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PETROLOGY OF PIERCE CANYON REDBEDS, DELAWARE BASIN, TEXAS AND NEW MEXICO[1]

D. N. MILLER, JR.[2]
Carbondale, Illinois

ABSTRACT

The Pierce Canyon Formation of the Delaware basin is a brick-red siltstone about 350 feet thick that conformably overlies the Permian Rustler Formation and unconformably underlies the Upper Triassic Santa Rosa Sandstone. Field and laboratory data suggest that the Pierce Canyon is a first-cycle sediment derived from a granitic source in northern Mexico under the influence of an arid climate, transported by the wind, and deposited in a shallow saline lagoon that covered western Texas and southeastern New Mexico at the close of the Permian.

In addition, surface and subsurface data from the encompassing strata substantiate the opinion that the Dewey Lake Formation of the southern Permian basin and the Quartermaster Formation of the Texas Panhandle and northwestern Oklahoma have essentially identical mineral assemblages and occupy the same stratigraphic position as the Pierce Canyon. Eight distinct mineralogic differences make it possible to distinguish these formations from the redbeds in the overlying Triassic Dockum Group. The name Pierce Canyon probably should be discontinued in favor of the name Dewey Lake.

INTRODUCTION

The most complete Permian section in North America has been described from the Delaware basin of western Texas and southeastern New Mexico (Fig. 1) and includes, in ascending order, the Wolfcamp, Leonard, Guadalupe, and Ochoa Series (Adams *et al.*, 1939).

A brick-red siltstone about 350 feet thick overlies the youngest proved Permian Rustler Formation and underlies the Upper Triassic Santa Rosa Sandstone (Fig. 2). Since 1935, when Walter B. Lang designated these redbeds as the Pierce Canyon Formation, their relation to the Triassic has been poorly understood.

The writer attempts to resolve the lithologic identity of the Pierce Canyon redbeds and offers a comparison of similar features in adjacent strata. Outcrop and subsurface samples of the Rustler and Santa Rosa Formations of the Delaware basin, and the Dewey Lake, Tecovas, and Quartermaster Formations of the Midland basin and Central Basin platform are described. The original detailed data that support these comparisons and conclusions are on file at the University of Texas library (Miller, 1955a).

The striking similarity in texture, detrital mineral content, mineral cement, and bedding characteristics of the Permian Pierce Canyon and Dewey Lake Formations has been verified. Eight distinct mineralogic differences make it possible to distinguish these formations from the redbeds in the overlying Triassic Dockum Group.

PERMIAN-TRIASSIC STRATIGRAPHY

During the final stages of Permian deposition, more than 5,000 feet of evaporite deposits accumulated in the central part of the Delaware basin (Cartwright, 1930). The youngest of these chemical deposits is the Rustler Formation, an erratic sequence of limestone and dolomite with some thin shale beds, sandstone lentils, and lenses of gypsum and anhydrite. In the subsurface the Rustler contains significant amounts of red clay and halite and traces of polyhalite in addition to the rock types listed above; the Rustler ranges in thickness from 400 to 500 feet in the basin center.

G. B. Richardson originally described the formation in 1904 from an outcrop in the Rustler Hills between Cottonwood and Hurds Pass Draws, eastern Culberson County, Texas. More accurate descriptions of the Rustler outcrops were made by P. B. King, DeFord, Adams, Lang, and numerous University of Texas graduate students (University of Texas Master's theses). A maximum thickness of 375 feet, exclusive of the upper anhydrite which is not exposed, was reported by Adams (1944, p. 1613).

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[2] Southern Illinois University. The writer acknowledges R. K. DeFord of the University of Texas, who first called attention to the problem and who materially aided the writer in many ways as the work progressed; and Robert L. Folk for his patient guidance and quiet inspiration which led to a more comprehensive understanding of sedimentary rocks. He also thanks Pan American Petroleum Corporation for its financial assistance through a Research Fellowship.

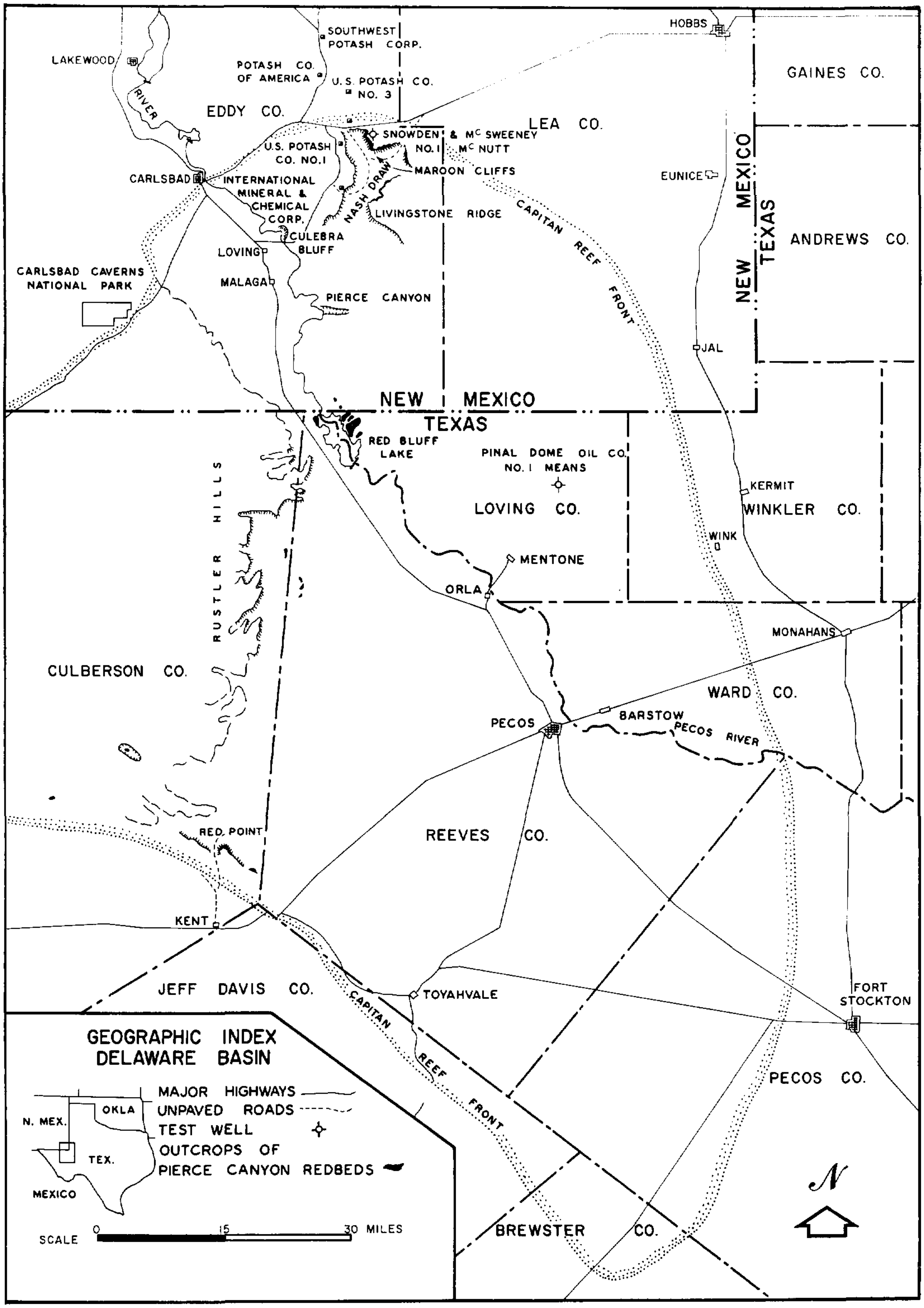


FIG. 1.—Geographic index map of Delaware basin.

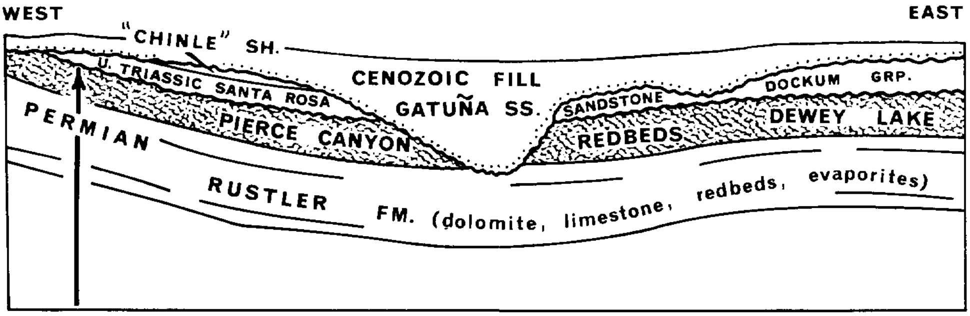


FIG. 2.—Diagrammatic cross section of uppermost Permian, Upper Triassic, and Cenozoic redbeds in Delaware basin. The name "Chinle" has been applied here to show presence of a Chinle-type shale above Santa Rosa.

RUSTLER-PIERCE CANYON CONTACT

R. K. DeFord, who has done extensive field work in the area, states that he has never seen the Rustler-Pierce Canyon contact exposed. Other geologists have suggested to the writer that the contact between gypsiferous limestone (below) and red siltstone (above) along the eastern side of the Pecos River Valley in Eddy County, New Mexico, is the Rustler-Pierce Canyon contact. This gypsiferous limestone is, in fact, a thick indurated caliche deposit on an eroded Rustler surface and may be one of the caliches referred to by Bretz and Horberg (1949b, p. 492). The overlying red siltstone (Gatuña Formation) is part of the Cenozoic fill, described by Maley and Huffington (1953, p. 541), that can be traced through most of the Delaware basin. An excellent example of this Rustler-caliche-red siltstone sequence is present in the Southwest Potash Company mine (SE. ¼, sec. 9, T. 19 S., R. 30 E.), where cores from two pilot-holes, 5A and 6A, clearly demonstrate why the Rustler-Pierce Canyon contact has been misidentified. In hole 5A the contact between the dolomitized Rustler Formation and the overlying Pierce Canyon siltstone is a distinct, undisturbed, non-transitional contact 207 feet below the surface and 3,153 feet above sea-level. In contrast, in pilot-hole 6A, 450 feet north of 5A, the Rustler dolomite at 3,130 feet above sea-level is overlain by 16 feet of caliche containing clay and silt, and 2 feet of caliche and reworked red siltstone of the Gatuña Formation.

The Rustler-Pierce Canyon contact was observed in cores from U.S. Potash Company's No. 3 shaft (SE.¼, sec. 13, T. 20 S., R. 30 E.), 7 miles southeast of the Southwest Potash Company mine. Thin sections from samples above and below the contact show a marked textural and lithologic change from gray anhydrite, containing a trace of red clay, below, to thin, evenly bedded, reddish brown siltstone, above. A similar Rustler-Pierce Canyon contact was observed in pilot-hole cores from U.S. Potash Company's shaft No. 1 (center of S.½, sec. 12, T. 21 S., R. 29 E.), 5 miles south of shaft No. 3.

PIERCE CANYON REDBEDS

W. B. Lang (1935, p. 264) described the Pierce Canyon redbeds from the subsurface as a series of finely sandy to earthy redbeds, polka-dotted with green reduction spots and usually irregularly veined with thin secondary selenite fillings. This description is based on 350 feet of drill cuttings from the Eldridge core test (sec. 22), drilled in 1926 as a western offset to the Pinal Dome Oil Company's No. 1 Means dry hole, drilled in 1921. The cuttings from both bore holes provided the type section for the formation. The Means test is in the southeast corner of section 23, Blk. C-26, PSL, in central-eastern Loving County, Texas. The name "Pierce Canyon" was taken from a small canyon on the eastern side of the Pecos River, 7 miles east-southeast of Malaga, Eddy County, New Mexico (secs. 23, 26, T. 24 S., R. 29 E.), and 35 miles northwest of the Eldridge and Means tests. The source of the geographic name is not the type locality of the formation; in fact, the redbed outcrop of Pierce Canyon itself is part of the Cenozoic Gatuña Formation (DeFord, oral communication). The subsurface redbeds described by Lang, however, do form a lithologically distinct and continuous stratigraphic unit between the Rustler and Santa Rosa Formations. They blanket the eastern two-thirds of the Delaware basin and extend northward to the Loco Hills, Eddy County, New Mexico.

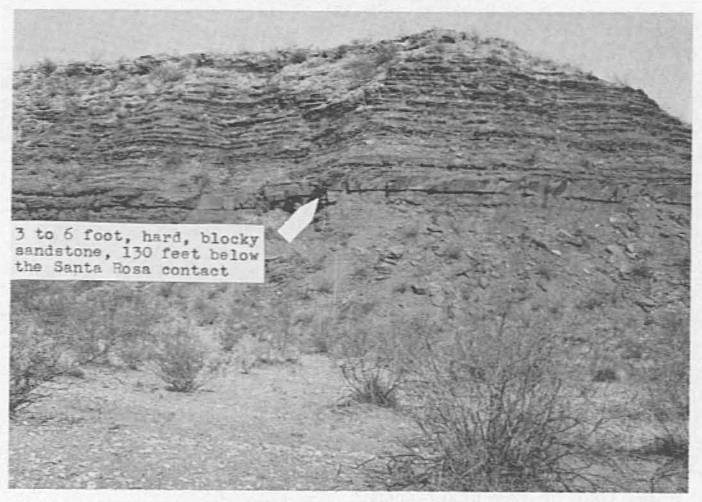


FIG. 3.—Outcrop of Pierce Canyon redbeds at Maroon Cliffs, Eddy County, New Mexico, illustrating difference in weathering features above and below "blocky" marker bed.

Within the Delaware basin exposures of the Pierce Canyon redbeds are limited to a narrow, intermittent belt which extends from Red Point in southeastern Culberson County, Texas, through Red Bluff Lake, to Maroon Cliffs in Eddy County, New Mexico (Fig. 1).

The thickest exposed section of the Pierce Canyon redbeds is in Maroon Cliffs along the northern escarpment of Nash Draw, eastern Eddy County, New Mexico (Fig. 3). The structural setting of Nash Draw has been described by Vine (1960). Approximately 120 feet of section is exposed 0.5 mile south of U.S. Highway 62 (Carlsbad-Hobbs) and 3.9 miles east of the most easterly intersection of U.S. Highway 62 and State Highway 31 (secs. 5, 9, T. 21 S., R. 30 E.; DeFord *et al.,* 1940, p. 2).

The red or maroon color of the Pierce Canyon Formation ranges from pale to moderately reddish brown. The most prominent stratigraphic marker in the cliffs is a 3–6-foot, hard, "blocky," fine- to very fine-grained sandstone that forms a ledge approximately 130 feet below the Santa Rosa Sandstone (Fig. 3). A few light greenish gray leached zones, less than 1 inch thick, parallel the uniformly thin-bedded siltstone at irregular intervals, giving the escarpment a faintly banded appearance. The leached zones underlie and include thin laminae sufficiently permeable to permit the infiltration of water from the closely spaced joints (Fig. 4). Some of the greenish gray zones result from the chemical reduction of hematite by weak humic acids. The sandy beds are lighter colored than the more impermeable clayey beds.

Current ripple-marks and low-amplitude cross-bedding (Fig. 5) are common in some beds both above and below the hard, "blocky" sandstone. The ripple-marks have an average height from trough to crest of 0.15 inch and show a dominant transport direction from northwest to southeast. Cross-beds above the "blocky" sandstone have an amplitude of 1–2 inches and a foreset dip of about 13° south, indicating a direction of transport from north to south; the cross-beds below the "blocky" sandstone have an average dip of 13° north, indicating a direction of transport from south to north. The dip direction, within individual sets of cross-beds in the same 2–3-foot section, ranges within an arc of 55°.

There are two sets of joints in Nash Draw that allow surface water to enter and hence alter the Pierce Canyon redbeds. Most of the joints have 0.25–1.0-inch separation and are straight-sided. At depth the majority of "open" joints are partly clogged with decomposed plant debris which accumulates each year as the result of rainstorms that flush the debris into the crevices. Organic acids derived from the decayed plant life permeate into the strata below and leach and otherwise after the permeated zones. Seven miles south of Maroon Cliffs, along Livingston Ridge, the same joint pattern is present, but there the joints are filled completely with fibrous satin spar gypsum (Fig. 4).

Approximately 210 feet of Pierce Canyon

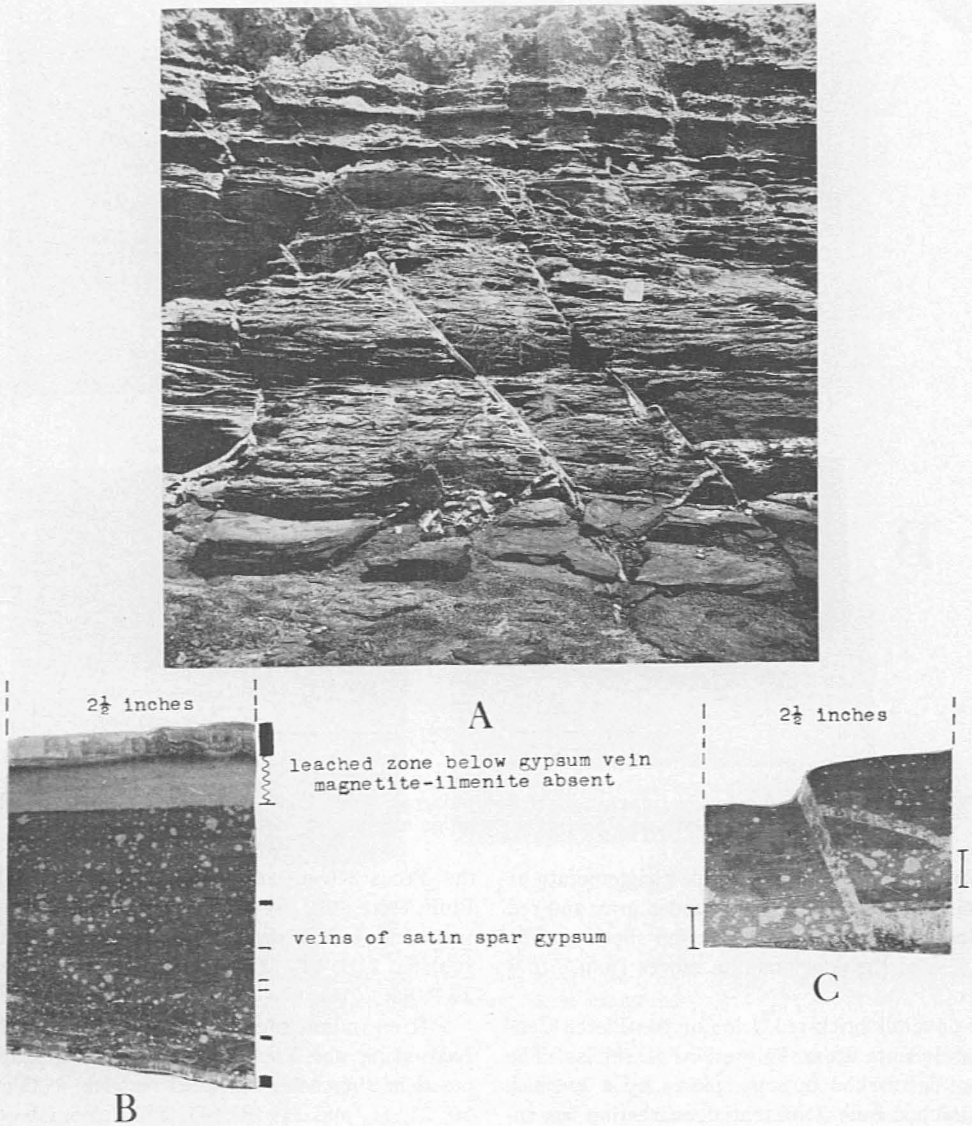


FIG. 4.—Gypsum-filled joints in Pierce Canyon redbeds; (A) at outcrop on Livingston Ridge; (B) core, showing extent of leaching and vertical separation of beds; (C) core, showing both vertical and horizontal separation and displacement.

redbeds is exposed at Maroon Cliffs below the Santa Rosa contact; an additional 30 feet was measured in Livingston Ridge, 150 feet northeast of the road connecting the Crawford Ranch headquarters and Hill Tank (W.¼, sec. 14, T. 22 S., R. 30 E.). A total of 318 feet of Pierce Canyon redbeds was measured in Snowden and McSweeney's No. 1 McNutt dry hole, 0.5 mile east of Maroon Cliffs (center of S.½, sec. 4, T. 21 S., R. 30 E.).

The Pierce Canyon redbeds are overlain unconformably by the Upper Triassic Santa Rosa Sandstone. The erosional surface at the top of the Pierce Canyon is especially well exposed at Maroon Cliffs on the eastern side of a small ravine (Fig. 6), 1 mile south of U.S. Highway 62 (east-central part of NW.¼, SE.¼, sec. 5). Thin, nearly horizontal beds of Pierce Canyon are overlain by the sweeping cross-beds of the Santa Rosa Sandstone at this locality, the exact contact being

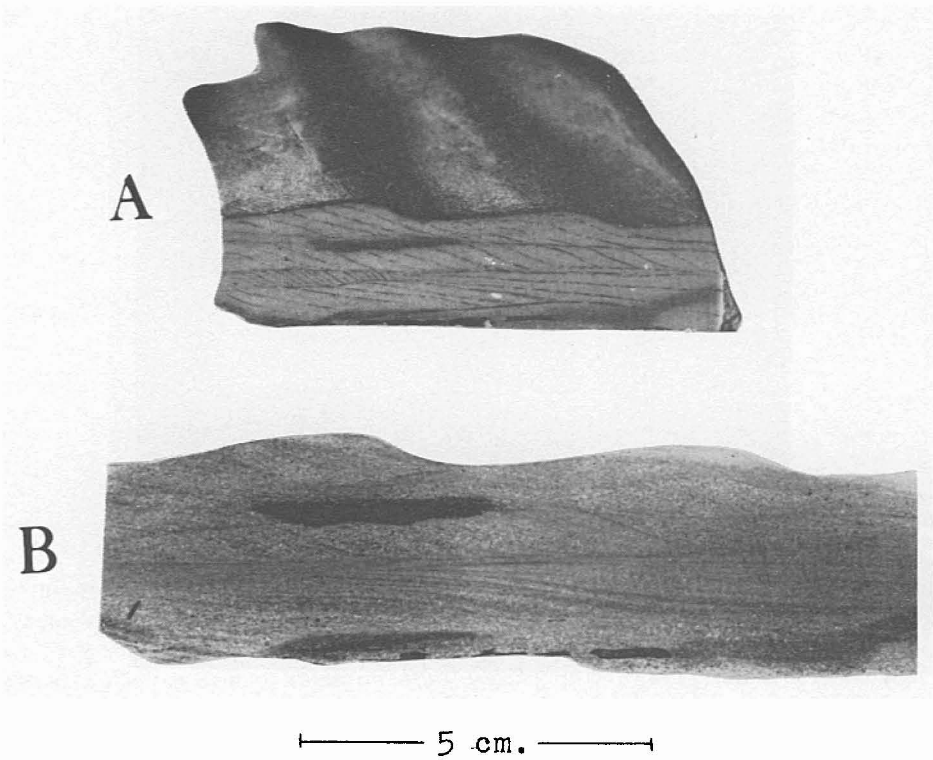


FIG. 5.—Ripple-marks and retouched cross-laminations in Pierce Canyon redbeds illustrating delicate manner of silt and very fine sand distribution at time of deposition.

the base of a gray, clayey pebble-conglomerate or coarse sandstone containing rounded gray and red pebbles of reworked Pierce Canyon siltstone. The thickness of the conglomerate ranges from 3 to 9 inches.

The overall brick-red color of the Pierce Canyon and Santa Rosa Formations is similar. The contact is marked in some places by a greenish gray leached zone. Differential weathering has accentuated the textural differences of the two formations; the contact usually is evident beneath a small undercut ledge of Santa Rosa Sandstone. Along the outcrop, a distance of 1.25 miles, there is no evidence of textural gradation.

West of Maroon Cliffs, the Pierce Canyon redbeds are exposed on numerous excavated hillsides in the vicinity of the U.S. Potash Company mine. Along the eastern side of the Pecos River Valley in southern Eddy County, measured sections (sec. 22, T. 26 S., R. 29 E.), compiled by Leve (1952, p. 20), have a maximum thickness of 30 feet, but neither contact is exposed. East of the Pecos River, and 1–3 miles north of Red Bluff Lake, 110 feet of Pierce Canyon redbeds was measured in sink holes by Komie (1962, p. 16; sec. 2, 3, 11, 12, 13, and 14, Blk. 57, Tr. 1, T&P RR. Co.).

Fifteen miles south-southwest of Red Bluff Lake dam, the Pierce Canyon redbeds are exposed in sink holes scattered through sections 3, 10, 23, 26, and 35, Blk. 45, PSL, along the Culberson and Reeves county line. The exposures are dark reddish brown, much darker than any of the other outcrops because of concentrations of dark minerals. The redbeds occur as low, evenly rounded hills surrounded by gypsiferous soils.

The southernmost outcrop of the Pierce Canyon redbeds lies beneath a vertical cliff of Cretaceous conglomerate at Red Point in southeastern Culberson County (NW.¼, sec. 20, Blk. 59, Tr. 7, T&P RR. Co.). Fitzpatrick (1950, p. 60, Measured Section 2) reported that 143 feet is exposed, and samples from Deep Rock Oil Company's No. 1 Seay dry hole, 0.75 mile to the east,

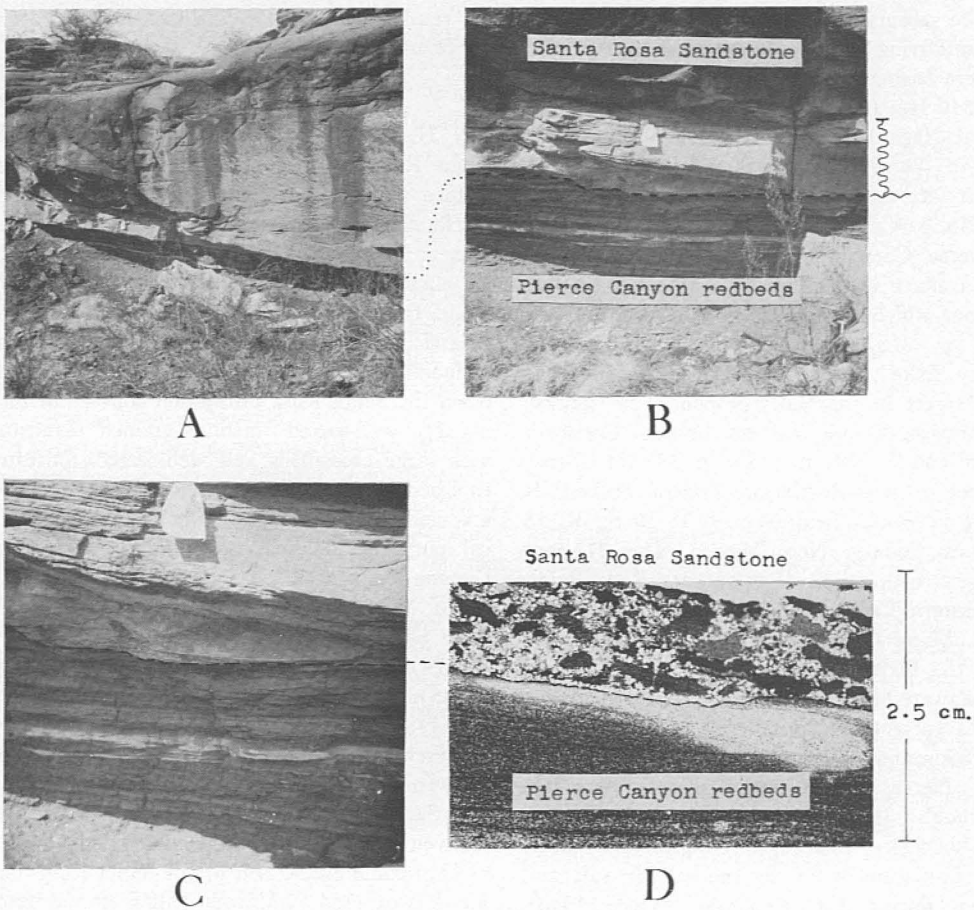


FIG. 6.—(A) Distant northeast view of prominent lower Santa Rosa Sandstone cliff just above Pierce Canyon-Santa Rosa contact at Maroon Cliffs, Eddy County, New Mexico. (B & C) Close-up views show lower leached zone above unconformity. (D) Thin section at lower right shows granule-size fragments of Pierce Canyon siltstone incorporated into basal beds of Santa Rosa Sandstone.

indicate a Rustler top 130 feet below the surface. Thus, 273 feet may be the thickness of the Pierce Canyon redbeds in this vicinity.

The lowest 90 feet of section at this outcrop is dull, moderately reddish brown, thin-bedded siltstone and fine-grained sandstone with intercalated dark red clay laminae. The bedding planes are persistent and slightly undulate. The only lithologic change occurs just below the Cretaceous contact where 5 feet of light greenish gray leached clay caps the Pierce Canyon redbeds. The unconformable contact between the Pierce Canyon and the overlying Cretaceous is an irregular undulate surface with a maximum local relief of 1.5 feet.

The westernmost exposure of the Pierce Canyon redbeds observed by the writer is 18 miles west of the Culberson-Reeves county line, northwest of Kent, where 45 feet of section is preserved in the trough of a northwest-trending syncline (NW.¼, NW.¼, sec. 5, Blk. 91, PSL; Travis, 1951, p. 37). DeFord (oral communication) reports one other small exposure in the SW.¼, NE.¼ of Blk. 87, PSL, Culberson County.

Pierce Canyon outcrops in Culberson County are small and isolated; stratigraphic correlation was not practicable because no common horizon was recognized. Nevertheless, identification at these outcrops is verified by (1) subsurface relations to the top of the Rustler Formation, and (2) nearly identical mineral assemblages with only slight textural variation.

At the subsurface type section and in other oil tests in Loving County, near the center of the Delaware basin, the Pierce Canyon Formation is about 350 feet thick. On the northern rim of the basin at Nash Draw, the formation is 318 feet thick in Snowden and McSweeney's No. 1 McNutt dry hole. In U.S. Potash Company's shaft No. 3, 4 miles north of the McNutt No. 1, the Pierce Canyon is 320 feet thick and the upper contact is overlain by a medium-grained sandstone which is the Cenozoic Gatuña. DeFord (1942, p. 216) reported about 470 feet of "Dewey Lake" redbeds between the depths of 395–873 feet in the Halfway pool, Lea County, New Mexico, 30 miles east-northeast of Carlsbad. DeFord and Wahlstrom (1932, p. 59) stated that 193 feet of post-Rustler-pre-Triassic redbeds is present in Hobbs field (sec. 9, T. 19 S., R. 38 E.), Lea County, New Mexico. The 273-foot thickness of Pierce Canyon at Red Point, southeastern Culberson County, has been mentioned. Many thousands of oil tests have penetrated the Pierce Canyon redbeds in and around the Delaware basin, but for the most part reliable samples are not available because of sample disaggregation and caving.

The Pierce Canyon redbeds were deposited throughout a structural basin that has undergone slow subsidence induced by solution and subsequent displacement of the underlying salt and gypsum during the Cenozoic (Vine, 1960). Stream erosion accompanied the subsidence, and a maze of channels was cut and filled in the Pierce Canyon strata. A few of these channels are known because of the erratic thicknesses of the post-Rustler deposits. All of these formations were truncated along the northern and western margins of the basin, with the result that all that remains on the surface of the Pierce Canyon redbeds is preserved in synclines and sink holes. Most of the detritus resulting from the erosion was transported into solution depressions in the basin that presently contain as much as 2,000 feet of Cenozoic fill. The thickness of the detritus has been discussed by Maley and Huffington (1953, p. 541); they recognize three separate accumulations. Red siltstone, originating in part from the reworked Pierce Canyon redbeds, is a common constituent of this detritus. Thus it appears that, without more cores, it may never be possible to measure accurately and to separate reliably the originally deposited Pierce Canyon redbeds from the reworked Pierce Canyon that now is part of the Cenozoic fill.

SANTA ROSA SANDSTONE

N. H. Darton (1921, p. 183) applied the name Santa Rosa to a prominent sandstone-shale sequence, about 350 feet thick, near the base of the Dockum Group in the mesas of Guadalupe County near Santa Rosa, New Mexico. On the basis of vertebrate fossils and position beneath the Chinle Shale, the Santa Rosa is considered to be Upper Triassic and equivalent to the Shinarump Conglomerate farther northwest. In the Delaware basin the Santa Rosa Formation consists of moderately well-sorted medium-grained sandstone with large cross-beds and well-sorted, uniformly thin-bedded siltstone. The sandstone and siltstone are moderately reddish brown and for all practical purposes identical in color with the Pierce Canyon redbeds.

No comprehensive description of the Santa Rosa Sandstone in Texas has been published, although Sidwell and Gibson (1940), Sidwell (1945), Lang (1947), Adams (1929), Green (1954), and others have mentioned its occurrence or described its mineral content at specific localities. In the northern half of the Delaware basin the Santa Rosa Sandstone overlies the Pierce Canyon redbeds and underlies the Chinle Shale.

Approximately 50 feet of the Santa Rosa Sandstone is exposed at Maroon Cliffs. At the base is a well-exposed unconformable contact with the Pierce Canyon redbeds; the Santa Rosa is truncated at the top by a Pleistocene erosion surface now marked by caliche (Bretz and Horberg, 1949b, p. 493).

In the central part of the Delaware basin the Santa Rosa Sandstone once was referred to locally as the "Barstow sand" (Adams, 1929, p. 1052). It forms a low, red, south-trending escarpment that intersects U.S. Highway 80 (Pecos to Odessa) just east of Barstow, Texas. A smaller exposure of this same trend crops out 12 miles south of Barstow along U.S. Highway 285 (NE.¼, sec. 12, Blk. 51, Tr. 7, T&P RR. Co.).

Petrology

TEXTURE

The Pierce Canyon redbeds range in thickness from 350 to 450 feet and consist generally of brick-red siltstone with a few minor beds of very fine- and fine-grained sandstone. There are no evaporite beds in the section. Gypsum, calcite, and hematite are the common mineral cements. Nearly all of the detritus is silt-size, although thin discontinuous beds of claystone and clay-pebble conglomerate are present in a few places.

The 10-foot zones containing large (0.4 mm.), rounded and frosted quartz and orthoclase grains are present at Maroon Cliffs; one zone is 265 feet and the other 115 above the top of the Rustler Formation. R. K. DeFord (oral communication) has found similar sandy zones to be useful as stratigraphic markers as far distant as Monument, in eastern Lea County, New Mexico. However, there is no assurance that these zones are the same as those at Maroon Cliffs.

Grain-size analysis was accomplished on 15 samples by leaching the cement from the sample in warm dilute hydrochloric acid and sieving the dried disaggregated residue on a ¼ø (¼ Wentworth grade) screen. The silt and clay fractions were then analyzed by pipette procedure (Krumbein and Pettijohn, 1938, p. 167) using a 0.002 molar solution of sodium pyrophosphate as a dispersing agent.

The results of these analyses are shown in Table I and in Figures 7 and 8, based on parameters defined by Folk (1954) as follows:

$$\text{Mean Size } M_Z = \frac{\phi16 + \phi50 + \phi84}{3}$$

Sorting (Inclusive Graphic Standard Deviation) O_I

$$O_I = \frac{\phi84 - \phi16}{4} + \frac{\phi95 - \phi5}{6.6}$$

Skewness (Inclusive Graphic Skewness) Sk_I

$$Sk_I = \frac{\phi16 + \phi84 - 2\phi50}{2(\phi84 - \phi16)} + \frac{\phi5 + \phi95 - 2\phi50}{2(\phi95 - \phi5)}$$

$$\text{Kurtosis } K_Z = \frac{\phi95 - \phi5}{2.44(\phi75 - \phi25)}$$

The sand-size detritus consists of quartz and orthoclase with minor amounts of microcline, chert, and sanidine. Grains larger than 0.1 mm. are typically moderately to well rounded with moderate sphericity and normally have frosted surfaces; they are uniformly covered with crescent-shaped percussion pits evidently derived from impact during wind transport. Grains in the finer grade-sizes tend to be much more angular and less spherical. The predominant coarse silt mode of the Pierce Canyon is attributed to eolian transport as indicated by (a) the uniform size, sorting, and lateral distribution through more than 15,000 square miles of flat terrain; (b) the median grain-size of 4.2ø–5.8ø which compares favorably with a median grain-size of 4.3ø–5.6ø for wind-blown loess deposits of Kansas (Swineford and Frye, 1951, p. 309); and (c) the percussion marks on the larger grains.

TABLE I. TEXTURAL ANALYSIS OF PIERCE CANYON DETRITUS

Phi Median Md_ϕ	*Mean size* ϕ M_Z	*Mean size mm.* M_Z	*Sorting* O_I	*Skewness* Sk_I	*Kurtosis* K_Z
5.0	5.3	.024	0.95	+0.53	1.30
4.3	4.3	.049	1.22	+ .16	1.64
4.7	4.7	.038	0.68	+ .30	2.82
5.2	5.5	.022	0.97	+ .59	1.63
5.0	5.4	.023	0.91	+ .58	1.32
5.0	5.4	.023	0.78	+ .68	0.69
4.8	5.2	.027	1.36	+ .47	0.86
4.7	4.9	.035	0.93	+ .73	1.60
5.1	5.2	.027	0.92	+ .38	2.80
4.4	4.2	.052	1.35	− .16	3.08
5.5	5.8	.018	1.56	+ .50	1.37
4.6	5.0	.031	0.83	+ .57	1.23
5.0	5.3	.024	0.83	+ .42	0.92
5.0	5.3	.024	0.89	+ .39	1.18
5.0	5.6	.021	1.47	+ .75	2.54

The Pierce Canyon redbeds contain only a small amount of clay. Inasmuch as the feldspar grains in this detritus are fresh and unaltered, except for a small amount of sericitization, the evidence suggests that the source of the detritus had little clay.

SEDIMENTARY STRUCTURES

Outcrop and thin-section examination shows that most of the detritus was deposited as very fine cross-laminae (Fig. 6D). Most of the cross-laminations are visible only in thin section. The larger cross-beds are more obvious, and their foreset beds range in length from a few millimeters to 4–5 feet. The smaller, more common, type of very fine cross-lamination originated on a rippled surface (Fig. 5).

The detritus must have been shifted continually by uniform and gentle currents, for elongate and platy minerals are well oriented with the longest dimension parallel with the bedding planes. Similarly, heavy-mineral placers of magnetite-ilmenite, leucoxene, apatite, tourmaline, zircon, and hematite-stained mud balls are arranged in perfect laminae, one or two grains thick, parallel with the cross-laminations. Graded bedding, which might indicate different settling

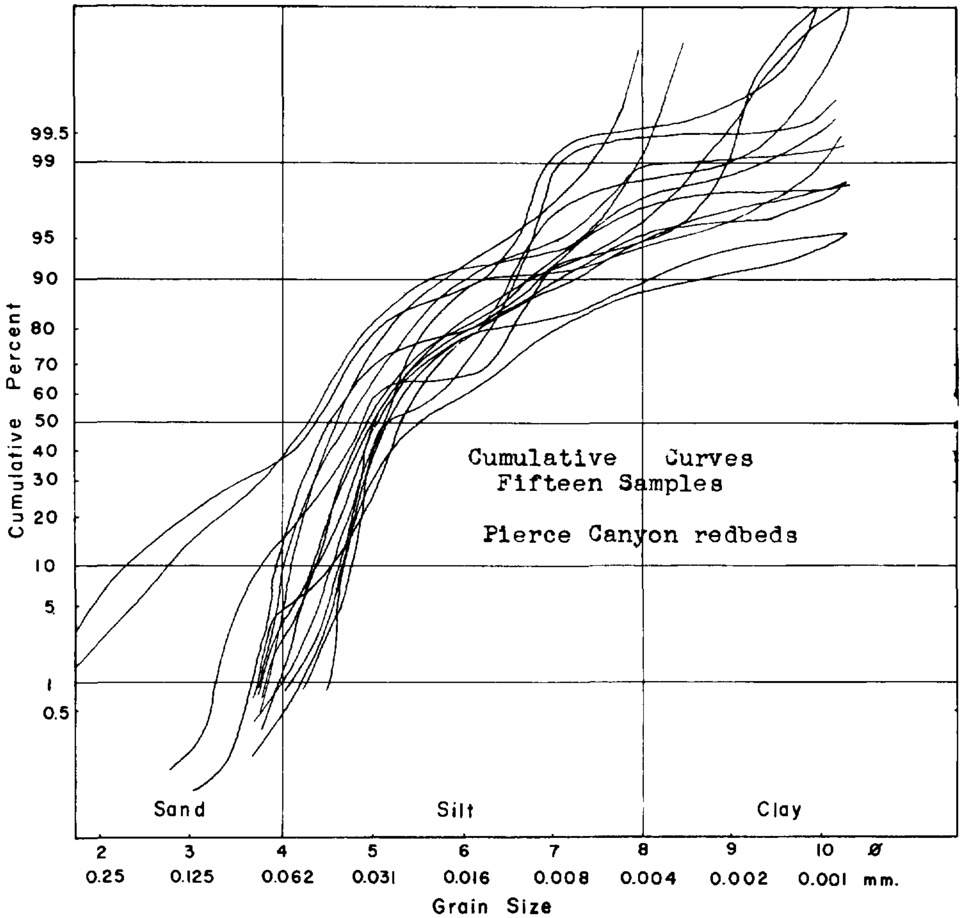


FIG. 7.—Distribution of 15 representative cumulative curves showing grain-size distribution of Pierce Canyon redbeds from Eddy County, New Mexico.

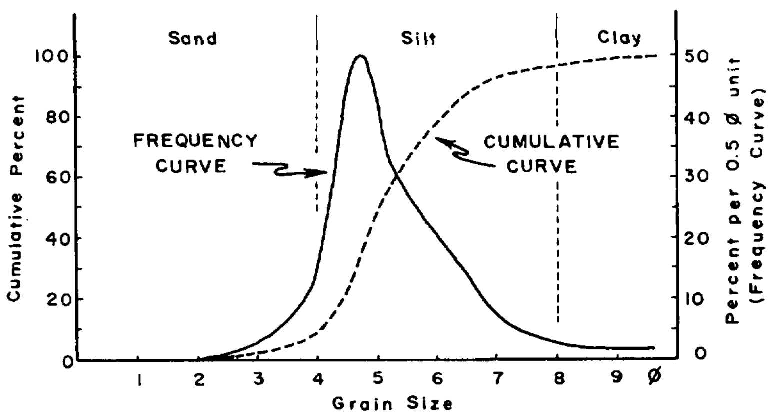


FIG. 8.—Summation of textural data from 15 representative samples of Pierce Canyon redbeds, Eddy County, New Mexico.

rates, is lacking. The small amount of clay in the detritus was aggregated by rolling during transport to form minute balls which were deposited with the heavy minerals in placers.

INTERPRETATION OF TRANSPORT

Two major transporting agents carried the Pierce Canyon detritus to the final depositional site. The first was the wind, which deflated the silt and sand as dust; the second was the water, which received the wind-blown detritus, re-sorted it with gentle currents and small waves, and deposited it finally almost grain by grain in finely laminated cross-beds.

DETRITAL MINERALS

The detrital minerals of the Pierce Canyon redbeds constitute a distinct and homogeneous assemblage, which is similar to the detrital-mineral assemblage of the Rustler Formation below and unlike that of the Santa Rosa Formation above. Outcrop and subsurface samples from the Delaware and Midland basins (including the Dewey Lake Formation), more than 200 miles apart, have almost identical mineral assemblages and texture.

Quartz.—Quartz constitutes 60–80 per cent of the detrital mineral content. The grains range in size from 0.005 to 0.7 mm. and have a mean diameter of 0.04 mm.

Although there are three distinctly different types of quartz in the Pierce Canyon redbeds, more than 99 per cent of the grains consist of a single crystal with straight or very slightly undulose extinction (Fig. 9B). Grains with composite crystallinity and (or) strongly undulose extinction occur only in traces. Euhedral dipyramidal quartz with embayed surfaces is equally scarce. Most of the grains contain a few discontinuous subparallel lines of vacuoles. About 20 per cent of the quartz grains contain mineral inclusions of euhedral apatite, tourmaline, zircon, and rutile needles in various amounts. Pale blue tourmaline, the most conspicuous microlite, occurs in about 10 per cent of the grains. Colorless euhedral zircon occurs in 5–10 per cent of the grains, and only a few grains contain rutile needles. There is no discernible relation between microlite types and grain-size.

Of the remaining 1 per cent, the composite quartz grains, with strongly undulose extinction, are smaller than 0.07 mm. Composite quartz occurs only in trace amounts, although it is uniformly distributed throughout the entire formation.

Another type of quartz occurs only in trace amounts and ranges in size from 0.03 to 0.09 mm. The grains are typically euhedral with slightly rounded corners and straight smooth surfaces, many of which are embayed. Vacuoles and euhedral apatite are the only inclusions.

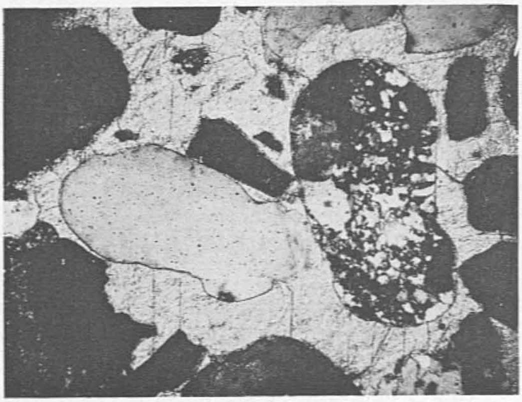
There seems to be a very real relation between sedimentary units and the type of quartz present, a relation similar to that described by Krynine (1940, p. 15), Folk (1961), and others, and illustrated in Figure 9. The writer disagrees with Blatt and Christie's (1963, p. 573–574) conclusion that it is useless to classify undulatory extinction in quartz, because the distribution of quartz types in many stratigraphic units of different areas changes across formational boundaries; such changes in distribution also occur here in the Pierce Canyon redbeds. In fact, the undulatory character of the quartz together with the microlite content have been found to be very useful for stratigraphic zonation in many places; this method commonly is far superior to heavy-mineral zonation which is based on only a fractional percentage of the detritus.

Orthoclase.—Orthoclase grains range in size from 0.009 to 0.6 mm. with a mean grain-size of 0.04 mm. They typically constitute 20–30 per cent of the detritus. Like the quartz, orthoclase in the very fine sand and silt classes is typically subangular with moderate to low sphericity. The larger grains have a higher sphericity and are better rounded. Unlike the quartz, the frosted surfaces of the grains of medium- and coarse-sand-size orthoclase are lined by cleavage. Authigenic overgrowths of orthoclase, which formed in the Pierce Canyon redbeds, are rare but may explain the fresh surfaces on the larger grains. A very few microlites of euhedral tourmaline, zircon, apatite, and rutile are present in the orthoclase and are smaller but otherwise similar to the microlites in the quartz. Nearly all the orthoclase is clear and unaltered; less than 5 per cent contains vacuoles along cleavage planes.

Microcline.—Microcline constitutes less than 5 per cent of the total detritus and is similar in size-distribution to orthoclase; it typically occurs as subrounded to well-rounded grains with moderate to high sphericity. The surfaces of the larger grains are frosted and, like the orthoclase, the in-

A

"Authigenic", euhedral, dipyramidal quartz grains a common constituent in the redbeds of the Rustler Formation. Notice the large void (black) spaces within the crystals which are partially filled with hematite stained clay.

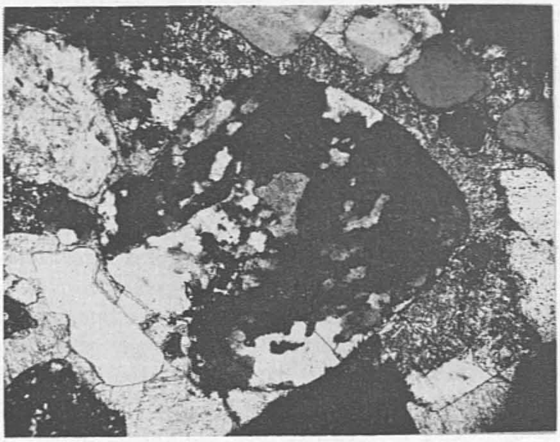


B

"Plutonic" igneous quartz grain (left), a single crystal with straight extinction and a few small vacuoles and microlites

Chert grain (right) grossly composite with abundant vacuoles but no microlites

The intergranular void space has been filled with sparry calcite.



C

"Metamorphic" quartz grain, a common constituent in the Santa Rosa Sandstone which shows a grossly composite and strongly undulose habit.

FIG. 9 (A, B, C).—Obvious quartz types that can be useful in distinguishing Rustler, Pierce Canyon, and Santa Rosa redbeds. Classification of types based on descriptions by Folk (1961).

terior is unaltered. Thin overgrowths are present on a few grains. Vacuoles are present in a very few grains along the cleavage planes. Microlites of euhedral tourmaline, zircon, and apatite are rare. The similarity between the inclusions in the microcline and the orthoclase suggests that both minerals were derived from the same source.

Sanidine.—Sanidine grains range in size from 0.07 to 0.3 mm., the majority of the grains having a long dimension of 0.12–0.14 mm. The grains are subrounded with moderate to high sphericity and their surfaces are corroded. In some siltstone lenses, sanidine constitutes as much as 35 per cent of the detritus; in most samples it occurs only as traces. The hollow and zoned character of the grains has been illustrated and described by Miller (1955b).

The holes or cavities in the sanidine grains probably formed after deposition. Many of the grains now are only fragile shells that would have been destroyed during transport. None of the holes are coated with hematite, although a few do contain calcite.

Neither the Santa Rosa Sandstone above nor the Rustler evaporites and redbeds below the Pierce Canyon contain hollow sanidine. The presence of hollow sanidine grains in the Pierce Canyon redbeds of the Delaware basin, the Dewey Lake redbeds of the Midland basin, and the Quartermaster redbeds farther north in the Texas Panhandle suggests that the regions where these three units are present received detritus from the same source.

Plagioclase.—Plagioclase constitutes less than 1 per cent of the total detritus. All of the grains are smaller than 0.13 mm. and average about 0.04 mm. in length. They are typically subangular to subrounded. Both the exterior and interior of the grains are unaltered, but abraded edges and small embayments are common. Vacuoles are abundant; most of them are grouped along cleavage planes. More randomly scattered vacuoles are present in plagioclase than in either microcline or orthoclase. Microlites appear to be common in all the grains, but none could be identified.

Chert.—Chert constitutes much less than 1 per cent of the detritus and occurs as well-rounded, slightly elongate grains, sparsely and randomly distributed through the formation (Fig. 9b). The length of the grains ranges from 0.03 to 0.06 mm. Grain surfaces are pitted as the result of impact with other grains during transport. The presence of chert is significant because it indicates that at least a small part of the Pierce Canyon detritus was derived from a sedimentary source.

Calcite.—Detrital calcite is not a common constituent of the formation, but in a few places it constitutes as much as 3 per cent of the detritus. The grains, composed of clear sparry crystals about 0.01 mm. long, have a median diameter of about 0.03 mm. They are moderately rounded and have a moderate to high sphericity.

Muscovite.—Muscovite is a widespread constituent in the formation but comprises less than 1 per cent of the detritus. Flakes of muscovite as much as 0.8 mm. in length, but averaging 0.07 mm., are concentrated in fine silt and clay laminae. The flakes are elliptical with well-rounded edges, which probably resulted from eolian transport or from abrasion in the gentle currents of the Pierce Canyon sea.

Biotite.—Biotite is approximately twice as abundant as muscovite. Brown, pale green, and colorless (leached) biotite types constitute about 1 per cent of the detritus. Brown biotite is much more abundant than the green or colorless varieties. Dark brown euhedral biotite (pseudo-hexagonal flakes) with a long diameter of 0.06 mm. was detected in a few samples and is probably of volcanic origin. Most of the biotite is at least slightly rounded and a few flakes occur as moderately thick packets.

Chlorite.—Rare flakes of blue-green chlorite about 0.08 mm. long are randomly dispersed in the fine detritus. They may have been derived from small exposures of schist or gneiss associated with granite, but more probably were formed as a result of post-depositional alteration of other ferromagnesian minerals.

Metamorphic-rock fragments.—Irregularly shaped rock fragments with schistose or slaty structure constitute less than 1 per cent of the detritus. The fragments are small, about 0.04 mm. in diameter, and are randomly dispersed with the other detritus. The complete mineral content of these fragments could not be determined.

Glauconite.—Glauconite is rare and occurs as well-rounded grains with moderate sphericity randomly distributed in the formation as pale green, silt-size grains 0.03–0.04 mm. long.

Magnetite-ilmenite.—Magnetite and ilmenite are the most abundant heavy minerals in the Pierce Canyon redbeds. Heavy-mineral separation indicates that about half the grains are magnetite, because they are strongly magnetic, and half are ilmenite. Magnetite-ilmenite, with a mean grain-size of 0.03 mm., constitutes 1–3 per cent of the detritus, occurring as well-rounded, shiny, black grains, with a moderate to high sphericity.

Magnetite-ilmenite is abundant in the heavy-mineral placers throughout the red oxidized parts of the rock; it occurs only in trace amounts in the gray-green reduced spots or beds, as described by Miller and Folk (1955).

Leucoxene.—Leucoxene, one of the most abundant heavy minerals, forms about 1 per cent of the detritus. It occurs as well-rounded, slightly elongate grains with high sphericity, which are readily detectable under reflected light because of their dull white color. The grains range in diameter from 0.02 to 0.05 mm. and have a mean long diameter of 0.03 mm.

Leucoxene is a stable heavy mineral which usually results from the alteration of ilmenite; however, there are no partly altered ilmenite grains with leucoxene rims present. Hence, the leucoxene grains probably are still in their first sedimentary cycle; the alteration from ilmenite probably took place at the source or during transport, but not in the Pierce Canyon redbeds.

Tourmaline.—Subhedral and euhedral, blue, pale pink, and colorless tourmaline grains are less common than leucoxene, composing less than 1 per cent of the detritus. Most of the grains are pale blue. The tourmaline ranges in size to a maximum of about 0.6 mm., but typically the longest dimension is 0.03–0.04 mm. Most of the crystals are slightly rounded, and a few broken crystals are well rounded. Elongate rectangular vacuoles and scattered rutile needles are the only inclusions.

The euhedral tourmaline crystals are believed to have been derived from the same source as the quartz because of the similarity between these grains and the tourmaline inclusions in the quartz. The well-rounded, broken crystals of tourmaline suggest a different source or a reworked material from older sediments.

Zircon.—Zircon, slightly less abundant than tourmaline, occurs as euhedral crystals with slightly rounded corners and an average grain diameter of 0.03 mm. Scarce grains, 0.2–0.4 mm. long with well-rounded edges, were, like the tourmaline, probably derived from some other source or underwent longer abrasion. The zircon is colorless.

Apatite.—The fact that euhedral apatite grains are abnormally abundant suggests that the apatite, the abundant biotite, and the embayed quartz crystals (grains) may have been derived from a volcanic source. The crystals are slightly rounded and most of the grains are about 0.03 mm. long. In a few samples the apatite content equals that of the tourmaline or zircon.

Garnet.—The diameter of the garnet ranges from 0.02 to 0.03 mm. The grains are typically well rounded and have corroded or pitted surfaces. Most of the grains are colorless or pale pink. Garnet is a rare constituent in the heavy-mineral placers.

Rutile.—The scarce rutile grains are about 0.02 mm. long and occur as pale yellow, near-perfect squares with slightly rounded corners.

Fossils.—Only two fossils were recovered from this detritus, both of which were unidentifiable broken fragments about 0.03 mm. long consisting of a simple, perforate calcite or phosphatic plate. The perforations are abundant, randomly but closely spaced, and circular. The intervening lattice is featureless.

Illite.—Ten fresh clay samples from cores obtained from U.S. Potash Company's mine shaft No. 3 (SE.¼, sec. 13, T. 20 S., R. 30 E.), Eddy County, New Mexico, were analyzed by X-ray diffraction. All the samples were identified as illite.

The illite is distributed homogeneously in thin beds throughout the Pierce Canyon redbeds and constitutes only 4 per cent of the detritus. There are relatively few beds of claystone, and these are only a few inches thick. The lateral distribution of illite also is homogeneous. Most of the illite is stained completely with hematite, with the result that it is darker red than the coarser-grained material. All of the illite seems to be absorbent; it tends to swell to the point of disaggregation when water is added.

AUTHIGENIC MINERALS

Gypsum.—Clear fibrous gypsum is the predominant cement in the Pierce Canyon redbeds. It forms 10–20 per cent of the rock, occurring as subparallel, mosaic patches of fibrous crystals 0.01–0.03 mm. long. The fact that nearly all the gypsum is clear and free of inclusions suggests that the crystals were precipitated in the intergranular void space of the sediment after burial.

Calcite cement also occurs in the redbeds. There is no manifest order of precipitation for the calcite and gypsum, but both formed after the hematite. This is shown clearly by the fact that all the quartz grains are coated with hematite, but the gypsum and calcite overlie the hematite and are not themselves stained with it.

Veins of gypsum (Fig. 4), which penetrated the formation through joints and fractures during the Cenozoic as the result of subsurface solution and slump, contributed additional cement to the lower half of the Pierce Canyon redbeds. In many places the gypsum has displaced the detrital grains (Fig. 10).

Calcite.—Clear sparry calcite cement constitutes approximately 5 per cent of the volume of the rock (Fig. 9B). In most of the beds the calcite content is less than 1 per cent, but in a few it may be as much as 30 per cent. It occurs as individual crystalline patches 0.01–0.02 mm. long, in many places in direct contact with the hematite-stained grains.

Sand-crystal calcite is present in a few localized zones on the outcrops. These zones are cemented completely within a mosaic of individual crystals that are in optical continuity through an area of about 1 square centimeter. Each crystal encloses hundreds of sand grains. In most places the crystals seem to grade or feather into each other. None of the sand-crystal zones contains gypsum.

Sand-crystal calcite is most abundant in the Dewey Lake outcrops on the banks of Champion Creek near Colorado City, Texas; it is less abundant on the higher outcrops such as Maroon Cliffs. Only one subsurface sample of sand-crystal calcite was obtained. Sand-crystals form as a result of recrystallization that takes place in regions where ground or surface water dissolves and reprecipitates the calcite at about the same slow rate—removing it from one part of the crystal and precipitating it at another.

The occurrence of calcite is random in the lower part of the Pierce Canyon redbeds, where it is much less abundant than gypsum. There is a marked change, however, in the uppermost 100 feet of section at the U.S. Potash Company mine shaft No. 3 (SE.¼, sec. 13, T. 20 S., R. 30 E.), Eddy County, New Mexico, where calcite is the predominant cement between the depths of 40 feet (the upper contact) and 140 feet. The increase in calcite corresponds to an abrupt increase in the sanidine content in this one core. No increase of calcite cement or sanidine was detected in other stratigraphic sections in the vicinity.

Anhydrite.—Anhydrite constitutes less than 1 per cent of this formation and in most places occurs only in trace amounts. It occurs most commonly as rectangular crystals about 0.02 mm. long in mosaic patches 0.05 mm. square, adjacent to or completely surrounded by fibrous gypsum. The clear crystals are in direct contact with the hematite-stained grains in a few places, but none contain hematite.

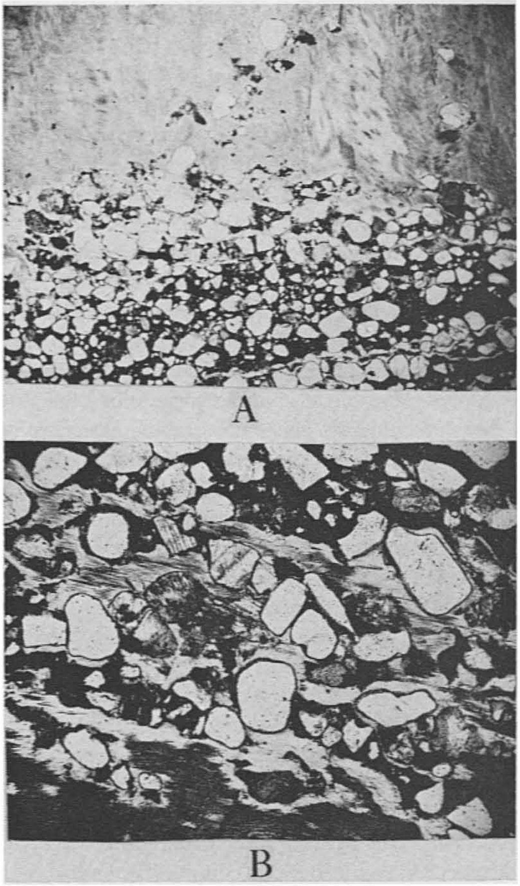


FIG. 10 (A, B).—Thin sections of gypsum veins disrupting bedding and displacing grains of Pierce Canyon redbeds. All fibrous-appearing material in photographs is gypsum. Detrital grains are predominantly quartz and feldspar.

Dolomite.—Dolomite occurs only in trace amounts in a few of the samples. The crystals are typically 0.02–0.03 mm. long; in most places they exhibit a rhombic zonation.

Hematite.—The red color of the Pierce Canyon results from a thin hematite coating on the surface of the sand and silt grains and from disseminated hematite-stained clay. Hematite, constituting less than 5 per cent of the rock, was deposited as a chemical precipitate that formed very soon after deposition and prior to cementation of the detritus by calcite and gypsum. The hematite stain is about the same thickness on all parts of the grains, including the sharp corners.

Even the well-rounded and frosted quartz and orthoclase grains have hematite-stained surfaces, indicating that precipitation of hematite occurred after transport.

This type of hematite accumulation is described from recent sediments by Walker (1965) as post-depositional but pre-consolidation (*in situ*).

As evidenced by the abundance of magnetite-ilmenite and probably part of the abnormally high biotite content, the source area of this detritus was rich in iron-bearing minerals. An igneous source that contains large amounts of magnetite-ilmenite and biotite normally contains other iron-bearing minerals such as hornblende and pyroxene, but these are not present in the Pierce Canyon redbeds. Hence, a large part of the iron that now occurs as hematite probably originated from the destruction of the hornblende and pyroxene and part of the magnetite-ilmenite. Inasmuch as hornblende and pyroxene are unstable in oxidizing environments, it is likely that they were destroyed soon after burial.

Biotite.—Biotite occurs as an authigenic mineral in a few of the spheroidal reduction spots. The flakes are concentrated in a spheroidal zone between the crystals of fibrous gypsum cement near the center of the reduced spot. The dark brown flakes are extremely thin and have a maximum length of about 0.05 mm. The origin of this mineral has been described by Miller (1957).

INTERPRETATION OF POST-DEPOSITIONAL ALTERATION

From the data at hand, it appears that the Pierce Canyon sediments were deposited in a mildly oxidizing and slightly basic saline environment similar to that of normal marine water (James, 1954, p. 240). Hematite very probably was the first chemical precipitate to form after deposition (Walker, 1965; Van Houten, 1948; ZoBell, 1946). Subsequent deposition buried the loosely packed, hematite-stained detritus which was saturated with sea water. The interior of the sanidine grains was then dissolved after precipitation of the hematite and before precipitation of the gypsum and calcite. There is no manifest order of crystallization for the predominant gypsum and the lesser amount of calcite cement; yet, inasmuch as none of the hollow sanidine grains contains hematite and a few do contain calcite or gypsum, both calcite and gypsum must have been precipitated after the cavities had formed in the sanidine.

Gray-green reduction zones.—Numerous gray-green reduction spots and zones in the Pierce Canyon redbeds range in size from microscopic specks to entire beds an inch or two thick that extend for more than a quarter of a mile.

The presence of more gray-green reduction zones in outcrops than in the subsurface suggests that at least part of the reduction is the result of surface leaching (Krumbein and Garrels, 1952). There are more gray-green reduction zones in the sandy beds than in the clayey beds. Some of these reduction zones are the result of leaching by ground water; other smaller, nearly spherical, reduction spots may have resulted from the oxidation of local accumulations of organic matter (Miller, 1957).

Chemical analyses.—Two cores of the Pierce Canyon Formation from U.S. Potash Company shaft No. 3 (NE.¼, SE.¼, sec. 13, T. 20 S., R. 30 E.), Eddy County, New Mexico, depth 47–52 feet, were analyzed by the Texas Bureau of Economic Geology for the iron content. Sample No. 1 is a typical hematite-stained red sample, and sample No. 2 is a leached green-gray sample without visible hematite. The results follow:

	Sample No. 1 (red)	*Sample No. 2 (white)*
SiO_2	59.01%	76.52%
Fe_2O_3	5.84	1.87
CaO	4.57	0.36
MgO	5.19	0.76
Na_2O	1.14	1.33
K_2O	5.32	6.52
S	0.0x	—
CO_2	5.22	—

INTERPRETATION OF PETROGRAPHIC DATA

Location and composition of source.—The petrographic study of the Pierce Canyon detritus suggests that this is a first-cycle sediment, derived principally from a single, plutonic igneous source with a composition close to that of granite. A granitic source area is suggested by the persistent abundance and homogeneous distribution of colorless, strain-free quartz and the virtual lack of strained or composite grains. All of the quartz contains about the same type and amount of microlites and vacuoles, which would not be true if the detritus had been derived from reworked older sediments. The notable absence of smoky and milky quartz, the relative abundance of orthoclase, and the extremely low microcline content further suggest that the detritus was derived from a granitic core or basement rock and not from part of the outer peripheral zones of an igneous body where hydrothermal veins and pegmatites commonly are more abundant. Most of the accessory minerals probably were derived from the same source, as indicated by the persistent ratios of several minerals to quartz, including magnetite-ilmenite, leucoxene, and pale blue tourmaline. Only a few minerals (*e.g.*, sanidine) have a range in abundance that is independent of the persistent quartz and orthoclase.

The location of the granitic source was at the south, very likely in northern Coahuila, Mexico, south of the Marathon fold belt (Fig. 11). P. B. King (1942, p. 731) has speculated on the presence of such a source south of the Delaware basin where pre-Permian mountains and the Marathon fold belt were eroded deeply during the Permian. Moreover, middle and upper Guadalupe beds in the Midland basin contain thin layers of bentonite and volcanic rocks that thicken southward, indicating a volcanic source in that direction.

Plutonic igneous rocks of Permian age have been reported from northern Mexico, 250 miles south of the Delaware basin, by Kellum *et al.* (1936), Kelly (1936), Böse (1923), R. E. King (1934), and more recently by several graduate students at the University of Texas. The published descriptions show that granite or granodiorite was intruded into Permian sedimentary rocks that are now overlain by unmetamorphosed Cretaceous rocks. Kelly (1936, p. 1021) has stated that the granodiorite at Las Delicias and Coyote Ranch in northern Coahuila has caused "exomorphism" of the Permian rocks, whereas the Cretaceous rocks which overlie the igneous body are separated from it by "red gritty material" and are not metamorphosed. He suggested (p. 1021) that the intrusion occurred shortly after folding as part of an orogeny in the late Paleozoic. Kellum *et al.* (1936, Table I) have described the Permian igneous rocks at Las Delicias as lavas and fine-grained granite. They stated that hornblende granite, quartz porphyry, and fine-grained diorite are overlain unconformably by Cretaceous rocks and that the porphyry complex probably represents the marginal phase of a granite batholith. A. F. Buddington identified the igneous rock at Coyote Ranch for Kellum *et al.* (1936, p. 1020) and, from thin sections, described it as a biotite-hornblende granodiorite composed of andesine, quartz, orthoclase, hornblende, and biotite, with magnetite and apatite as accessory minerals. Whether these rocks antedate the deposition of the Pierce Canyon redbeds, or *vice versa*, is a question that may never be decided completely until much more work has been done in Mexico.

Less than 2 per cent of the Pierce Canyon detritus was derived from eruptive or extruded volcanic rocks. This conclusion is suggested by the sanidine and supported by the abnormally high apatite and biotite content and the trace amounts of volcanic quartz. The volcanic source probably was nearer the site of deposition than the granitic source, perhaps in the Marathon fold belt, where chemically unstable volcanic minerals have undergone little alteration or abrasion. The presence of sanidine especially suggests either a nearby trachyte or dacite source or contributions from ash falls.

Metamorphic rocks contributed less than 2 per cent to the detritus, and sedimentary rocks less than 1 per cent of the material whose source is identifiable. The metamorphic contributions include strained composite quartz, schist, and phyllite fragments. Sedimentary contributions include a trace amount of chert from outside the basin and reworked sparry calcite from inside the basin of deposition.

Climate.—Climatic conditions prior to and during deposition of the Pierce Canyon redbeds probably were warm and arid as suggested by the thickness and distribution of salt, gypsum, anhydrite, and other evaporites of the underlying Rustler Formation, as well as by the gypsum and calcite cement of the Pierce Canyon redbeds.

Aridity at the source is indicated by the lack of chemical alteration of the less stable minerals: plagioclase, microcline, and orthoclase. Nearly all the orthoclase, regardless of size, is brilliantly fresh.

Transport.—Most of the detritus was transported to the basin of deposition by wind. A smaller part was carried by water. Eolian transportation is suggested by the uniform distribution of silt and very fine sand throughout the Pierce Canyon sediments through more than 15,000 square miles in west Texas and southeastern New Mexico. Were it not for the presence of intricate

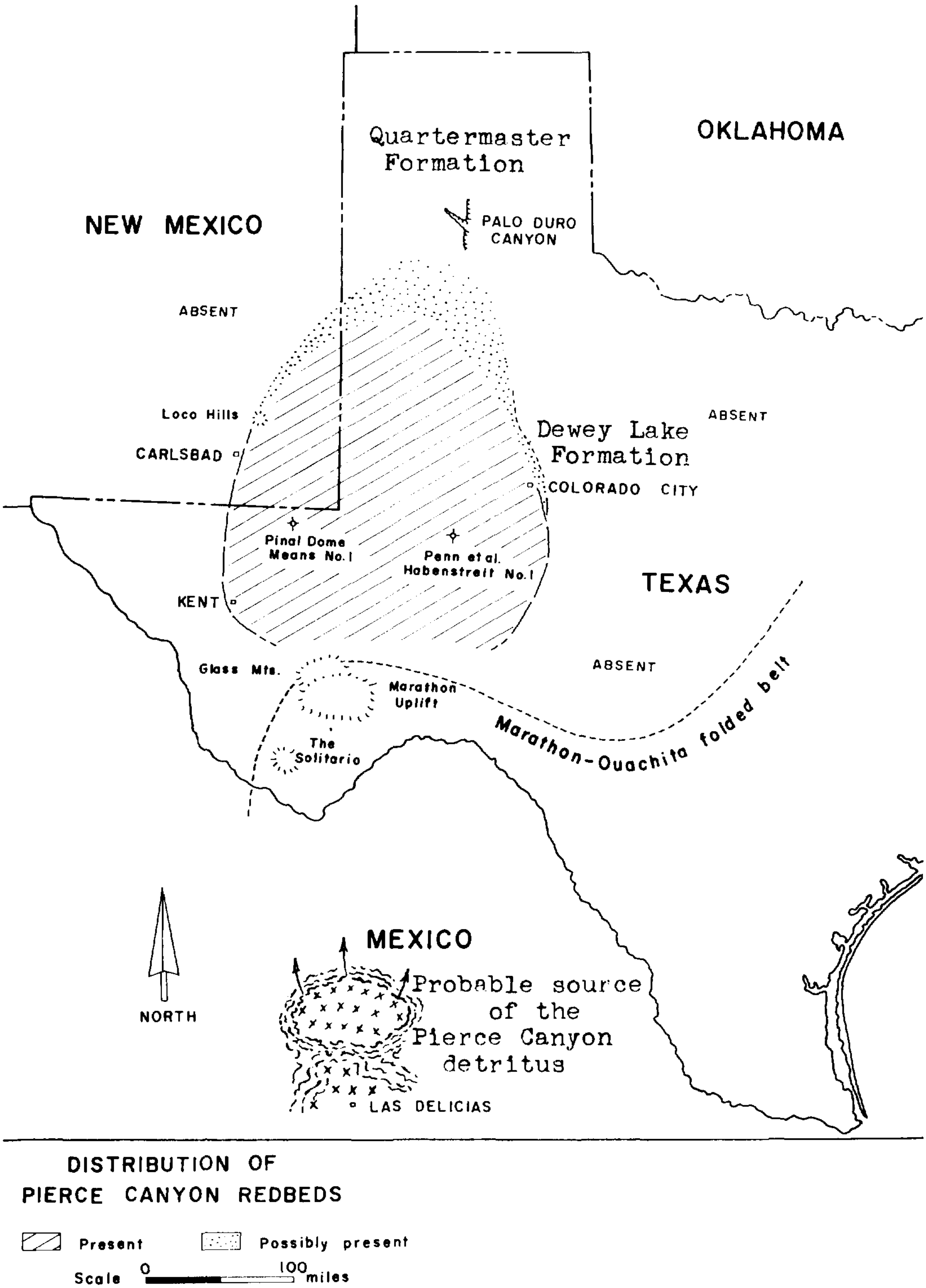


FIG. 11.—Distribution and probable source area of Pierce Canyon redbeds.

cross-bedding and ripple-marks, which indicate subaqueous deposition, the siltstone would have an appearance much like that of a typical Mid-Continent loess deposit.

Environment of deposition.—The Pierce Canyon sediments were deposited in a broad, shallow, saline body of water which covered at least the eastern part of the Delaware basin. The water extended north at least to Loco Hills in northeastern Eddy County, New Mexico, and eastward across the Central Basin platform into the southern half of the Midland basin (Fig. 11).

The saline environment of the Pierce Canyon "sea" and the barren mud flats adjoining it probably were not conducive to life or well suited to the preservation of animal or plant remains. No identifiable fossils, casts, molds, or other indications of organic life have been reported from this formation.

Comparison with Other Permian and Triassic Redbeds

Permian Rustler Formation

The underlying redbeds in the Permian Rustler Formation consist of 60–95 per cent clay and 5–40 per cent silt and sand. This is a subarkose or orthoquartzite (Fig. 11) as defined by Folk (1961). The detrital quartz grains are practically identical with those in the Pierce Canyon redbeds. About 90 per cent of the quartz grains are in fact authigenic, consisting of dipyramidal crystals about 0.22 mm. long (Fig. 9A). The crystals are colorless, although a few contain pale red, cloudy inclusions of hematite-stained clay; they also contain a few randomly dispersed colorless vacuoles. All of the crystals have an adamantine luster, the corners and edges are sharp, and none show abrasion. The crystals probably formed in the unconsolidated muds. As these red claystone and siltstone beds are eroded (as in the Pecos River Valley), the quartz crystals accumulate in the alluvium where they are known as "Pecos River diamonds."

Orthoclase constitutes about 5 per cent of the silt and sand fractions as subrounded grains with moderate sphericity; its median grain-size is 0.04 to 0.05 mm. About 99 per cent of the orthoclase grains have been decomposed slightly by illitization or sericitization along the cleavage planes (Folk, 1955); only about 1 per cent is completely fresh. The grains are more altered than the orthoclase in the Pierce Canyon redbeds and probably have been reworked within the basin of deposition. Some of the orthoclase may be authigenic.

Less than 1 per cent of the detritus is microcline, which has the same physical characteristics as the orthoclase. Plagioclase occurs only in trace amounts and has a mean grain-size of about 0.01 mm.

Muscovite and biotite, common in these redbeds, occur most commonly as fresh elongate flakes about 0.04 mm. in length. Muscovite is more abundant than biotite, and together they form about 1 per cent of the detritus.

Grains of calcite are present in trace amounts in a few places. The particles have a mean grain-size of about 0.03 mm. and consist of a mosaic of clear crystals about 0.005 mm. in diameter.

Fibrous gypsum occurs only as a trace. The grains are well rounded and about 0.07 mm. in diameter.

The only heavy minerals in the red claystone of the Rustler Formation are a few rounded grains of zircon or tourmaline.

Most of the redbeds in the Rustler are cemented and veined with colorless, fibrous, satin spar gypsum. Sparry calcite cement is much less abundant than gypsum and together they are less than 5 per cent of the rock. Gypsum and calcite also occur as pseudomorphs after halite.

The lower part of the Rustler Formation contains a few silty and sandy limestone beds, which are not directly associated with redbeds. The detrital material in the limestone is 30–40 per cent silt and fine sand, and 60–70 per cent sparry calcite. Of the detrital mineral assemblage in the limestone, 80–90 per cent is colorless, strain-free igneous quartz, 2–4 per cent orthoclase, 1 per cent microcline, and 2 per cent muscovite and biotite. There are trace amounts of plagioclase. This assemblage is, with the exception of a few unstable minerals like calcite and gypsum, almost identical with that of the Rustler redbeds.

Permian Yates Sandstone

The Permian Yates Sandstone has been described most recently by Mear (1963) and Tait *et al.* (1962). A problem has arisen regarding whether or not the large, rounded quartz grains in the Pierce Canyon could have been derived from the Yates. Mineralogical differences show that the rounded and frosted sand grains of the Pierce Canyon redbeds and those of the Yates Sandstone have different properties and probably were derived from different sources.

Approximately 50–60 per cent of the Yates Sandstone is detrital quartz; of this, about 80 per cent is colorless, with uniform extinction. Most of the grains contain a moderate number of vacuoles, part of which are filled with liquid. Rutile needles are the most abundant microlites and occur in about 10 per cent of the quartz grains. Tourmaline microlites are rare. About 15 per cent of the quartz grains consist of multiple (2–4) crystals with sweeping (undulose) extinction; almost all are devoid of microlites. About 5 per cent of the quartz grains are grossly composite, made up of a mosaic of smaller crystals with parallel elongation and sweeping extinction. If the quartz grains from the Yates Sandstone had been reworked and deposited with the Pierce Canyon sediments, a considerable amount of the quartz in the Pierce Canyon detritus would be composite with undulose extinction. Because only a very few grains of this type are present in the Pierce Canyon redbeds, the reworking hypothesis seems unlikely.

The Yates Sandstone contains 5–7 per cent chert, whereas only trace amounts of chert occur in the Pierce Canyon redbeds.

About 20 per cent of the Yates sand fraction is feldspar (orthoclase, microcline, and plagioclase); practically all of it has been at least partly decomposed. Almost all of the feldspar in the Pierce Canyon redbeds is brilliantly fresh; it could not have been derived from the altered feldspar of the Yates Sandstone.

Judging from the differences in quartz types, chert content, and degree of alteration of the feldspars, the Yates Sandstone probably did not contribute any significant quantity of material to the Pierce Canyon redbeds.

SANTA ROSA SANDSTONE

The redbeds of the Upper Triassic were not derived from the same source as the Pierce Canyon redbeds as indicated by the differences in the detrital minerals. In addition, the degree of alteration of the minerals suggests that the climate was more humid during Late Triassic than during Pierce Canyon time. These mineralogic and alteration differences are conspicuous in thin section; hence, they provide a practical means for differentiating the Upper Triassic redbeds from the Pierce Canyon redbeds or older Permian rocks (Fig. 12).

The Santa Rosa Sandstone is a feldspathic subgraywacke (Folk, 1961) consisting of 50–70 per cent quartz. About 10 per cent of the quartz is composite (Fig. 9C) with strongly undulose extinction. About 5 per cent of the quartz is milky or white because of abundant vacuoles, some of which are filled with liquid. Colorless, plutonic igneous quartz grains, containing a moderate number of vacuoles, abundant rutile needles, and sparse tourmaline and zircon microlites, make up the remaining 85 per cent. Commonly the composite grains with undulose extinction are smaller than the grains with single crystals, suggesting derivation from different sources. Almost all of the sand-size quartz was severely abraded during prolonged transport, as indicated by the moderately to well-rounded shapes and frosted surfaces of the grains.

Approximately 10 per cent of the detritus is orthoclase, about half of which is colorless and fresh. The rest of the orthoclase shows various stages of bubbly alteration (Folk, 1955, p. 356–357) and slight to intense sericitization. Microcline, which constitutes about 2 per cent of the detritus, has the same degree of alteration as the orthoclase. About 1 per cent of the detritus is plagioclase, which occurs only as small grains approximately half the size of the orthoclase grains. Almost all the plagioclase is altered by sericitization. Green (1954, p. 119, 143) also has reported that most of the feldspar in the Santa Rosa is altered or weathered.

Chert is common in the Santa Rosa Sandstone and constitutes 5–25 per cent of the detritus. The grains are typically well rounded and elongate; they probably were derived from older sedimentary rocks.

Muscovite, biotite, and chlorite are abundant in the Santa Rosa Sandstone, but altogether they constitute only about 1 per cent of the detritus. The mica is most abundant in the silty beds, where the majority of flakes are oriented parallel with the bedding planes. Muscovite and biotite are equally abundant in the Santa Rosa Sandstone. In the Pierce Canyon redbeds, the biotite content is approximately twice that of the muscovite. Most of the Santa Rosa mica is fresh, but many of the flakes have been rounded by abrasion.

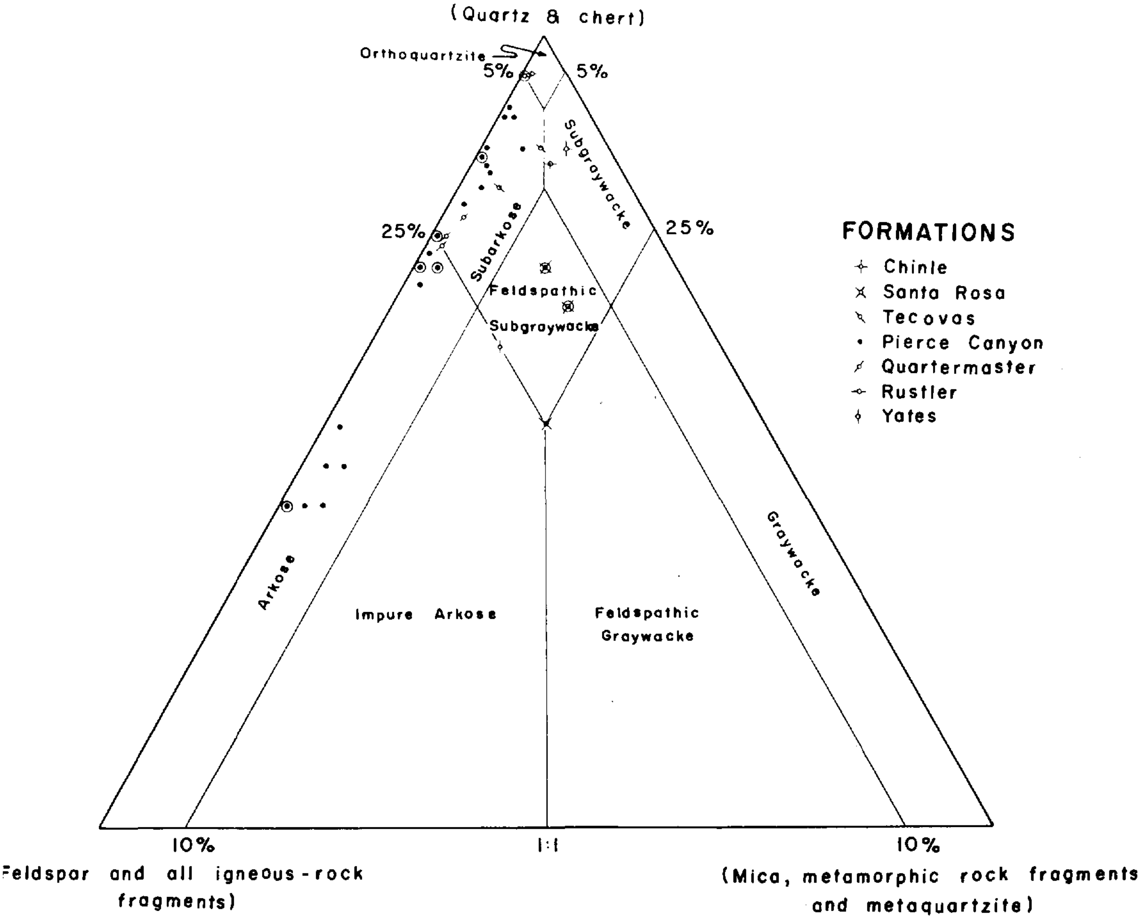


FIG. 12.—Rock composition diagram (after Folk, 1961); each vertex represents 100 per cent; corresponding base represents 0 per cent. Double circles indicate two samples with same composition.

Approximately 10 per cent of the detritus consists of rock fragments, which include metaquartzite and mineral aggregates with schistose or slaty structure. In most of the fragments, the minerals are elongate and subparallel. All of these fragments probably were derived from the same source, an interpretation supported by the composite, strongly undulose quartz; together they suggest that at least 10–15 per cent of the Santa Rosa was derived from metamorphic rocks.

Magnetite-ilmenite is the most abundant heavy mineral in the red, hematite-stained part of the Santa Rosa Sandstone. Light gray or gray-green beds are practically devoid of magnetite-ilmenite, very probably because it was dissolved during diagenesis. Almost all of the grains are well rounded and fresh, although a few have been partly altered to red iron oxide, probably hematite, in those cases where leaching was not complete. Leucoxene is abundant and occurs as slightly elongate, rounded grains, presumably as an alteration product of ilmenite. Zircon and tourmaline also are common. Garnet and rutile are the least abundant of all the heavy minerals. Sidwell (1945, p. 50–54) has reported essentially the same heavy mineral assemblage in the Santa Rosa Sandstone from northeastern New Mexico and the Texas Panhandle.

In most places the Santa Rosa Sandstone is cemented with sparry calcite. Authigenic quartz also is common but is much less abundant than calcite. Some silica was precipitated as thin, colorless overgrowths on the quartz grains. The overgrowths are separated from the detrital grains by bubbles and flakes of hematite which outline the older abraded surface. Mosaics of interlocking quartz crystals (overgrowths) are common. No quartz overgrowths were detected in the Pierce Canyon redbeds.

The chief mineralogic differences between the Santa Rosa Sandstone and the Pierce Canyon redbeds that may be observed in practically any sample containing silt and sand-size material are the following.

1. The Santa Rosa Sandstone generally is coarser grained and contains 10–15 per cent metamorphic rock fragments and composite, strongly undulose quartz, whereas the Pierce Canyon contains less than 2 per cent of these constituents.

2. White or milky vein-quartz with abundant vacuoles constitutes about 5 per cent of the Santa Rosa detritus; this type of quartz occurs only in trace amounts in the Pierce Canyon redbeds.

3. The Santa Rosa Sandstone contains 5–25 per cent of well-rounded chert. The Pierce Canyon redbeds contain only trace amounts of chert.

4. The total feldspar content of the Santa Rosa Sandstone is about 10 per cent of the detritus, whereas it typically ranges from 25 to 30 per cent in the Pierce Canyon redbeds.

5. Practically all the feldspar in the Pierce Canyon redbeds is fresh (unaltered); about half of the feldspar in the Santa Rosa Sandstone shows a moderate amount of alteration.

6. Almost all the Pierce Canyon redbeds contain discernible hollow sanidine; no sanidine has been detected in the Santa Rosa Sandstone.

7. Quartz grains with overgrowths of authigenic silica are common in the Santa Rosa Sandstone. The quartz grains in the Pierce Canyon redbeds do not have overgrowths.

8. The Pierce Canyon redbeds are cemented predominantly by gypsum with lesser amounts of calcite and (rarely) anhydrite. The predominant mineral cement in the Santa Rosa Sandstone is calcite with lesser amounts of quartz.

These mineralogic differences show that the Pierce Canyon and Santa Rosa sediments were derived from different sources. Adams (1929, p. 1050) has suggested that the Santa Rosa Sandstone, like the other sediments in the Dockum Group, probably was derived from older sediments. This analysis suggests that about one-third of the detritus was reworked from older sediments, one-third from a metamorphic source, and one-third from plutonic rocks. The alteration of the feldspar in the Santa Rosa Sandstone suggests a moderately humid climate; Adams (1929, p. 1050) also reached this conclusion after studying the sedimentary structures, pebbles, and mineralized wood at the outcrop, and Green (1954) has postulated both humid and semi-arid conditions after studying the petrography and paleontology of the Dockum Group.

DEWEY LAKE REDBEDS OF MIDLAND BASIN

The stratigraphy of the Permian Dewey Lake redbeds of west Texas and southeastern New Mexico has been described most recently by Mear (1963), Tait *et al.* (1962), and Mear and Yarbrough (1961). In order to study the lithology of the Permian Dewey Lake redbeds for comparative purposes, thin sections were prepared from cable-tool cuttings of the subsurface type section in R. R. Penn's No. 1 Habenstreit (dry hole) in Glasscock County, Texas. Surface samples also were obtained from a thin-bedded red and white gypsiferous siltstone, regarded in part as Dewey Lake by DeFord (1941, p. 56), that crops out beneath the Santa Rosa Sandstone along Champion Creek, 4.2 miles south of Colorado City in Mitchell County, Texas. Approximately 50 feet of red siltstone is exposed westward along Champion Creek from the single-span wooden bridge.

Petrographic analysis shows that the red siltstone at the Dewey Lake type section and the red siltstone at Champion Creek are essentially identical in texture and mineral composition. Furthermore, the texture and composition of the Dewey Lake redbeds are practically identical with the Pierce Canyon redbeds of the Delaware basin. Both the Dewey Lake redbeds and the red siltstone along Champion Creek contain hollow sanidine grains which are characteristic of the Pierce Canyon redbeds. The Tecovas Formation is not present at the outcrop on Champion Creek, although Page and Adams (1940, p. 63) have described a light-colored zone, called the "Tecovas," from the subsurface nearby. This light-colored zone may be just an upper leached part of the Pierce Canyon redbeds just below the unconformity, similar to the 50-foot leached zone beneath the Cretaceous rocks described from Red Point, Culberson County, Texas.

Quartermaster and Tecovas shales of Palo Duro Canyon.—In order to determine whether or not the name "Tecovas" was justified in this work, the writer sampled the Triassic Tecovas

Formation in Palo Duro Canyon 13 miles east of Canyon, Randall County, Texas. The Tecovas Formation was described and named from outcrops along Tecovas Creek, but many good exposures are present along the Canadian River and in Palo Duro Canyon.

The lowest beds exposed in the canyon are the red shale and siltstone of the Permian Quartermaster Formation. Above the Quartermaster, and separated from it by an unconformity, is a pebble-conglomerate that grades upward into sandstone and multicolored shale and siltstone that are part of the Upper Triassic Tecovas Formation. The contact between the Quartermaster and Tecovas is conspicuous along the west wall of the canyon where the basal conglomerate forms a nearly vertical cliff 6–15 feet high. The Tecovas Formation is about 200 feet thick and is overlain by the red sandstone and shale of the Trujillo Formation, believed by Sidwell (1945, p. 50), Green (1954, p. 118), and others to be the stratigraphic equivalent of the Santa Rosa Sandstone farther south.

Petrographic analysis of the rocks at Palo Duro Canyon shows that the Quartermaster shale is similar lithologically to the Pierce Canyon redbeds of the Delaware basin and to the Dewey Lake redbeds of the Midland basin (Fig. 12). The Quartermaster is composed of about 80 per cent silt and very fine sand, 10 per cent clay, and 10 per cent gypsum and hematite cement. The detritus consists of 70–75 per cent non-undulatory quartz with tourmaline, zircon, some apatite microlites, and a moderate number of vacuoles, some of which are filled with liquid. Feldspar, chiefly unaltered orthoclase, is about 20 per cent of the detritus; microcline, plagioclase, and sanidine also are present and together make up about 2 per cent of the detritus. Almost all the feldspar is fresh or only slightly altered, suggesting that this material, like the Pierce Canyon redbeds, was derived from an igneous source to be deposited as a first-cycle sediment. Sanidine is especially significant here because the grains are hollow just as they are in the Pierce Canyon Formation on the south. Only trace amounts of chert were detected. Muscovite and biotite constitute less than 1 per cent of the detritus; both minerals are equally abundant. Chlorite occurs only in trace amounts.

The heavy minerals of the Quartermaster Formation include fresh, black magnetite-ilmenite, tourmaline, zircon, and traces of apatite and garnet. Hematite-stained clay balls containing aggregates of mica are the only detrital rock fragments.

About 10 per cent of the shale in the Quartermaster is mineral cement. Fibrous gypsum makes up 85–90 per cent of the cement, which occurs as colorless crystals and as microscopic veins. Sparry calcite and hematite constitute the remaining 10–15 per cent.

The mineralogic similarity between the Quartermaster and Pierce Canyon Formation—specifically, the preponderance of non-undulatory quartz, freshness of the feldspar, presence of hollow sanidine, virtual absence of metamorphic constituents, and low chert content—strongly suggests that these two formations were derived from the same or similar source areas, under the influence of an arid or semi-arid climate, and deposited in a similar shallow-saline environment.

The Tecovas Formation at Palo Duro Canyon is mineralogically similar to the other Upper Triassic redbeds farther south (Fig. 12). The predominant grain-size of the Tecovas ranges from silt to fine sand, although the extremes range from pebbles in the basal conglomerate to clay in other beds. About 80 per cent of the detritus is quartz, 90–95 per cent of which is non-undulose; the other 5–10 per cent is metamorphic. Orthoclase and traces of microcline comprise about 10–15 per cent of the detritus. About 30 per cent of the feldspar is fresh, 15 per cent is intensely altered, and the remaining 55 per cent ranges from slightly to moderately altered. Chert is less abundant here than in the Santa Rosa Sandstone and is only about 2 per cent of the detritus. About 5 per cent of the grains are metamorphic rock fragments composed of metamorphic quartz and sericite. Sidwell (1945, p. 52) has described the heavy mineral content of the Tecovas Formation from this locality; his findings agree essentially with those described here, specifically, that magnetite-ilmenite, tourmaline, zircon, garnet, and rutile are present.

Conclusions

In the preceding descriptive sections, an effort was made to delineate the fundamental differences in lithology between the uppermost Permian and Upper Triassic rocks at three widely spaced localities (Fig. 12). The differences in the mineral assemblages of the formations are sufficiently important that it is possible to distinguish between the Pierce Canyon redbeds and the Santa Rosa Sandstone in the Delaware basin, between the Dewey Lake redbeds and the Santa Rosa Sandstone in the Midland basin, and between the Quartermaster and Tecovas Formations of Palo Duro Canyon in the Texas Panhandle. The eight mineralogic differences previously cited, contrasting the Santa Rosa and Pierce Canyon detritus, are a practical means of differentiating all of the Upper Permian and Upper Triassic formations described in this investigation. These eight mineralogic differences prove that the Pierce Canyon redbeds are more nearly like the Permian Rustler Formation below than the Upper Triassic Santa Rosa or Tecovas Formations above.

Having shown that the Pierce Canyon and the Dewey Lake redbeds are for practical purposes one and the same, it seems reasonable to discontinue, as most geologists have done, the use of the name Pierce Canyon in favor of the priority recognized for the name Dewey Lake (Page and Adams, 1940).

It is unlikely that detailed petrographic methods ever will be completely acceptable to everyone for solving stratigraphic problems; nevertheless, they offer a quantitative measure of lithologic character vital to the interpretation of sedimentary rocks if geologists are ever to resolve the stratigraphic problems that lithologic generalizations have created.

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