.5-minute quadrangle 1 km west of Texas Highway 1614 at UTM 3623410N, 341000E, zone 14). A similar section is also present, but less well exposed, just east of highway 1614 at UTM 3624650N, 341750-342000E, zone 14. At the first section, the top of the Camp Springs Member is trough crossbedded grayish-pink (5 R 8/2) to pale red (10 R 6/2) sandstone and conglomerate. It is overlain by 20.6 m of strata dominated by grayish-red (10 R 4/2), smectitic mudstones. About 4.6 m above the base of these mudstones is a coprolite-bearing bed that also contains large metoposaurid bone fragments suggestive of a late Carnian age. These fossils, lithology and stratigraphic position indicate that the mudstone-dominated strata above the Camp Springs belong to the Tecovas Formation. Sandstone and conglomerate above these strata (units G and F of section II, Fig. 5) display typical Trujillo Member lithologies, further justifying assignment of underlying mudstone-dominated strata to the Tecovas. This stratigraphic section thus further demonstrates that the Camp Springs and Trujillo Members are separate stratigraphic units (contra Lehman, 1992).

Champion Creek Lake, Mitchell County, Texas

The Permian-Triassic boundary can be examined along the southeastern shore of Champion Creek Lake south of Colorado City (Colorado City SE, Texas, 1950 [revised 1978], 7.5-minute quadrangle; UTM 3572950N, 326000E, zone 14 and vicinity). The top of the Quartermaster Formation here is moderately reddish brown (10 R 4/6) and light olive-gray (5 Y 6/I) siltstone and silty mudstone. At least 13 m of Camp Springs strata follow and are dominated by quartzite-pebble conglomerates very similar to those exposed at White River Reservoir in Crosby County (Fig. 7D).

Maroon Cliffs, Eddy County, New Mexico

Two accessible exposures of the Permian-Triassic boundary are located northwest of Maroon Cliffs: (A) UTM 3598380N, 598900E, zone 13; and (B) UTM 3598700N, 599090E, zone 13. Section A (Fig. 5, section 13) is located in a collapse feature just north of US Highway 180 and was described briefly by Lucas and Anderson (1992). The top of the Quartermaster Formation is moderately reddish-brown (10 R 4/ 6) calcareous siltstone. The overlying Triassic strata were assigned to the Santa Rosa Formation by Lucas and Anderson (1992), an eastern New Mexican correlative of the Camp Springs Member (Lucas, 1993). The basal unit of the Santa Rosa is a 2.0 m-thick, trough crossbedded conglomerate consisting of clasts of Quartermaster siltstone up to 8 cm in diameter in a yellowish gray (5 Y 7/2) to pale reddish brown (10 R 5/4) matrix of very fine- to medium-grained micaceous litharenite. The overlying conglomerate (unit 3 of section 13, Fig. 5) has quartzite clasts and mud chips. Santa Rosa strata are 20 m thick at this section and are overlain by grayish red purple (5 RP 4/2) and moderately reddish brown (10 R 4/6) smectitic mudstone of the San Pedro Arroyo Formation.

Vine (1963, fig. 9) illustrated the railroad cut section (B) above (Fig. 7E-F) and incorrectly placed the Permian-Triassic boundary at the base of a sandstone within the Quartermaster Formation. This is a typical Quartermaster Formation sandstone—variegated pale reddish brown (10 R 5/4) and very pale orange (10 YR 8/2), very fine grained, well sorted, subrounded, gypsiferous and quartzose. The base of the Triassic is actually 3.1 m above the base of this sandstone, at the base of a 0.3 m-thick conglomerate of clasts of Quartermaster sandstone up to 20 cm in diameter, in a matrix of light greenish-gray (5 GY 8/1) and pinkish-gray (5 YR 8/1) calcareous sandy siltstone (Fig. 7F).

Mesa Diablo, Chaves County, New Mexico

The Permian-Triassic boundary is well exposed at two localities on the western escarpment of Mesa Diablo: (A) UTM 3702000N, 571240E, zone 13; and (B) UTM 3702660N, 570620E, zone 13 (L-E Ranch, New Mexico, 1949 [revised 1975], 7.5-minute quadrangle). At locality A (Fig. 5, section 15) the top of the Guadalupian Artesia Group is a yellowish gray (5 Y 8/1), bioturbated, gypsiferous sandstone above moderately reddish brown (10 R 4/6) siltstone. The top of the Artesia Group at section B (Fig. 5, section 16) is a similar siltstone. Overlying basal strata of the Santa Rosa Formation (Lucas and Anderson, 1992) are conglomerates composed of rip-up clasts of Artesia Group sandstone and siltstone in a matrix of grayish red (10 R 4/2) micaceous litharenite.

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Contact, below hammer, of conglomeratic sandstone of the Upper Triassic Santa Rosa Formation on siltstone and sandstone of the Upper Permian Quartermaster (Dewey Lake) Formation (Day 1, Stop 7).