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PETROLOGY OF PIERCE CANYON REDBEDS:

DELAWARE BASIN, TEXAS AND NEW MEXICO

Approved:

Ronald K. DeFord

Hunt L. Fish

Samuel P. Ellison Jr.

A. B. Stewart

W. C. Bell

Kenneth O. John

W. M. Waldschmidt

PETROLOGY OF PIERCE CANYON REDBEDS:
DELAWARE BASIN, TEXAS AND NEW MEXICO

DISSERTATION

Presented to the Faculty of the Graduate School of

The University of Texas in Partial Fulfillment

of the Requirements

For the Degree of

DOCTOR OF PHILOSOPHY

By

Daniel Newton Miller, Jr., B.S., M.S.

Austin, Texas

June, 1955

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

Daniel N. Miller, Jr.

A B S T R A C T

The Pierce Canyon formation of the Delaware Basin is a red siltstone sequence about 350 feet thick that overlies the Permian Rustler evaporites and underlies the Upper Triassic Santa Rosa sandstone. It consists of crosslaminated, gypsiferous, slightly sandy and slightly clayey siltstone and ranks as submature to mature arkose or subarkose containing 20 to 30 per cent feldspar. Petrographic and textural analyses show that there is little variation in composition or texture either vertically or horizontally. These redbeds typically contain hollow sanidine grains which may prove useful as a stratigraphic marker. Authigenic biotite was detected in a few of the reduction spots.

The Pierce Canyon redbeds were probably derived predominantly from a granitic source in northern Coahuila, Mexico, under the influence of an arid climate, transported by the wind, and deposited in a shallow saline sea in west Texas and southeastern New Mexico.

Comparison with other redbeds shows that the Dewey Lake formation of the Midland Basin, and the Quartermaster formation of the Texas Panhandle, have compositions that are essentially identical with that of

the Pierce Canyon redbeds.

The Pierce Canyon differs mineralogically from the Yates, Rustler, Tecovas, Santa Rosa, Chinle, and Gatuna formations. If the Pierce Canyon is assigned to the Permian system, then there are eight mineralogic differences to distinguish Permian from Triassic redbeds.

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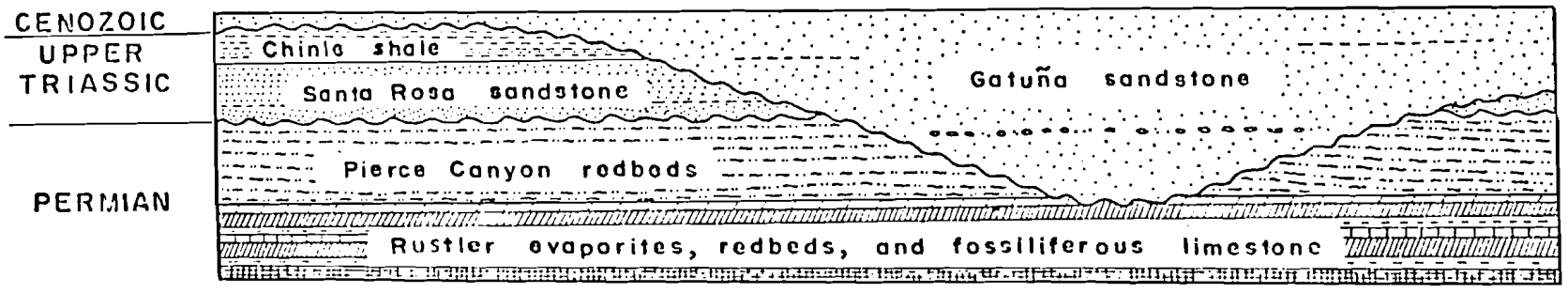
INTRODUCTION

Underlying the vast expanse of desert and prairie land of west Texas and southeastern New Mexico is a broad, shallow, structural basin filled with lithified Permian sediments. Although it represents only a small part of the widespread area once covered by the Permian sea, the Delaware Basin provides the most nearly complete sequence of Permian rocks on the North American continent. The standard Permian section of North America was established here (Adams et al.) in 1939; it consists of four stratigraphic series, in ascending order, Wolfcamp, Leonard, Guadalupe, and Ochoa. The position of the Permian-Triassic boundary has been and is a matter of disagreement among geologists. A considerable thickness of redbeds overlies the youngest proven Permian, the Rustler formation, and underlies the Upper-Triassic Santa Rosa sandstone. Since 1935, when Walter B. Lang designated these redbeds as the Pierce Canyon formation, placing the type locality in the subsurface of central-eastern Loving County, Texas, their age has been in question.

The writer has endeavored to bring together all the geological information that bears on the origin and history of the Pierce Canyon redbeds, including new data obtained by him. In order to study the Pierce Canyon formation, the outcrops were examined. More than 500 surface and subsurface samples, from widely scattered geographical locations were critically studied. Eighty thin sections provided a fairly

PERMIAN-TRIASSIC BOUNDARY
DELAWARE BASIN



Dockum group (Chinle + Santa Rosa) has Upper Triassic vertebrate fossils
Pierce Canyon redbeds are unfossiliferous
Rustler formation has Upper Permian invertebrate fossils

Plate 1

complete assay of the detrital minerals and chemical cements, and their relationship to the entire rock unit. Heavy-mineral studies combined with textural, chemical, and X-ray analyses were also made. Many of the samples and all the thin sections have been deposited in the stratigraphic petrography collection of the Department of Geology, The University of Texas in Austin.

Conclusions, describing the probable source of the detritus, means of transport, depositional environment, and the paragenetic history of the strata, follow the description of the rocks. 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 the Texas Panhandle were similarly investigated. The differences and similarities of detrital constituents in these formations have been described.

The striking similarity in texture, detrital minerals and chemical cements of the Pierce Canyon and Dewey Lake formations, which heretofore had been presumed by some geologists, has been verified.

Acknowledgments.- In grateful appreciation of contributions made by others throughout this study, the writer wishes to thank Professors Ronald K. DeFord and Robert L. Folk of the Department of Geology, The University of Texas. Professor DeFord suggested the problem to the writer in 1952, and throughout the entire investigation, from 1952 to 1955, provided financial assistance, encouragement, and a wealth of

knowledge concerning the stratigraphy and history of west Texas and southeastern New Mexico. Secondly, I wish to express my sincere gratitude to Professor Folk for the many patient hours of instruction, help, and criticism that he provided in the interpretation of the petrography of these fine-grained sediments. The results of this work have indeed been gratifying to the writer, largely through the efforts of Professors DeFord and Folk.

A large part of the financial assistance in this research was provided by the Stanolind Oil and Gas Research Fellowship in Geology. The writer wishes to thank the Stanolind Oil and Gas Company for the opportunity of being the recipient of this award, and further wishes to extend his appreciation to Messrs. Charles E. Mear, Wilbur D. Wilson and the other Stanolind geologists in the Midland and Roswell offices who provided office space, subsurface data and ideas which facilitated the completion of this work.

During the summer of 1953 the writer attempted to collect as much surface and subsurface information as the summer field season would permit. Many individuals and companies assisted this endeavor and I wish to express my gratitude especially to Mr. Joe P. Smith and Mr. Donald L. Libbey of the U. S. Potash Company; to Mr. Donald E. Protz and Mr. L. P. Corbin, Jr. of the Potash Company of America, and to Mr. Reed Waltman, acting geologist for Southwest Potash Company, of Carlsbad, New Mexico. Conversations and personal correspondence with Mr. George

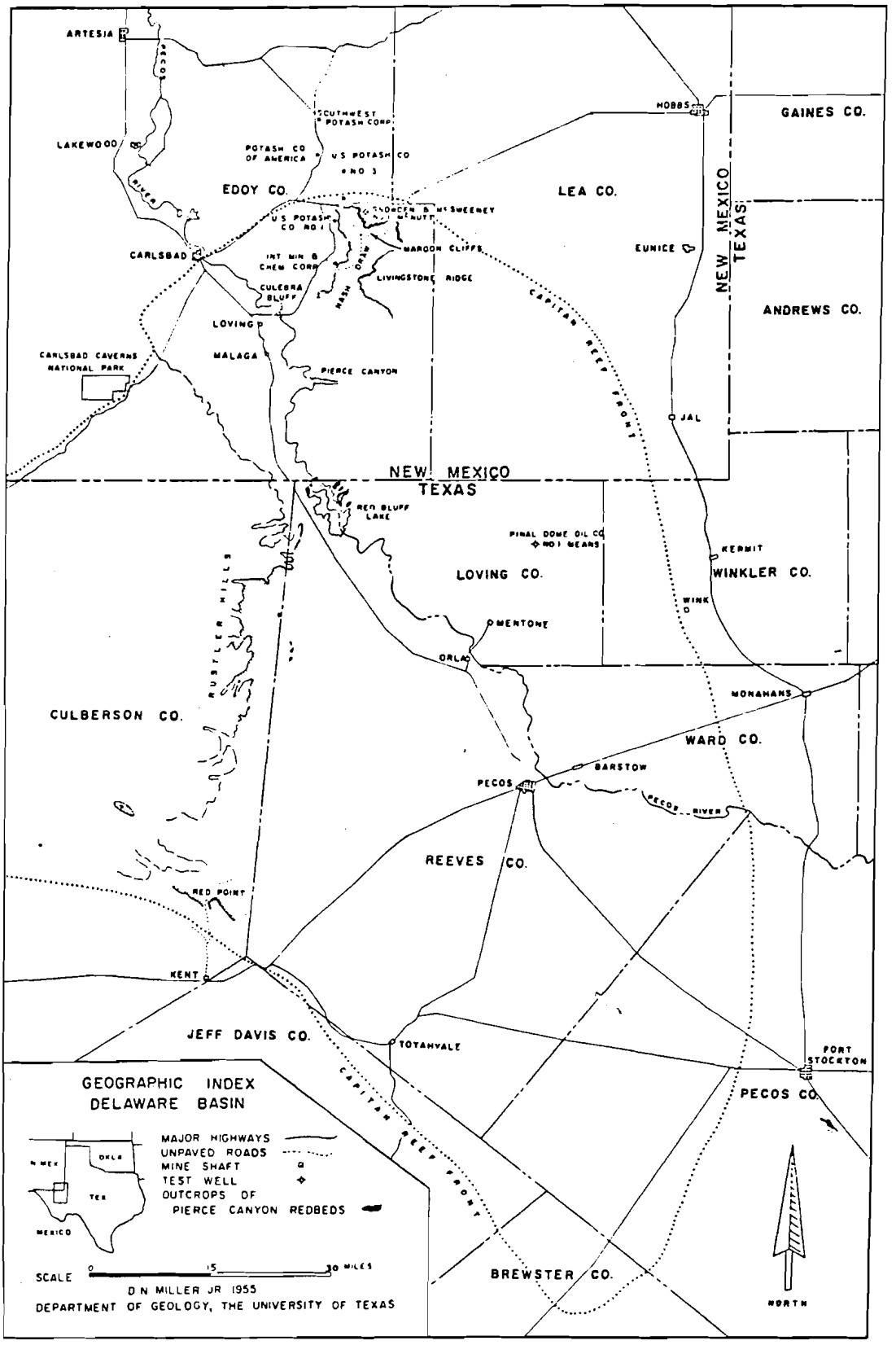
D. Riggs, independent oil operator of Carlsbad, New Mexico, Dr. William A. Waldschmidt, geological consultant of Midland, Texas, and Mr. John E. Adams, geologist for the Standard Oil Company of Texas in Midland assisted many of the interpretations presented by the writer, although the writer alone remains wholly responsible for all of the material presented in this report.

The writer wishes to thank personally Professors R. K. DeFord (Chairman), R. L. Folk, H. B. Stenzel, S. P. Ellison, W. C. Bell, K. H. Jehn, and Dr. W. A. Waldschmidt who acted as an advisory committee for the writer and who gave freely of their time during the preparation and completion of the manuscript.

The writer further wishes to extend his gratitude to the many members of the graduate school and faculty at The University of Texas for enlightening discussions.

Evaporites and Redbeds in Delaware Basin

Ochoa deposition.- The final stage of Permian deposition in the deepest part of the Delaware Basin is represented by more than 5,000 feet of saline residues and redbeds. These deposits belong to the Ochoa series which includes the following formations in ascending order: Castile gypsum, anhydrite and salt; Salado salt and anhydrite; and the Rustler gypsum, anhydrite, dolomite, limestone, red claystone, siltstone, and sandstone. Since 1924, the drilling of thousands of deep


ARTESIA
PECOS
LAKEWOOD
RIVER
SOUTHWEST POTASH CORP
POTASH CO OF AMERICA
U S POTASH CO NO 3
EDDY CO.
U S POTASH CO NO 1
CARLSBAD
INT MIN & CHEM CORP
CULEBRA BLUFF
LOVING
MALAGA
CARLSBAD CAVERNS NATIONAL PARK
PIERCE CANYON
HOBBS
GAINES CO.
LEA CO.
NEW MEXICO
TEXAS
EUNICE
MAROON CLIFFS
LIVINGSTONE RIDGE
CAPITAN REEF FRONT
ANDREWS CO.
JAL
NEW MEXICO
TEXAS
RED BLUFF LAKE
PINAL DOME OIL CO NO 1 MEARS
KERMIT
WINKLER CO.
LOVING CO.
WINK
MENTONE
ORLA
RUSTLER HILLS
CULBERSON CO.
MONAHANS
WARD CO.
BARSTOW
PECOS
PECOS RIVER
REEVES CO.
RED POINT
KENT
JEFF DAVIS CO.
TOYAHVALE
FORT STOCKTON
PECOS CO.
GEOGRAPHIC INDEX
DELAWARE BASIN
N MEX
OKLA
TEX
MEXICO
MAJOR HIGHWAYS
UNPAVED ROADS
MINE SHAFT
TEST WELL
OUTCROPS OF PIERCE CANYON REDBEDS
SCALE 0 15 30 MILES
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tests for petroleum and many core tests for potash, and the working of the potash mines near Carlsbad, New Mexico, have revealed the widespread occurrence of these sedimentary units in southeastern New Mexico and west Texas. They have been described in numerous publications.

When originally deposited from the Permian sea these sediments covered vast areas outside the Delaware Basin. There were many transgressions of the sea northward and eastward beyond the rim of the basin and undoubtedly just as many regressions southward when little or no material was deposited. Extensive accumulations of gypsum and salt and local deposits of potash minerals in the Salado indicate regional desiccation during Castile and Salado time. Clay and silt, interbedded with the evaporites, evince a terrain of low relief. Where the retreating sea had only recently exposed the surrounding land, surface drainage was probably restricted to slowly moving streams with wide channels, which were constantly being clogged by flood plain deposits. The virtual absence of organic remains suggests the desolate condition of the entire region. Salt, interbedded with clay and silt in the Rustler formation, indicates that these conditions persisted until almost the end of the Permian period.

The Rustler formation oversteps the Salado salt to the north and east and records a transgression of the sea beyond the Delaware Basin. It consists of red claystone, siltstone, fine sandstone, interbedded with evaporites which by their repeated occurrence suggest slowly but

continually changing conditions. Thin beds of fossiliferous limestone indicate a greater abundance of marine life during periodic intervals.

The uppermost Rustler beds are sulphate, which prove that the region was still beneath sea level at the end of Rustler time.

Intervening redbeds.- Overlying the Rustler evaporites is a sequence of redbeds (the Pierce Canyon formation) which have not been studied in detail heretofore, although several writers (Lang, 1935, p. 264 and 1947, p. 1673; DeFord and Wahlstrom, 1932, p. 59; DeFord, in P. B. King, 1942, fn. 151, p. 613; P. B. King, 1942, p. 612; Adams, 1929, p. 1052 and 1935, p. 1021; Page and Adams, 1940, p. 62) have described them. These redbeds, like the Rustler evaporites, are widespread in west Texas and southeastern New Mexico, but unlike the Rustler, are lithologically homogeneous; they consist of very thinly and evenly bedded, clayey and sandy feldspathic siltstone cemented with gypsum and calcite. Most of the beds are crosslaminated, a few are ripple-marked and crossbedded. A few scattered bits of calcitic or phosphatic fossil fragments have been recovered from these beds, but all are too worn to permit identification. Within the Delaware Basin the thickness of this redbed sequence ranges from zero to 450 feet.

Upper-Triassic redbeds.- The Upper Triassic Santa Rosa sandstone, the lowest formation of the Dockum Group in the Delaware Basin, overlies the post-Rustler redbeds and is separated from them, at least in Eddy County, New Mexico, by an erosional unconformity. Although variable in

texture in different areas, the Santa Rosa is predominantly a reddish brown, silty, medium-grained sandstone cemented with calcite and some quartz. The sandstone is typically crossbedded. Adams (1929, p. 1047) has described sand dunes and other characteristics of the Santa Rosa that suggest continental deposition. Pebble conglomerate and siltstone with parallel bedding are associated with the crossbedded sandstone in most places. In general, the Santa Rosa sandstone becomes finer westward. The source of part of the detritus may have been to the south and east (Adams, 1929, p. 1049); another part was probably derived from southeastern Colorado. In the Delaware Basin, near the southern limit of the Santa Rosa sandstone, the total thickness ranges from 100 to 300 feet.

The Chinle shale (Upper-Triassic) overlies the Santa Rosa sandstone in the Delaware Basin; the contact is gradational and conformable. Adams (1929, p. 1052) and Dickey (1940, p. 50) have described the Chinle shale in this region as a thick sequence of red and green shale, sandstone, limestone, and conglomerate. The Chinle shale is believed to be a terrestrial flood-plain or alluvial deposit laid down on a west- and northwest-sloping, post-Permian terrain (Adams, 1929, p. 1052).

Cenozoic redbeds.- Overlying the Permian and Triassic formations of the Delaware Basin is a heterogeneous mixture of pale red detritus that closely resembles the Pierce Canyon redbeds but is Cenozoic and probably Pleistocene in age; it was designated the Gatuña formation by

Lang (1938, p. 84) as follows:

> The name Gatuña is here given to an assemblage of rocks of various kinds that were laid down in the Pecos Valley in post-High Plains time and apparently after the completion of the maximum cycle of erosion in this valley. . . . The dominant material of which they are composed is fine red sand. However the material is largely of local derivation and therefore the character of the source of the material has had a controlling influence on the composition and color of the resulting deposits. Conglomerates, stream gravels, gypsum, and limestone, as well as bedded and unconsolidated sands and silts, comprise this formation.

The Gatuña sandstone crops out along the Pecos River Valley in southeastern Eddy County, New Mexico, and extends southward over the eastern half of the Delaware Basin as indicated by Maley and Huffington (1953, p. 541). The thickness ranges from zero to 1,900 feet.

Fig. 1. Brecciated limestone and gypsum in the upper part of the Rustler formation in west face of Culebra Bluff northeast of Loving, Eddy County, New Mexico. Notice void spaces in this brine aquifer.

Fig. 1. Brecciated limestone and gypsum in the upper part of the Rustler formation in west face of Culebra Bluff northeast of Loving, Eddy County, New Mexico. Notice void spaces in this brine aquifer.

STRATIGRAPHY OF PERMIAN-TRIASSIC FORMATIONS

Rustler Formation

The Rustler formation was described by G. B. Richardson in 1904 in the southwestern extension of the Rustler Hills, between Cottonwood and Hurds Pass draws, eastern Culberson County, Texas. Subsequent reports of Rustler outcrops in this area by P. B. King, R. K. DeFord, J. E. Adams, W. B. Lang, and numerous University of Texas students (unpublished Master's Theses) have resulted in a more accurate description than that originally published by Richardson.

The Rustler formation consists at the outcrop of limestone and dolomite separated by shale, sandstone, and local lenses of gypsum. A maximum thickness of 375 feet, exclusive of the upper anhydrite, was reported by Adams (1944, p. 1613). This thickness is 70 feet greater than a section measured in the north half of Salt Draw Quadrangle, Culberson County, by Hughston (1950, p. 13). Local lensing and interbedding of the rock types on scattered outcrops make correlation of individual units difficult. The approximate eastern limit of Rustler outcrop is shown on Plate 4.

The Culebra limestone member is exposed at Culebra Bluff along the east bank of the Pecos River, 3½ miles northeast of Loving, Eddy County, New Mexico (SE¼ Sec. 2, T. 23 S., R. 28 E.). Because of local brecciation and solution channels, this part of the

Rustler formation is permeable to ground water. Void spaces up to 8 inches in diameter are common as indicated in Figure 1. The potash mining companies, whose shafts are situated a few miles northeast of Culebra Bluff, report almost uncontrollable quantities of water pouring into their shafts from the lower part of this permeable zone during the excavation process. The water is highly mineralized and of no economic value.

Red clay, anhydrite, and salt overlie the aquifer and are in turn overlain by gray dolomite banded with gypsum. A small roadcut on New Mexico State Highway 31, half a mile due west of the International Minerals and Chemical Corporation mine in eastern Eddy County, exposes about 7 feet of the banded dolomite.

In the subsurface the Rustler consists of dolomite, anhydrite, gypsum, limestone, salt, and polyhalite irregularly interbedded with lenses of red clay, siltstone, and sandstone. The thickness of the Rustler formation ranges from 400 to 500 feet in the center of the basin.

Pierce Canyon Redbeds

Overlying the Rustler evaporites is a sequence of red siltstone, the Pierce Canyon formation. W. B. Lang (1935, p. 264) described the red siltstone from the subsurface as

> A series of fine sandy to earthy red beds, polka-dotted with green reduction spots and usually

irregularly veined with thin secondary selenite fillings.

Lang described the redbeds from 350 feet of cuttings recovered from the Eldridge core test (Sec. 22), drilled in 1926 as an offset to the Pinal Dome Oil Company's Means No. 1 dry hole, drilled in 1921, to supplement the upper part of the section absent in the Means test. The cuttings from both bore holes provide the type material for the formation. The Means test is in the SE corner of Sec. 23, Blk. C-26, PSL, in central-eastern Loving County, Texas, 31 miles due north of the city of Pecos and 8 miles south of the Texas-New Mexico state line. The name Pierce Canyon was derived from a small canyon on the east side of the Pecos River, 7 miles east-southeast of the town of Malaga in Eddy County, New Mexico (Secs. 23 and 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, for the redbed outcrop is what R. W. Richards (in Adams, 1944, p. 1601) described as pre-Gatuña redbeds, and what DeFord (oral communication, Feb. 1955) calls Gatuña. For all that, the subsurface redbeds described by Lang form a lithologically distinct and continuous stratigraphic unit between the Rustler and the Santa Rosa formations. They blanket the eastern two-thirds of the Delaware Basin and extend northward to the Loco Hills, Eddy County, New Mexico. Their occurrence to the north and east in Texas has been cited by DeFord (1941, p. 56), and described by Adams (1944, p. 1601) as follows:

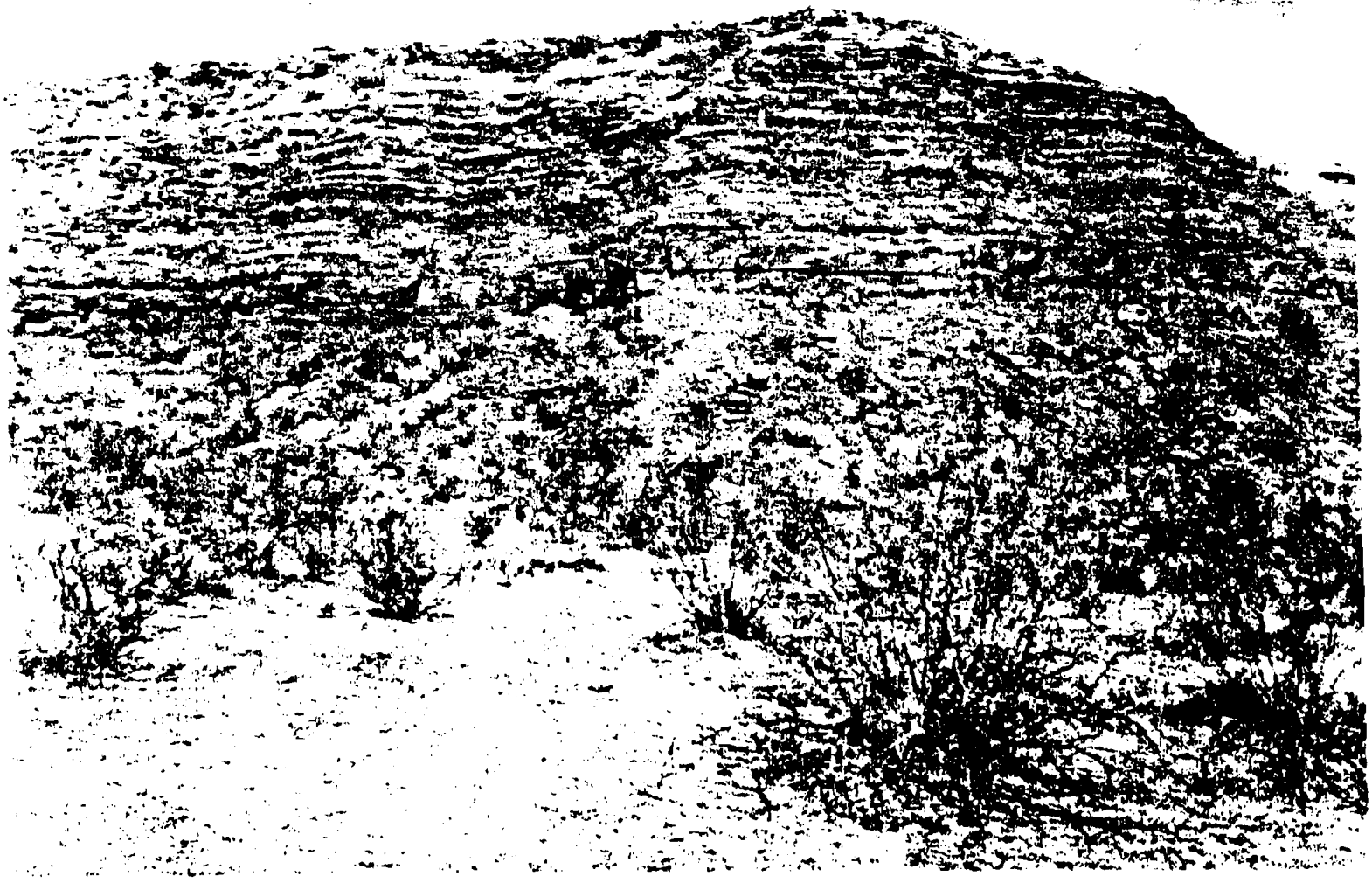
> The outcropping Pierce Canyon redbeds of the Pecos Valley are similar lithologically to the post-Dewey Lake redbeds of the southern Permian basin and to the Quartermaster of the Panhandle. They occupy the same position with respect to the upper Triassic Santa Rosa sandstone and, judged by sections encountered in thousands of intervening wells, form a continuous stratigraphic unit ...

Within the Delaware Basin there are only a few scattered exposures of the Pierce Canyon redbeds. These are limited to a narrow, sinuous, and intermittent belt which extends from Red Point, 10 miles north of Kent in southeastern Culberson County, Texas, through Red Bluff Lake, Texas, to Maroon Cliffs, 18 miles east-northeast of Carlsbad in Eddy County, New Mexico.

Maroon Cliffs and vicinity.- The thickest single exposure of the Pierce Canyon redbeds is in Maroon Cliffs along the northern escarpment of Nash Draw in eastern Eddy County, New Mexico (DeFord, 1940, p. 2). 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 and 9, T. 21 S., R. 30 E.). The outcrop is accessible by automobile both on the high road, which follows the eastern escarpment, or by the low road through Nash Draw (topographic sheets, Nash Draw and Clayton Basin Quadrangles, 1943 ed., U. S. Geol. Surv.).

Nash Draw is an elongate, slumped depression approximately 12 miles long and 3.5 to 4.5 miles wide. It has been described (Theis

Fig. 2. West scarp of Pierce Canyon redbeds at Maroon Cliffs (Sec. 9, T. 21 S., R. 30 E.), Eddy County, New Mexico. The 6-foot "blocky" sandstone extends across the middle of the 120-foot escarpment.



et al., 1942, p. 64-75) as an unfilled solution valley and is part of the vast interior drainage system resulting from the removal of salt from the subsurface by ground water. Maximum relief occurs along the northern end of the draw where more than 120 feet of exposed redbeds have given rise to the name Maroon Cliffs. Except for a truncated wedge of overlying Santa Rosa sandstone at the northernmost end of Maroon Cliffs, these redbeds belong to the Pierce Canyon formation.

The red or maroon color of the Pierce Canyon formation ranges from pale to moderate reddish brown (10R5/4 to 10R4/6). The most prominent stratigraphic marker in the cliffs (Fig. 2) is a 3- to 6-foot, hard, "blocky", fine- to very fine-grained sandstone ledge approximately 130 feet below the contact with the Santa Rosa sandstone. The rocks beneath the "blocky" sandstone are thin, evenly bedded siltstone with the exception of a 10-foot section near the base of the outcrop, which contains from 2 to 5 per cent rounded and frosted sand grains greater than 0.4 mm. in diameter. Above the "blocky" sandstone differential weathering of thin-bedded clayey siltstone and very fine sandstone gives the outcrop a ragged appearance in contrast to the smooth slope below the "blocky" sandstone. A few light greenish gray (5GY8/1) zones less than one inch thick parallel the uniformly thin-bedded siltstone at irregular intervals giving the escarpment a faint banded appearance. These leached zones underlie and include thin laminae permeable enough to permit the infiltration of water from the closely spaced joints.

Some of these greenish gray zones result from the chemical reduction of hematite by weak humic acids. The sandy beds are lighter colored than the more impermeable zones and typically display a mottled gray and orange (N8, 10YR7/4) appearance.

Current ripple-marks and low-amplitude crossbedding (Figs. 3 and 4) 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 inches and show a transport direction from northwest to southeast. Crossbeds above the "blocky" sandstone have an amplitude of 1 to 2 inches and a foreset dip (measured in sets) of about 13° south, indicating a direction of transport from north to south; the 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 crossbeds in the same 2- to 3-foot section, ranges within an arc of 55°.

The local dip of the strata on the east side of Maroon Cliffs is 2° northwest. There are two sets of joints in Nash Draw: one set strikes S. 60° E. and has a dip of 70° northeast; the other set strikes S. 55° W. and dips 80° northwest. The joint system intersects all the formations in this area up through the Chinle shale (Upper Triassic) which overlies the Santa Rosa sandstone. Most of the joints are open and straight-sided (Fig. 9). The majority of open joints are clogged at depth with vegetal debris. During one brief but intense rain shower

[illegible]

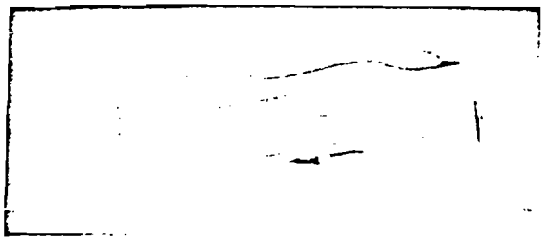


Fig. 3. Ripple marks with retouched cross-laminations from the Pierce Canyon formation, Maroon Cliffs, Eddy County, New Mexico.

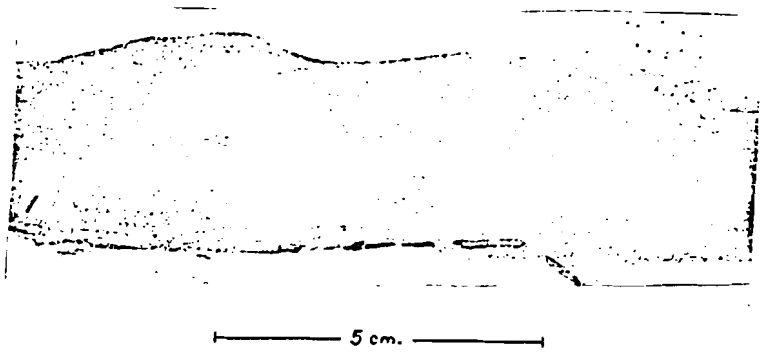
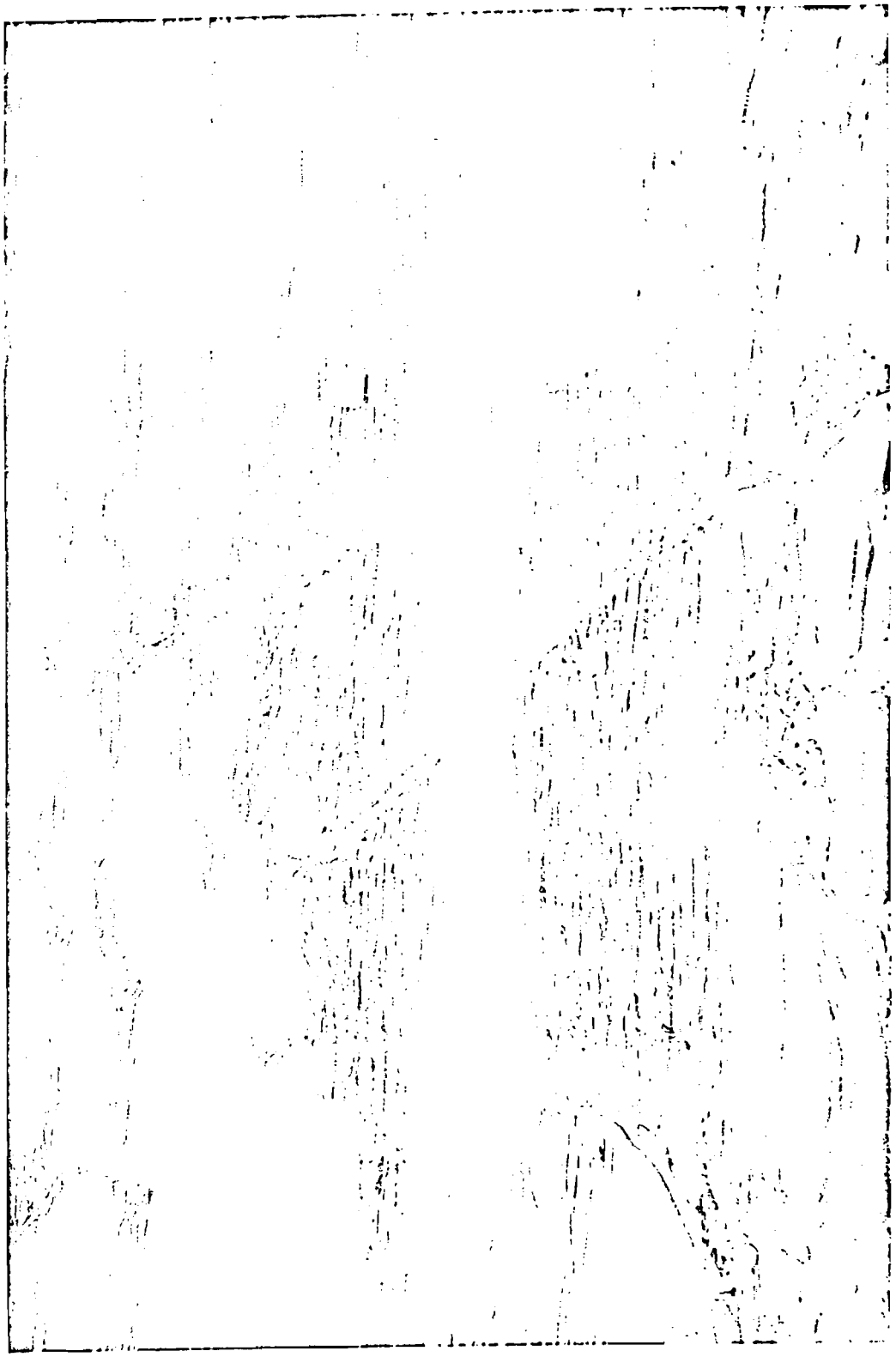


Fig. 4. Thin section of sample shown in Figure 3.

the writer observed run-off water transporting large quantities of fine grass, leaves and mesquite pods into the open joints of the Santa Rosa sandstone. During the dry seasons of the year, sand and silt are blown into the joints, filling most of them within an inch of the surface. Subsequent rains flush the sand and silt from the upper portion of the joints leaving them open once again. The walls of most of the joints have a thin white crust of gypsum and calcite and some have crystals of these minerals up to 0.25 inches long. Seven miles south of Maroon Cliffs, along Livingston Ridge, the same joint pattern is present; but there the joints are completely filled with fibrous gypsum. A few of the fibrous crystals in the veins are warped, indicating fairly recent movement.

Two types of gypsum veins are illustrated in Figures 5, 6, and 7: gypsum-filled joints that cut the strata at angles from 40° to 60° and gypsum-filled fractures that parallel the bedding. Similar gypsum veins up to 1.25 inches wide are abundant in the lower part of the Pierce Canyon redbeds in eastern Eddy County. Many of the veins separate beds that have been displaced as indicated in Figure 6. The maximum displacement detected at any one vein (fault) is one inch. A few geologists have misinterpreted the gypsum veins parallel to the bedding as bedded gypsum in the Pierce Canyon redbeds. The direct association with the gypsum-filled joints, and the elongate, near-vertical crystal habit, prove that these fractures were opened after consolidation of the sediment.

Fig. 5. North view of two sets of gypsum-filled joints in the lower part of the Pierce Canyon redbeds on Livingston Ridge, SW$\frac{1}{4}$ Sec. 14, T. 22 S., R. 30 E., Eddy County, New Mexico.



There is a direct relationship between the gypsum veins in the Pierce Canyon and the slump features induced during the Cenozoic. At Maroon Cliffs the beds are not displaced vertically along the joints near the top of the Pierce Canyon outcrop; they are displaced along the gypsum-filled joints in the lower part of the outcrop. Post-Chinle jointing, resulting from local and regional subsidence in and around the Delaware Basin, was probably accompanied by basinward slump as evidenced by erratic local dips at the surface and the displaced beds along joints and plastic clayey zones in the subsurface. Lateral as well as vertical displacement on the Rustler-Pierce Canyon contact is indicated by vertical dips, and steeply dipping strata with slickensides as described in L. P. Corbin's field notes (p. 35). Calcium- and sulphate-rich ground water probably passed upward along some of the joints because of the displacement of the rocks. As the underlying gypsum was dissolved, small blocks of the Pierce Canyon redbeds pulled loose, opening fractures along the bedding planes in the lower part of the formation. These near-horizontal fractures provided new avenues of escape for the water moving up the joints from below. Subsidence stopped at some later time and gypsum was precipitated from the ground water, filling the open joints and fractures with fibrous gypsum crystals.

Approximately 210 feet of section was measured on Maroon Cliffs below the Santa Rosa contact; an additional 30 feet was measured on Livingston Ridge, 150 feet northeast of the road connecting the Crawford

Fig. 6. Gypsum veins in [illegible] in the core separat[illegible] displaced beds. Notice concentration [illegible] reduction zones (Map [illegible], Sec. 13, T. [illegible] S., R. 30 E., Eddy County, New Mexico).

Fig. 7. Gypsum filled fractures parallel to the bedding in [illegible] core. Notice that the veins cut [illegible] indicating that the reduction [illegible] formed before the veins (same location as Fig. 6).

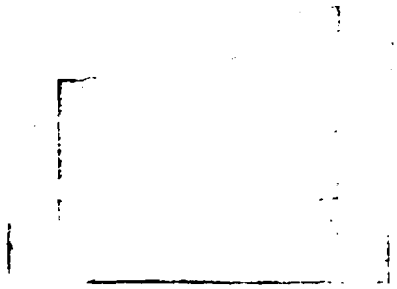


Fig. 6. Gypsum veins in $2\frac{1}{2}$ inch core separating displaced beds. Notice concentration of reduction zones (NE$\frac{1}{4}$ SE$\frac{1}{4}$ Sec. 13, T. 20 S., R. 30 E., Eddy County, New Mexico).

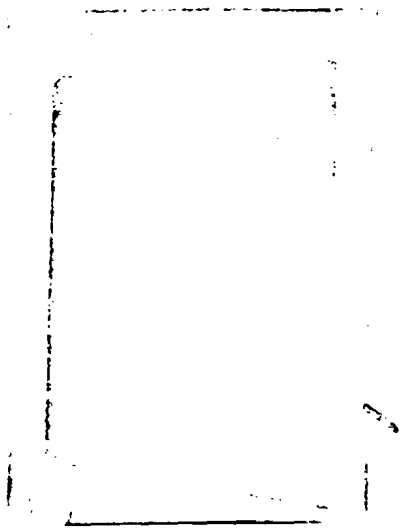


Fig. 7. Gypsum filled fractures parallel to the bedding in $2\frac{1}{2}$ inch core. Notice that the veins cut the reduction zones, indicating that the reduction zones formed before the veins (same location as Fig. 6).

Ranch headquarters and Hill Tank ($W\frac{1}{4}$ Sec. 14, T. 22 S., R. 30 E.).

The total thickness of the Pierce Canyon redbeds at Maroon Cliffs is 318 feet as measured in Snowden and McSweeney's McNutt No. 1 dry hole, 0.5 miles east of the cliff (center $S\frac{1}{2}$ Sec. 4, T. 21 S., R. 30 E.).

Pierce Canyon-Santa Rosa contact.- The Pierce Canyon redbeds are overlain unconformably by the Santa Rosa sandstone. The unconformable contact is well exposed throughout the $N\frac{1}{2}$ of Sec. 5, T. 21 S., R. 30 E. at Maroon Cliffs. An excellent exposure, shown in Figures 8, 9, and 10, occurs on the east side of a small ravine about 50 feet deep, one mile due south of U. S. Highway 62, in the east-central portion of the $NW\frac{1}{4}$ $SE\frac{1}{4}$ Sec. 5. Thin, nearly horizontal beds of Pierce Canyon are overlain by the sweeping crossbeds of the Santa Rosa sandstone at this locality, the exact contact being the base of a gray, plastic, clayey pebble-conglomerate or coarse-sandstone containing rounded gray and red pebbles of reworked Pierce Canyon siltstone (Fig. 11). The thickness of the conglomerate is less than 9 inches.

There is no significant difference in the overall color of the Pierce Canyon and Santa Rosa formation, but without exception the contact is marked by a leached greenish gray zone where vadose water has accumulated on top of the impermeable Pierce Canyon, or the clayey conglomerate overlying it. Differential weathering has accentuated the textural differences of the two formations; the contact is marked by a

Fig. 8. Southeast view of prominent lower Santa Rosa sandstone cliff immediately above Moenkopi Canyon-Santa Rosa contact at Maroon Cliffs, NW¼SE¼ Sec. 5, T. 21 S., R. [illegible] E., [illegible] County, New Mexico.

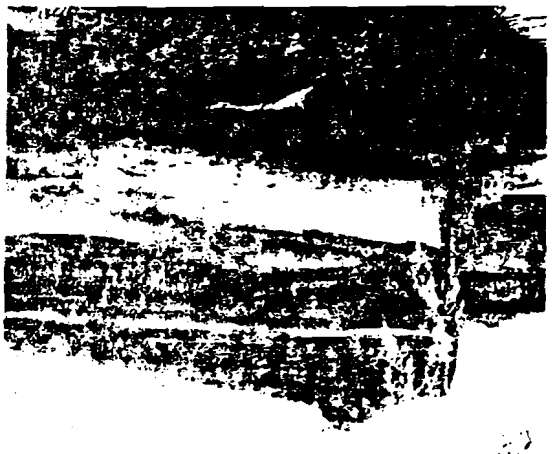


Fig. 9. [illegible] of figure 8 [illegible] lower [illegible]ened zone above the contact [illegible], and [illegible] joint.

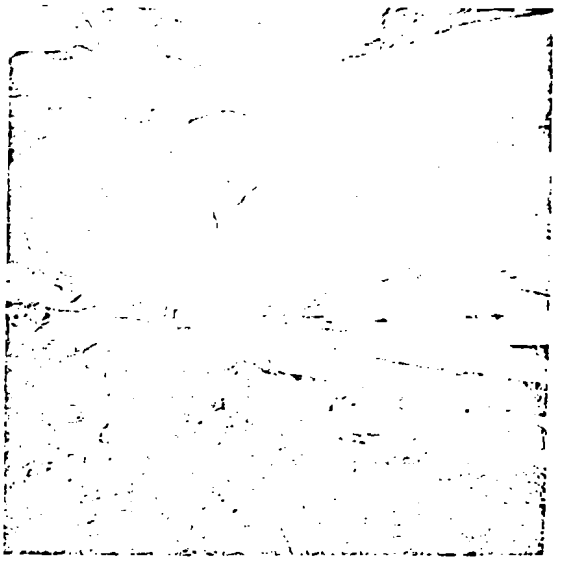


Fig. 8. Northeast view of prominent lower Santa Rosa sandstone cliff immediately above Pierce Canyon-Santa Rosa contact at Maroon Cliffs, NW¼SE¼ Sec. 5, T. 21 S., R. 30 E., Eddy County, New Mexico.

Fig. 9. Closeup of Figure 8 showing lower leached zone above the contact cut by an open joint.

[illegible] of Figure 8 showing bedding [illegible] and rewashed Pierre [illegible] cobbles on the basal [illegible] Santa [illegible].

Fig. [illegible] [illegible] the cover, [illegible] the contrast in average grain size.

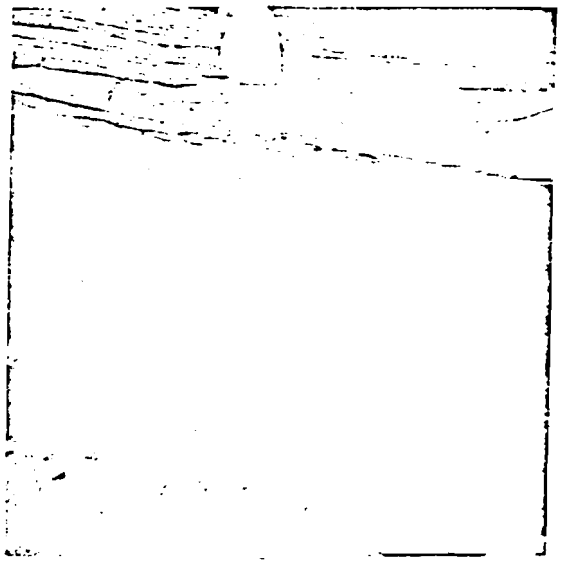


Fig. 10. Closeup of Figure 8 showing bedding relationships and reworked Pierce Canyon pebbles in the basal Santa Rosa.

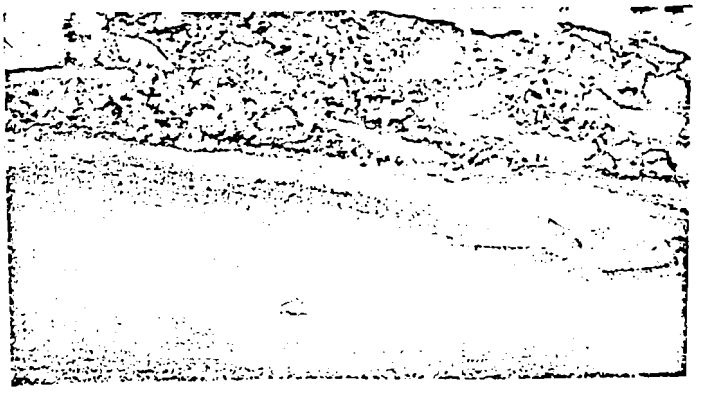


Fig. 11. Thin section No. 23 of Pierce Canyon-Santa Rosa contact, at Maroon Cliffs, Eddy County, New Mexico, showing reworked Pierce Canyon shale pebbles in the overlying Santa Rosa sandstone, and the contrast in average grain size.

small undercut ledge of Santa Rosa sandstone.

The Pierce Canyon-Santa Rosa contact was traced by the writer over a distance of 1.25 miles along Maroon Cliffs in which there is no evidence of a gradational contact between the two formations.

Other outcrops in Texas and New Mexico.- West of Maroon Cliffs the Pierce Canyon redbeds are exposed in numerous excavated hillsides in the vicinity of the U. S. Potash Company mine. Other small exposures were reported along the east side of the Pecos River valley in southern Eddy County, 2 miles north of the Texas state line. Measured sections compiled by Leve (1952, p. 20) show a maximum thickness at this locality (Sec. 22, T. 26 S., R. 29 E.) of 30 feet, but neither the upper nor lower contact is exposed. East of the Pecos River, and 1 to 3 miles north of the Red Bluff Lake bed the Pierce Canyon redbeds are exposed at numerous scattered localities in Secs. 2, 3, 11, 12, 13, and 14, Blk. 57, T. 1, T&P RR Co.; all these outcrops occur in sinkholes. The maximum thickness measured by Komie (1952, p. 16) in this locality was 110 feet.

Fifteen miles south-southwest of Red Bluff Lake dam the Pierce Canyon redbeds are exposed in sinkholes scattered through Secs. 3, 10, 23, 26, and 35, Blk. 45, PSL, along the Culberson and Reeves County line. Low relief in this area helps protect the redbeds from further erosion. These exposures are dark reddish brown (10R3/4), much darker than any of the other outcrops. The writer offers the following explanation for

this deceptive outcrop color. The Pierce Canyon redbeds in this area form low, evenly rounded hills which are surrounded by loose gypsiferous soils. During weathering, grains on the surface of the redbeds are loosened and dislodged from their original position. The individual grains or small rock fragments are moved by the wind which immediately introduces a sorting action. Shifting winds cause local deflation of the larger, lighter-weight material. The most abundant heavy mineral in the Pierce Canyon formation is fresh subspherical magnetite, averaging 0.03 millimeter in diameter, which is locally concentrated in placers less than 1 millimeter thick. Because the magnetite is more spherical and heavier than the lightweight quartz and feldspar fraction, it is the last to be deflated. The dislodged magnetite tends to concentrate in the cracks and open bedding planes of the parent rock while the lighter material is winnowed away. As there is little relief except for small shallow depressions cut into flat-lying siltstone, the rainwater run-off moves at a slow rate until it collects in the larger draws through the gypsiferous soils; hence, it does not remove the concentrated magnetite from the surface layer and the result is an abnormally dark red outcrop.

Red Point, the southernmost outcrop of the Pierce Canyon formation, is the north end of a steeply dissected northwest-trending escarpment in southeastern Culberson County, 10 miles north of Kent, Texas, 5 miles west of the Culberson-Reeves County line (NW¼ Sec. 20, Blk. 59, T. 7,

T&P RR Co.). Approximately 140 feet of Pierce Canyon redbeds are exposed at Red Point in the escarpment beneath a vertical cliff of Cretaceous conglomerate. The base of the outcrop is covered by talus, but the upper contact with the Cretaceous rocks is well exposed. Fitzpatrick (1950, p. 60, Measured Section 2) reported 143 feet of Pierce Canyon redbeds at Red Point. Samples from Deep Rock Oil Company's Seay No. 1 dry hole (Sec. 21, Blk. 59, T. 7, T&P RR Co.) 0.75 miles east of Red Point, indicate a Rustler top 130 feet below the surface. If 130 feet is added to the 143 feet, the figure of 273 feet so obtained may be a fair estimate of the thickness of the Pierce Canyon redbeds in this vicinity.

The lowest 90 feet of section on the outcrop is dull moderate reddish brown (10R4/6), thin-bedded siltstone and fine-grained sandstone with intercalated dark red clay laminae. The bedding planes are persistent and slightly undulose. A 10-foot ledge of silty, fine-grained sandstone is the only prominent change in the otherwise uniform slope below the Cretaceous contact zone. The uppermost 53 feet of section is lighter-colored; light brown to pale red (5YR6/4, 10R6/2), thin- to thick-bedded, silty, fine sandstone. The color change between the reddish brown and the light brown zones is gradational, but the contrast is most conspicuous immediately above a hard, clayey, very fine sandstone. All the beds included in the upper, light-colored zone are soft and crumpled. The only lithologic change is immediately beneath

the Cretaceous contact where 5 feet of light greenish gray (5GY8/1) clay caps the Pierce Canyon redbeds. There is a topographic break at the base of the vertical 5-foot clay zone that coincides with the brown to gray color change. The clay is not bedded, and there is no indication of structure other than vertical fissures which extend downward into the underlying brown siltstone. The fissures cross through the Pierce Canyon-Cretaceous contact immediately above the clay, but are hidden from view by the conglomeratic texture of the Cretaceous rocks.

The unconformable contact between the Pierce Canyon and the overlying Cretaceous is an irregular undulose surface with a maximum relief of 1.5 feet; it is marked by a distinct textural change from siltstone (Pierce Canyon) to sandy pebble-conglomerate (Cretaceous).

About 35 feet of Cretaceous rocks crop out above the contact along a dissected near-vertical cliff. Calcareous, silty clay forms the matrix of the pebble conglomerate in the lower part of the section; bedding is erratic and numerous thick-bedded silty-limestone lenses are interspersed with the conglomerate.

The westernmost exposure of the Pierce Canyon formation observed by the writer is 18 miles west of the Culberson-Reeves County line, 25 miles northwest of Kent, Texas, where 45 feet of Pierce Canyon redbeds (Travis, 1951, p. 37) occur in the trough of a northwest-trending syncline in the NW$\frac{1}{4}$. NW$\frac{1}{4}$ Sec. 5, Blk. 91, PSL. DeFord (oral communication) has reported one other small exposure in the SW$\frac{1}{4}$ NE$\frac{1}{4}$, Blk. 87, PSL,

Culberson County, Texas.

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

Rustler-Pierce Canyon contact.- The Rustler-Pierce Canyon contact is not exposed at the surface as far as the writer knows. R. K. DeFord (oral communication) states that he has never seen the contact exposed. Other geologists have suggested orally that the gypsiferous limestone overlain by red siltstone along the east side of the Pecos River valley in Eddy County, New Mexico, represents the Rustler-Pierce Canyon contact. The gypsiferous limestone referred to here 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 (1949, 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 throughout most of the Delaware Basin. An excellent example of this Rustler-caliche-red siltstone sequence is present in the subsurface 12 miles north-northwest of Maroon Cliffs. At this location, the Southwest Potash Company mine (SE¼ Sec. 9, T. 19 S., R. 30 E.), cores from two pilot-holes 5A and 6A clearly show the reason for the misidentification of the

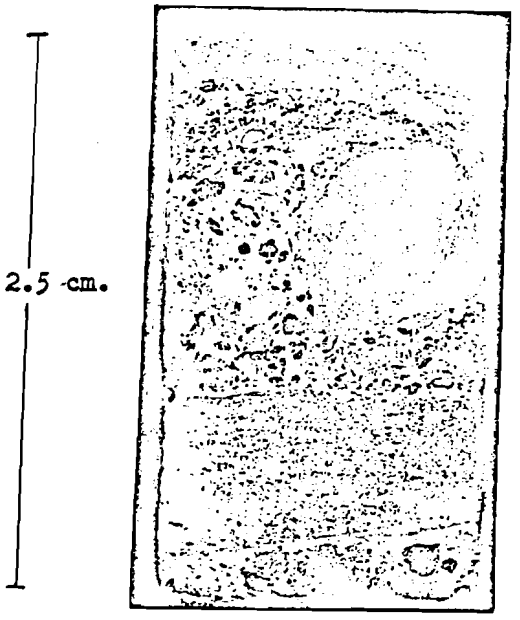


Fig. 12. Thin section No. 17 of core from Southwest Potash Company's pilot-hole 6A, SE¼ Sec. 9, T. 19 S., R. 30 E., Eddy County, New Mexico, showing reworked Pierce Canyon pebbles in the Gatuña sandstone (Cenozoic).

Rustler-Pierce Canyon contact. At 5A the contact between the Rustler dolomite 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 pilot-hole 6A, 450 feet north of 5A, the Rustler dolomite is overlain by 16 feet of caliche containing clay and silt and topped by 2 feet of caliche and reworked red siltstone from the Pierce Canyon formation (Fig. 12). The top of the Rustler dolomite in pilot-hole 6A is 3,130 feet above sea level or 23 feet higher than in pilot-hole 5A. Five thin sections representing 18 feet of core across the contact in pilot-hole 6A show that the lowest 4 feet of caliche contains about 4 per cent clay; the overlying 12 feet of caliche contains a few red rock fragments of siltstone and claystone that increase in abundance into the uppermost 2 feet of reworked Pierce Canyon pebbles and calcite cement. This upper 2-foot zone is the basal part of the Gatuña formation.

The caliche rests on an erosion surface. In some places where the caliche is absent the Gatuña sandstone, which is largely composed at this locality of reworked Pierce Canyon and Santa Rosa detritus, rests on the erosion surface; for example, in the Fletcher Potash Core Test (Lot 4, Sec. 1, T. 21 S., R. 28 E.) 12 miles northeast of Carlsbad, New Mexico, it is described by Lang (1942, p. 63) as follows:

> The 55 feet of material immediately beneath the surface sands and caliche are logged as gray sandstone. This may be interpreted as representing

> the basal part of the Santa Rosa sandstone which in surface exposures can be seen to grade into the underlying Pierce Canyon redbeds. The Pierce Canyon redbeds are 505 feet thick in this well. This thickness is exceptionally great for the formation and is especially surprising in view of the fact that the Rustler formation which underlies it is exposed at the surface less than a mile to the north. The Rustler section 320 feet thick in this well lacks about 100 feet of the top beds but otherwise it represents a normal thickness and succession of beds.

These samples were not available to the writer in 1953; nevertheless it seems evident that the redbeds are Gatuña rather than Pierce Canyon.

The coarse texture of the Gatuña sandstone is illustrated in Figure 12. This thin section was cut from a 2½-inch core that was almost indistinguishable in hand specimen from a typical sample of the Pierce Canyon redbeds. Differentiation of the Pierce Canyon redbeds from their reworked counterpart in the Gatuña sandstone in rotary drill cuttings is difficult because the size of the reworked pebbles is greater than the largest cuttings. Unless the Rustler or the Santa Rosa contacts can be verified, hand-specimen or binocular identification of these red siltstones (Pierce Canyon, Gatuña) is unreliable.

The Rustler-Pierce Canyon contact was observed in cores at U. S. Potash Company's No. 3 shaft (SE¼ Sec. 13, T. 20 S., R. 30 E.), 7 miles southeast of the Southwest Potash Company mine. Thin sections prepared from cores and representative of the lithology across the Rustler-Pierce Canyon contact show an abrupt textural and lithologic change from gray

anhydrite, containing a trace of red clay, to thin, evenly bedded, reddish brown siltstone. There are no reworked Rustler fragments in the Pierce Canyon, neither is there disturbed bedding to indicate the presence of reworked material in the past. A similar Rustler-Pierce Canyon contact was observed in pilot-hole cores at U. S. Potash Company's shaft No. 1 (center of S½ Sec. 12, T. 21 S., R. 29 E.) 5 miles south of shaft No. 3.

Distorted bedding and erratic Rustler "tops" have also been used as an argument in favor of a post-Rustler and pre-Pierce Canyon erosion surface. A surface of this type was described by L. P. Corbin, Jr. (Chief Geologist, Potash Company of America) during the sinking of Potash Company of America's shaft No. 4 (SE¼ Sec. 4, T. 20 N., R. 30 E.). Corbin's field note description of the subsurface contact is as follows:

to 90 feet; soft, red gritty mudstone (fine sand).

to 91 feet; very nearly pure shale with gypsum, very irregular pitching and sharp vertical dips, irregularities average 2 to 3 inches in width and depth.

to 97 feet; gypsum, on southwest side is a large zone, slickensided, dipping contact (dips northwest) between gypsum and shale. contact [Rustler-Pierce Canyon] very sharp no gradation. Contact 2 feet lower on southwest side than on northwest side.

to 101 feet; gypsum with red clay and granular gyp.

to 112 feet; at 107 feet horizontal fissures with black organic material, 3 inches above this fissure is a fine grained dolomite.

It is important to note once again, separately, the description of the exact contact as, "... very sharp no gradation" which has been the same in three widely separated cores previously discussed. There is evidence of movement along this surface, but cores of the Pierce Canyon redbeds typically show slickensided clay zones because of slump, and similar features at the contact have probably resulted from the same cause. In conjunction with the slickensided clay, the cores also show small-scale displacement, faulting, along the gypsum-filled joints (Fig. 6).

Slump and sinkhole features are common in the Rustler outcrops of Culberson County, Texas. Why then, should similar features be considered unusual when encountered in the subsurface of Nash Draw, Monument Draw, Clayton Basin, and the Pecos River valley where interior drainage is the rule rather than the exception? Ground water studies by Theis et al. (1942, p. 64) show that most of this region is lacking in surface drainage and that these surface depressions (Nash Draw, Monument Draw, Clayton Basin) were probably formed by the integration of chains of sinks. They have also stated that, in the vicinity of the potash mines where closely spaced potash test holes permit detailed correlation, there is a striking similarity between slumped beds in the Rustler and depressions in the underlying salt. Their correlations indicate that thin individual beds of the upper Rustler follow the undulations of the salt surface with little or no variation in thickness.

The erratic relief of the Rustler-Pierce Canyon contact has resulted from post-depositional slumping and/or Cenozoic erosion. Wherever the Rustler-Pierce Canyon contact was observed, either in shafts or cores, wherever thin sections and samples conclusively prove the Pierce Canyon to be in place, the contact is marked by an abrupt lithologic change from dense dolomite or anhydrite to thin-bedded siltstone.

Thickness of section.- At the subsurface type section in Loving County, near the center of the Delaware Basin, the Pierce Canyon formation is about 350 feet thick. Other oil tests in eastern Loving County have also encountered about the same thickness of red siltstone at the same stratigraphic position. Similarly, on the north rim of the basin at Nash Draw the formation has a thickness of 317 feet in Snowden and McSweeney's McNutt No. 1 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 sand which is believed to be Gatuña. DeFord (1942, p. 216) has stated that about 470 feet of "Dewey Lake" redbeds is present between 395 and 873 feet in the Halfway pool, Lea County, New Mexico, 30 miles east-northeast of Carlsbad. DeFord and Wahlstrom (1932, p. 59) have 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. At Red Point, in southeastern Culberson County, Texas, 273 feet of Pierce Canyon can be accounted for by combining the outcrop and subsurface thicknesses.

Elsewhere in the basin, reliable data are either not available or there is evidence that the sediments have been reworked during the Cenozoic.

Hundreds of deep oil tests have penetrated the Pierce Canyon redbeds in and around the Delaware Basin, but, before crediting thickness measurements derived from poorly preserved rotary-drill cuttings, one should consider the late-Cenozoic history.

The Pierce Canyon redbeds covered a structural basin that has during the Cenozoic Era undergone slow subsidence induced by solution and subsequent displacement of the underlying salt and gypsum. Stream erosion accompanied the subsidence and a maze of channels were cut and filled in the Pierce Canyon strata. A few of these channels are evidenced by the erratic thicknesses of the post-Rustler deposits. These formations were truncated along the northern and western margins of the basin. Synclines and sink holes protected all that remains of the Pierce Canyon redbeds in these regions. Most of the sediment resulting from this erosion was transported into the basin. Basinward slump along the reef-front, as indicated by the synclines on Plate 4, resulted in structural depressions that were filled with almost 2,000 feet of Cenozoic detritus. The thickness of this detritus has been discussed by Maley and Huffington (1953, p. 541); they recognize three separate major accumulations. Red siltstone, resulting in part from the reworked Pierce Canyon redbeds, is a common constituent of this detritus. Thus it appears that without more cores, we shall never be able accurately to measure and

separate the Pierce Canyon formation from its reworked counterpart in the Cenozoic fill, although the two could be distinguished in cuttings from the cable-tool wells of the preceding generation.

Santa Rosa Sandstone

N. H. Darton (1921, p. 183) applied the name Santa Rosa to a prominent sandstone-and-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 its vertebrate fossils and its position beneath the Chinle shale, the Santa Rosa is considered to be Upper Triassic in age and equivalent to the Shinarump conglomerate farther northwest. In the Delaware Basin the Santa Rosa formation consists of moderately well-sorted medium sandstone with large crossbeds and well-sorted, uniformly thin-bedded siltstone. The sandstone and siltstone are typically moderate reddish brown (10R4/6) and for all practical purposes identical in color to the Pierce Canyon redbeds.

No comprehensive description of the Santa Rosa sandstone in Texas has been published, although numerous writers (Sidwell and Gibson, 1940, and Sidwell, 1945; Lang, 1947; Adams, 1929; and Green, 1954) have mentioned its occurrence or described its mineral content at isolated 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, bounded at the base by a well exposed unconformable contact (Fig. 10) with the Pierce Canyon redbeds and truncated at the top by a Pleistocene (Bretz and Horberg, 1949; p. 493) erosion surface now marked by caliche. The Chinle formation, also of Upper Triassic age, is exposed in Sec. 4, T. 21 S., R. 30 E. about a mile east of Maroon Cliffs.

In the central part of the Delaware Basin the Santa Rosa sandstone is locally referred to as the Barstow (Adams, 1929, p. 1052). It forms a low, red, southward-trending escarpment that intersects U. S. Highway 80 (Pecos to Odessa) east of Barstow, Texas. A smaller, less prominent part of this same trend crops out 12 miles south of Barstow on U. S. Highway 285, approximately 13 miles southeast of Pecos in the NE¼ Sec. 12, Blk. 51, T. 7, T&P RR Co. The latter location is the most southerly outcrop of Santa Rosa sandstone known to the writer, although the Bissett sandstone crops out south of the Delaware Basin. The escarpment is the result of Cenozoic slump and truncation and is the western limit of Santa Rosa outcrops.

Triassic sandstone, presumably Santa Rosa, has been described in oil tests in the southern part of the Delaware Basin, beneath Cretaceous conglomerate.

At Maroon Cliffs in Eddy County, New Mexico, the Santa Rosa formation is composed of reworked Pierce Canyon pebbles in coarse sand which grades upward into medium-to-fine sand and silt. The lowermost

10-15 feet of the Santa Rosa sandstone contains large crossbeds, a few of which are foreset beds up to 15 feet long (Fig. 8); the crossbeds have a mean dip of 9° northwest and an amplitude of 2 to 3 feet. Lesser crossbeds, which terminate within a few inches, are common.

Interstratified with the crossbedded sandstone are thin layers of evenly bedded siltstone. The mineral assemblages of the sandstone and the siltstone are about the same, the most conspicuous difference being the abundance of platy minerals associated with the finer grain-sizes. Thin pebble-conglomerates, although not typical of any particular horizon, are common. Sidwell and Gibson (1940, p. 5) have reported two thin layers of conglomerate, one 15 feet above the base of the formation and the other 20 feet below the top in Guadalupe County, New Mexico.

In the vicinity of Roswell, New Mexico, the Santa Rosa sandstone is a persistent aquifer (Theis et al., 1942, p. 65; Sayre et al., 1942, p. 77). Little information is available concerning the quality of the water in Texas but it is useful for stock purposes near Pecos and farther east (Sayre et al., 1942, p. 77, 82, 97). Farther south, along the escarpment at Barstow, Texas, where the Santa Rosa sandstone is well cemented by calcite, vertical jointing has resulted in rectangular blocks; it was formerly quarried as a building stone. Quarrying operations were restricted to the Barstow vicinity.

Exploration for radioactive minerals in the Santa Rosa formation of Texas and southeastern New Mexico is currently active. Lignitized

and mineralized wood in the basal conglomerate of the Santa Rosa is slightly radioactive.

Stratigraphic Equivalents of Pierce Canyon Redbeds

Many of the formations in the Delaware Basin, Salado, Rustler, Pierce Canyon, Santa Rosa, and Chinle, have counterparts in the Midland Basin, east of the Central Basin Platform. The Pierce Canyon counterpart is currently referred to as the Dewey Lake formation. In brief chronological order the history of these two formations is as follows.

Adams (1929, p. 1045) was among the first to recognize the Permian-Triassic redbed problem as one of considerable importance. He described (p. 1052-53) ten criteria for differentiating Permian and Triassic redbeds in west Texas.

Cartwright (1930, Pl. 2, p. 970) originally correlated the redbeds, now assigned to the Pierce Canyon and Dewey Lake formations, with the Quartermaster redbeds of central Texas.

In 1932, DeFord and Wahlstrom (1932, p. 59) described the stratigraphic position of the redbeds from Hobbs field, Lea County, New Mexico as follows:

> ... these beds beneath the Santa Rosa sandstone and above the Rustler anhydrite are readily correlated with Red-beds in similar position elsewhere in Lea and Eddy counties that contain small amounts of anhydrite or gypsum which relate them to the

> underlying Rustler and distinguish them from the overlying Dockum. In short they have many of the characteristics of Permian Red-beds, which are well described by Adams (1929).

Walter B. Lang (1935, p. 264) described and named these redbeds the Pierce Canyon formation from the subsurface of the Delaware Basin in east-central Loving County, Texas. He described the Pierce Canyon as 350 feet of red siltstone above the Rustler and below the Santa Rosa formations and assigned it to the Permian.

The same year, John E. Adams (1935, p. 1021-22) reported the Pierce Canyon formation in the Midland Basin as "... the uppermost Permian clastics of the southern basin." Adams discussed the lithology in detail and his description is almost identical to Lang's original description. Adams described the lower contact of the Pierce Canyon formation as "... a sharp change from red clastics of the basal Pierce Canyon and the white evaporites of the upper Rustler." He stated that the Rustler itself grades into redbeds on the southern margin and that the two formations, Rustler and Pierce Canyon, are separated by a zone of frosted quartz grains. The upper contact was described by Adams as follows:

> The Pierce Canyon Red-beds are separated from the overlying Triassic by a marked erosional unconformity and a decided change in lithologic character.

The age was stated to be Permian.

> The Pierce Canyon forms a distinct subsurface unit over the central portion of the Permian basin. No outcrops are known and no fossils have been reported from the cuttings and cores. Unlike the older Permian beds, the Pierce Canyon clastics do not grade into Permian dolomites and limestones. But the close similarity of lithologic character and structure links these beds firmly with the underlying formations which are definitely of Permian age. Apparently, these Red-beds were the final deposits of the retreating Permian sea and they are, therefore, the youngest known Permian deposits in the southern United States.

Two years later Lang (1937, p. 876, fn. 38), having changed his ideas concerning the age of the Pierce Canyon, stated, "The Pierce Canyon redbeds are now placed in the Triassic and may be related to the Bissett [Triassic]." This change was made because he had found evidence of a gradational contact between the Pierce Canyon and the overlying Santa Rosa in northern Eddy County, New Mexico.

Page and Adams (1940, p. 62) redescribed the redbeds of the Midland Basin, previously named the Pierce Canyon formation, and after reviewing their lithology and stratigraphic position called them the Dewey Lake formation. They stated that the Dewey Lake redbeds have a conformable contact with the underlying Rustler formation and an unconformable contact, marked by a bleached zone, with the overlying Tecovas (pre-Santa Rosa, Triassic) formation. They described the Dewey Lake redbeds from cable-tool cuttings and designated a type subsurface stratigraphic section in R. R. Penn's Habenstreit No. 1 (dry hole) located near the center of Sec. 47, Blk. 36, T. 3 S., T&P RR Co., Glasscock County,

Texas, drilled in 1932 and abandoned at a total depth of 3,810 feet. The general lithology of the Dewey Lake formation was described from a 261-foot red siltstone sequence with gypsum cement and sporadic concentrations of rounded, frosted, quartz grains. The overlying Tecovas formation is described by Page and Adams (1940, p. 63) as 30 to 200 feet of rock that closely resembles the underlying, undisturbed Permian. With reference to the lithologic difference between the Tecovas and Dewey Lake formations Page and Adams described the Tecovas as having a "... rich crop of new heavy minerals", increased biotite content, and less induration. They further stated that the upper beds of the Tecovas grade into the overlying Santa Rosa formation.

Also during 1940 Dickey (1940, p. 50, fn. 22) concluded as the result of a regional subsurface study in the vicinity of Lea County, New Mexico, that

> ... the top of the Rustler is an erosion surface on which the Dewey Lake sands were deposited.

A few years later, Adams (1944, p. 1601) stated that the Pierce Canyon redbeds of the Pecos Valley were similar lithologically to the post-Dewey Lake redbeds of the southern Permian Basin and to the Quartermaster redbeds of the Texas Panhandle.

Later, Lang (1947, p. 1673) described some of the rocks exposed on the east side of the Pecos River valley in southeastern New Mexico. He identified two types of redbeds at this location: "(1) coarse to

fine-grained arkosic grits, sandstones and siltstone, ..." which he refers to as the Santa Rosa sandstone of the Dockum group, and

> "(2) another sequence of fine-grained, evenly bedded sandstones and siltstones described as the Pierce Canyon redbeds of the Dockum group and also considered to be Upper (?) Triassic in age, though no critical fossil evidence has ever been found in them. Field investigations, however, have disclosed that the Santa Rosa sandstone grades into the Pierce Canyon redbeds and that they are, in part, contemporaneous in origin."

Whether or not the Dewey Lake redbeds in the Midland Basin are stratigraphic equivalents of the Pierce Canyon redbeds, as originally described in 1935 by Lang, in the Delaware Basin, has remained a disputed question. In effect, no correlation has been completely acceptable, largely because of the lack of identifiable characteristics in these redbeds. The present investigation has shown that the Pierce Canyon, Dewey Lake, and Quartermaster formations have almost identical mineral assemblages.

PETROLOGY

Texture

The Pierce Canyon redbeds, which rest upon the Rustler evaporites, consist of 350 to 450 feet of siltstone, devoid of chemically deposited beds. Gypsum, calcite, and hematite cement constitute the only important chemical precipitates in the Pierce Canyon redbeds. There is no consistent textural difference within the redbeds either vertically or horizontally. Nearly all the material is classified as medium or coarse siltstone, and the extreme textural range is from claystone to clay-pebble conglomerate. Neither the claystone nor the pebble conglomerate forms persistent beds that extend more than 0.25 mile. Two 10-foot zones contain large, rounded, frosted quartz and orthoclase grains at Maroon Cliffs, Eddy County, New Mexico; one zone 265 feet above and the other 115 feet above the top of the Rustler, both contain 3 to 5 per cent well-rounded and frosted grains larger than 0.4 mm. in diameter. The two zones were not detected in U. S. Potash Company's shaft No. 3, 4 miles north-northwest of Maroon Cliffs, although DeFord states (oral communication) that he has made use of one of them in subsurface correlation as far as Monument, in eastern Lea County, New Mexico, 35 miles east of Maroon Cliffs.

Fifteen samples were selected from a pilot-hole core (U. S. Potash Company shaft No. 3, SE$\frac{1}{4}$ Sec. 13, T. 20 S., R. 30 E.) to represent the

entire textural variation in the section. Thirteen of the fifteen samples used in the textural analyses were thin-sectioned in order to provide an optical check on the size distribution of the grains. The 13 thin sections exhibit the typical size variation observed in the Pierce Canyon samples throughout the area studied.

From 20 to 30 grams of rock were crushed with a rubber pestle and leached in warm dilute (1:10) hydrochloric acid until all of the hematite stain and cementing minerals were removed. The wet sample was then rubbed with the fingers on rubber sheeting until disaggregation was complete. The samples were air dried and sieved at an interval of $\frac{1}{4}\,\phi$ ($\frac{1}{4}$ Wentworth grade) and the silt and clay were analyzed by means of the pipette procedure described by Krumbein and Pettijohn (1938, p. 167). A 0.002 molar solution of sodium pyrophosphate ($Na_2P_2O_7$) was used as a dispersing agent during pipette analyses. Results from these analyses are shown in Figure 14 and Table 1. Parameters used in this table are from Folk (1954*b*).

Mean Size $M_Z = \dfrac{\phi 16 + \phi 50 + \phi 84}{3}$

Sorting (Inclusive Graphic Standard Deviation) σ_I

$$\sigma_I = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

Skewness (Inclusive Graphic Skewness) Sk_I

$$Sk_I = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

Kurtosis $K_Z = \dfrac{\phi 95 - \phi 5}{2.44(\phi 75 - \phi 25)}$

TABLE 1

TEXTURAL ANALYSIS OF PIERCE CANYON DETRITUS

Phi Median Md_ϕ	Mean size ϕ M_Z	Mean size mm. M_Z	Sorting σ_I	Skewness Sk_I	Kurtosis K_Z
5.0	5.3	.024	0.95	+ .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

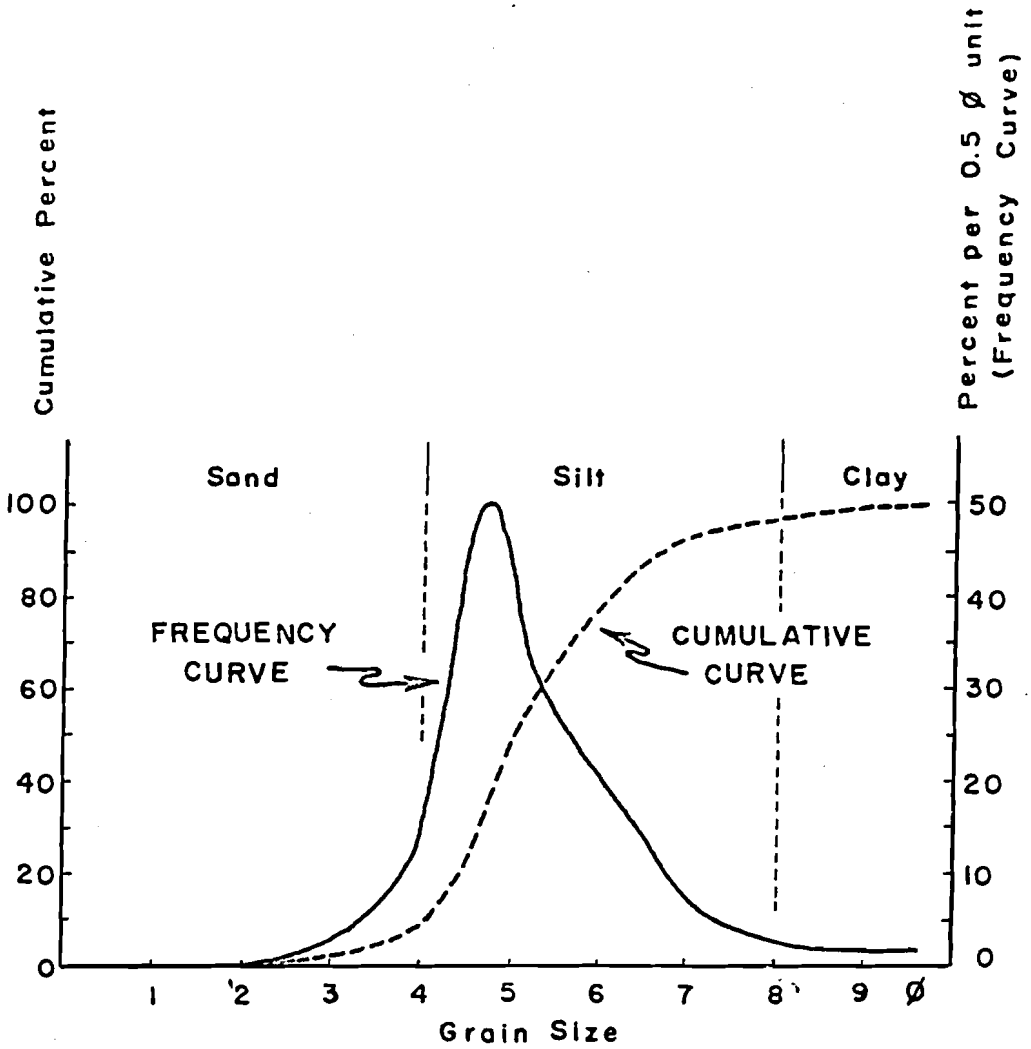


Fig. 13. Summation of textural data from 15 samples, representative of a vertical section of the Pierce Canyon redbeds, Eddy County, New Mexico.

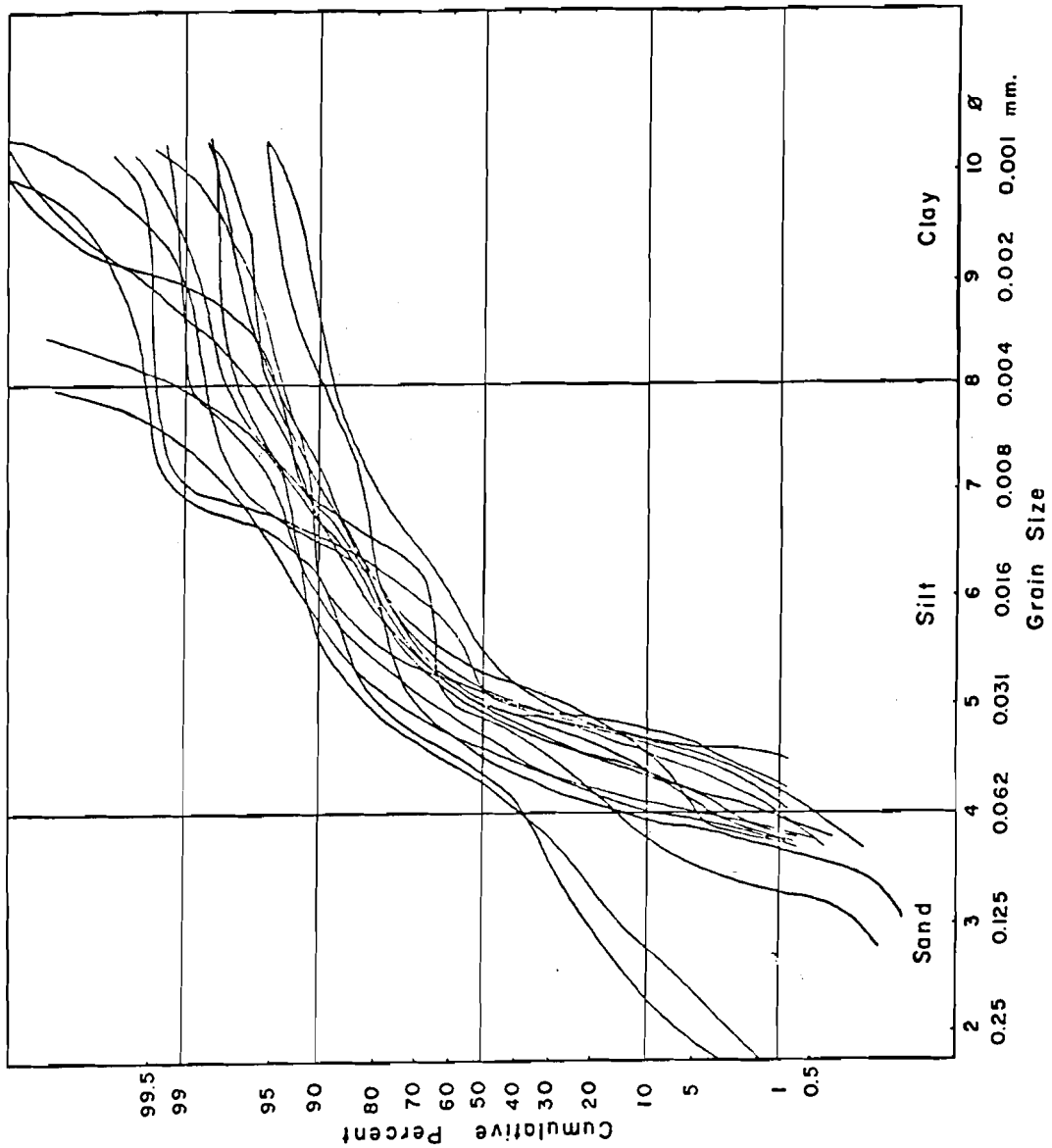


Fig. 14. Cumulative curves representative of the textural distribution of 15 samples from the Pierce Canyon redbeds, Eddy County, New Mexico.

These analyses show that none of the samples contained more than 10 per cent clay and that only 4 of the 15 samples contained more than 10 per cent sand. Summing the results of all the grain-size analyses yields a total size-distribution in this typical Pierce Canyon section of 9 per cent sand, 87 per cent silt, and only 4 per cent clay, as shown in the cumulative curve, Figure 13. The dominant type of sediment is a medium-to-coarse silt having a mode of 4.8ϕ (.036 mm.) a median diameter of 5.0ϕ (.031 mm.) and a mean of 5.2ϕ (.029 mm.). The grain-size analyses are illustrated in Figure 14 where the data have been plotted on phi-probability paper to accentuate the tails of the curves. Such a uniform grain-size distribution throughout the stratigraphic section suggests that the mechanics of transport and the size of the material contributed to the basin remained almost unchanged throughout Pierce Canyon time.

Optimum sorting occurred in the coarse-silt class where the standard deviation (σ_I) was 0.7 phi units (0.7 Wentworth grades), and values for σ_I ranged up to 1.5ϕ. A sorting value (standard deviation) of 0.7 means that 68 per cent of the sample lies within 0.7 Wentworth units on either side of the mean grain-size.

The sorting value σ_1 was plotted against mean grain-size (Fig. 15) to show sorting as a function of the mean grain-diameter. The linear relationship between the two variables is expressed by the equation $\sigma_1 = 0.60 + |M_Z - 4.9\phi| \pm 0.20$, which indicates that optimum sorting

occurred at a mean grain-size of 4.9ϕ (0.032 mm.), that is, both finer and coarser sediments are more poorly sorted. The definitions used here are: very well sorted sediments have a σ_1 less than 0.35; well sorted sediments, 0.35-0.50; moderately sorted, 0.50-1.00; poorly sorted, 1.00-2.00; and very poorly sorted sediments have a σ_1 larger than 2.00. These samples as a whole are poorly-to-moderately sorted because the sorting measure includes nearly all (90%: i.e. ϕ95 to ϕ5) of the curve. Consequently small amounts of clay and sand increase the sorting value. If σ were computed as the spread between ϕ16 and ϕ50, basing the sorting only on the coarse-silt mode, the standard deviation would then be between 0.4 and 0.7 (well to moderately sorted). In these samples, sediment with a mean diameter corresponding with the modal diameter of the predominant silt is also the best sorted. When weaker currents contributed finer silt and a little clay to this predominant silt grade they worsen the sorting. Stronger currents that contributed sand also worsened the sorting, because they added coarser grains to the dominant silt grade.

Notice that all but one of the 14 samples are fine-skewed, most of them markedly so, as shown by the open circles on the right side or fine wing of the size-vs.-sorting diagram (Fig. 15). This skewness was also caused by the depositional mechanism, i.e., samples having only the silt mode are symmetrical but the addition of subordinate amounts of finer materials to the unchanging silt grade causes the curves to have a

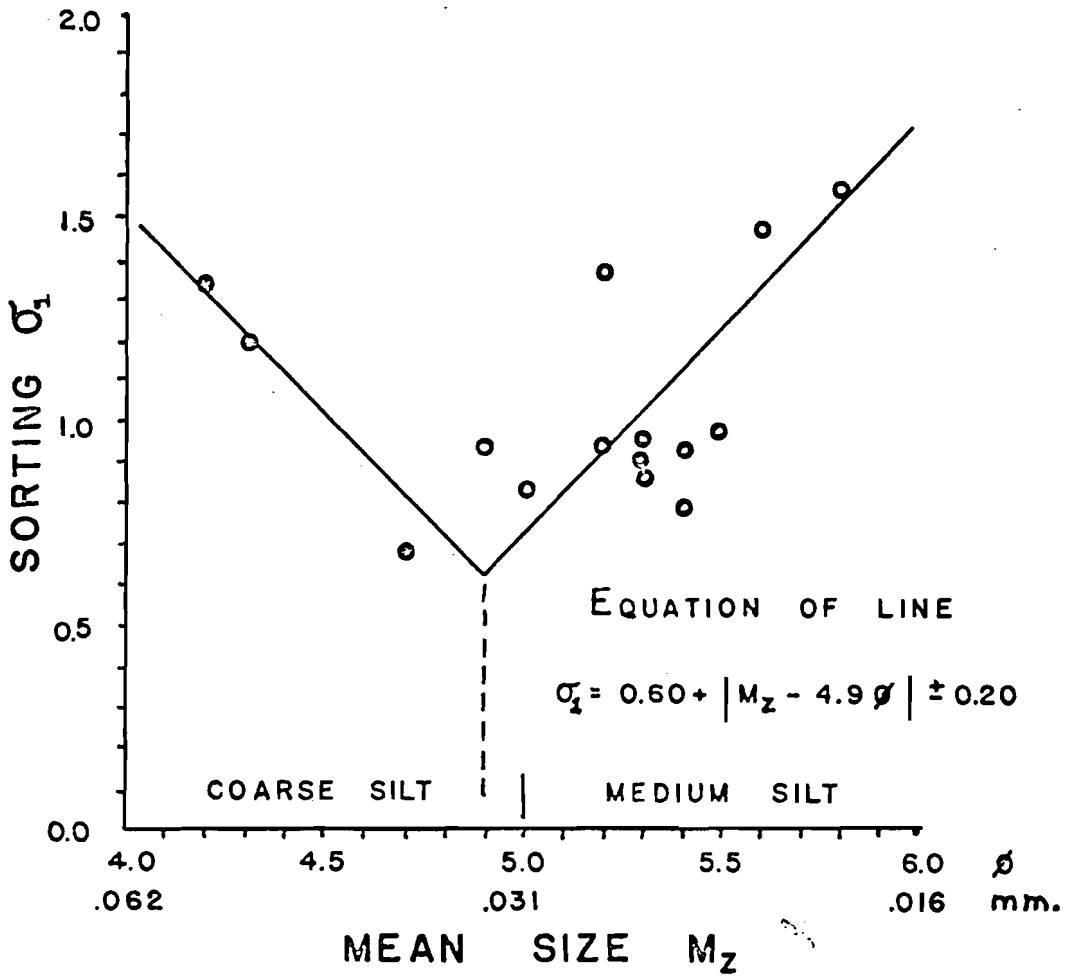


Fig. 15. Sorting vs. mean grain size: 4.9ϕ is the mean grain diameter for all the samples, open circles represent samples that are excessively fine-skewed, solid circles represent samples with nearly symmetrical frequency curves.

tail to the right and become fine skewed. Thus skewness is, like sorting, a function of mean grain-size as shown in Figure 16.

In most sedimentary distributions it has been found (Griffths, 1951, p. 237) that optimum sorting occurs at a mean size of about 2.5 ϕ (fine sand); for this reason, it is unusual that in the Pierce Canyon optimum sorting corresponds with a mean value of 4.9 ϕ. Most samples of sedimentary rocks that have a similar mean grain-size show a standard deviation of 1.5 to 3.0, representing much poorer sorting. The Pierce Canyon silt is much better sorted than other sediments of this mean grain size.

The equations for skewness and kurtosis may be new to many geologists. They are adapted from the mathematicians' standard, the Gaussian curve, and employ relationships utilized by statisticians for many years in the analysis of all types of data. The kurtosis measure as used here considers the grain-size spread from $\phi 95$ (95%) to $\phi 5$ (5%). In the normal Gaussian or probability curve the spread from $\phi 95$ to $\phi 5$ is exactly 2.44 times the spread from $\phi 75$ to $\phi 25$. Therefore, a curve more peaked than the normal Gaussian curve has a value of K_Z greater than 1.0, indicating an excessive concentration of grains about the mode and a deficiency of grains in the coarse and fine wings. Pierce Canyon redbeds are nearly all leptokurtic with K_Z greater than 1.00, again because of the uniform silt-mode with an abnormally large concentration of grains of silt size. There appears to be a relationship between

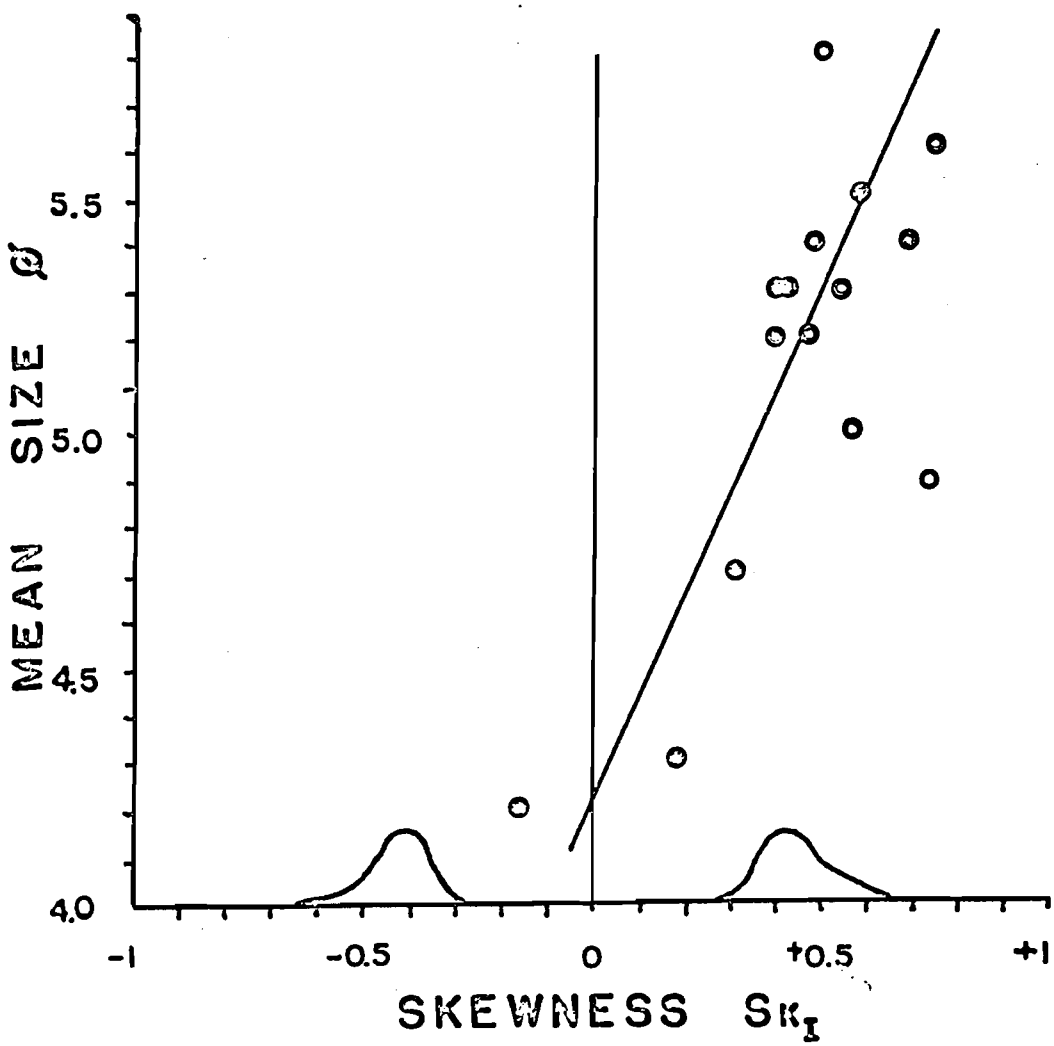


Fig. 16. Skewness vs. mean grain size: open circles represent samples that are excessively fine-skewed, solid circles represent samples with nearly symmetrical frequency curves.

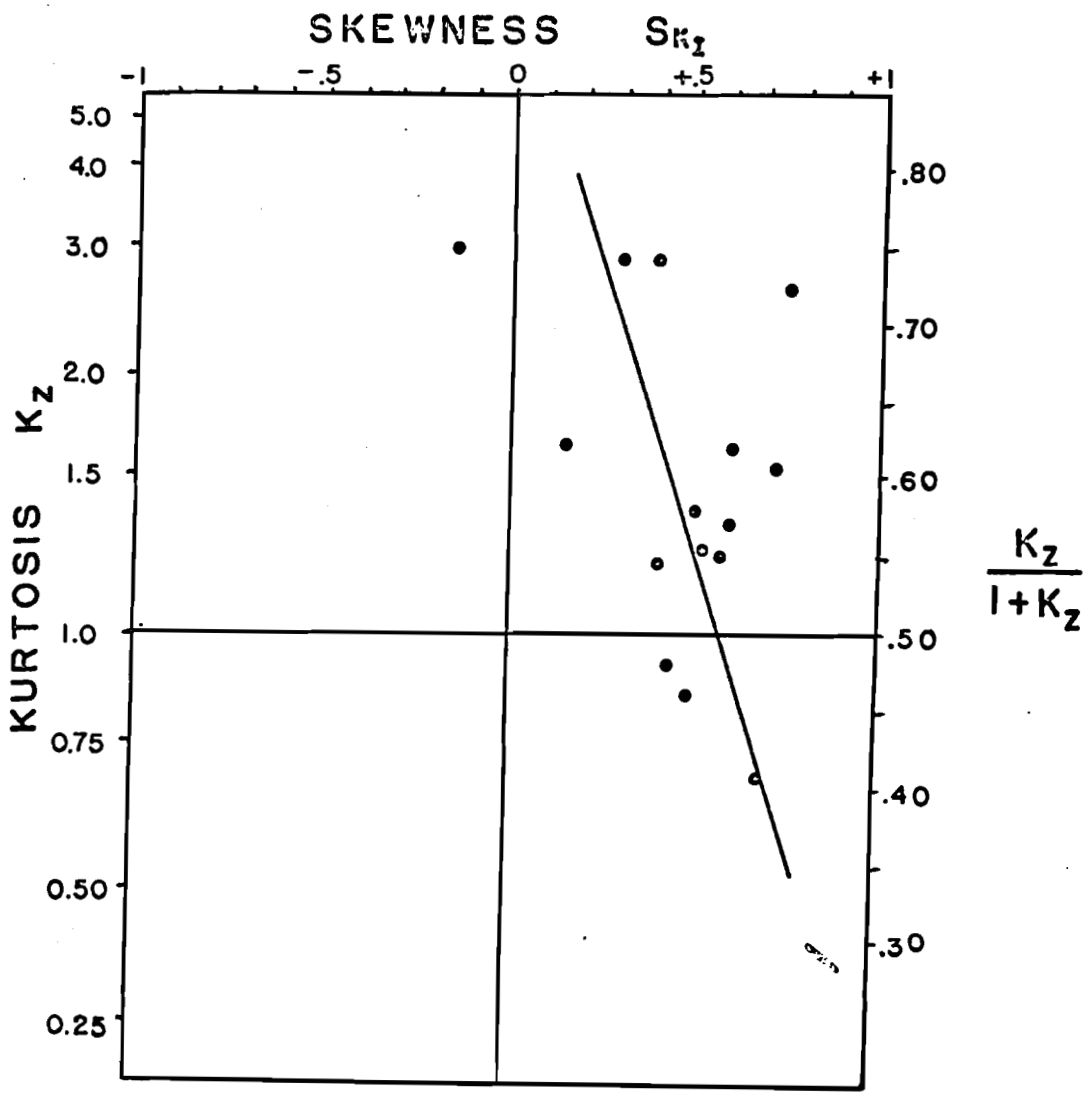


Fig. 17. Skewness vs. kurtosis for 15 samples of the Pierce Canyon redbeds from Eddy County, New Mexico.

skewness and kurtosis as indicated by the scatter diagram in Figure 17. Folk (oral communication) has found that plots of skewness versus kurtosis are of considerable help in differentiating sedimentary environments.

The coarsest material in the Pierce Canyon redbeds is pebble conglomerate, which consists of well rounded, slightly indurated mud-balls less than 2 cm. long, that were locally derived from partly consolidated sediment as the result of wave or current action, for their composition resembles that of the subjacent rock. Mud-balls and clay-balls of granule size (Fig. 18) are believed to have a similar origin. Neither the pebbles nor the granules form persistent beds.

The sand-size material consists of quartz and orthoclase and traces of microcline, chert, and sanidine. Grains larger than 0.1 mm. are typically moderately-to-well rounded with moderate sphericity, becoming progressively more angular in the smaller sizes. Grains larger than 0.1 mm. have frosted surfaces, uniformly roughened with shallow cresentic-shaped pits, probably by impact abrasion during wind transport, whereas the finer grains typically exhibit smooth irregular surfaces.

From 80 to 90 per cent of the Pierce Canyon formation is silt. With two minor exceptions (sanidine and illite), all detrital minerals listed under the heading "Mineralogy" are represented in the silt fraction. Except for chert, most of the grains in the coarse silt

[illegible] section [illegible] (AZ) of mud tank in [illegible] Canyon redbeds, Eddy County, New [illegible].

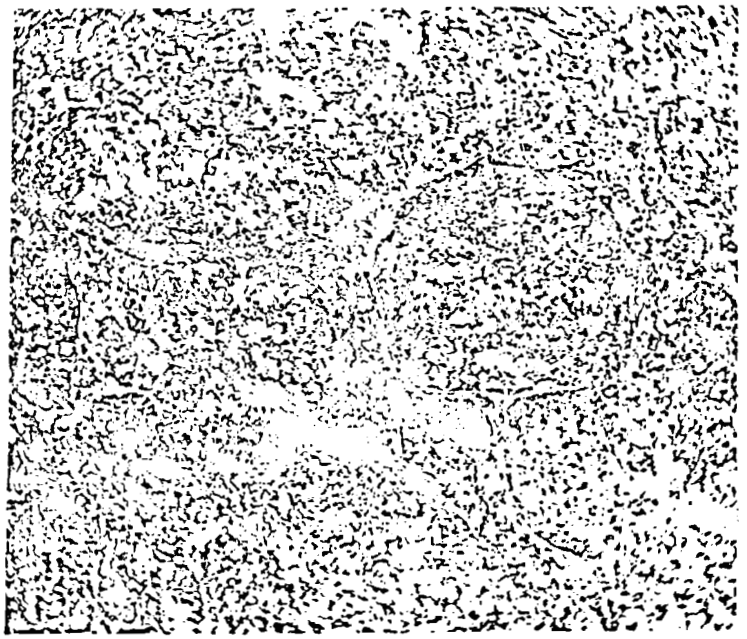


Fig. 18. Thin section No. 30 (X25) of mud balls in Pierce Canyon redbeds, Eddy County, New Mexico.

fraction (0.031 to 0.062 mm.) are subangular to subrounded. Grains finer than 0.031 mm. are subangular to angular. Grain surfaces are typically fresh and shiny regardless of their angularity.

The silt fraction is composed of 75 to 85 per cent quartz, 20 to 30 per cent orthoclase, 1 to 5 per cent microcline, traces of plagioclase, chert and detrital calcite, 1 to 3 per cent muscovite, biotite, chlorite, and 1 per cent metamorphic rock fragments, and 1 to 5 per cent magnetite-ilmenite, tourmaline, zircon, leucoxene, apatite, and garnet.

Clay, identified by X-ray diffraction patterns as illite by Carl Linden, Department of Ceramic Engineering, The University of Texas, is widely but sparsely distributed throughout the formation. Claystone is restricted in the formation to occasional laminae or beds less than 2 inches thick. Those who have seen the Pierce Canyon formation in the field or examined its cuttings under the low-power binocular microscope will question the small (less than 10 per cent) amount of clay reported herein, because outcrop and subsurface samples appear to contain a higher percentage of clay. Over-estimation is attributed to the smooth surface of the hematite stain, which connects the grains and masks their true size. What appears to be clay is actually very fine-grained quartz silt having a diameter of about 0.007 to 0.015 mm. The small amount of clay is significant, because it suggests the scarcity of clay at the source and winnowing during transport.

The predominant coarse silt mode in these samples is attributed to

eolian transport of the material. This hypothesis is partly verified by comparing the median grain-size of 4.2 ϕ to 5.8 ϕ, with the grain-size of wind-blown loess deposits in Kansas and elsewhere, 4.3 ϕ to 5.6 ϕ (Swineford and Frye, 1951, p. 309). Eolian transport is also evinced by the uniform size and the lateral distribution of this uniformly sorted sediment over more than 15,000 square miles of a flat terrane, which is now in western Texas and southeastern New Mexico. The vertical grain-size distribution is equally uniform; other than an occasional local accumulation of rounded and frosted sand grains, no textural difference shows any significant change in the mechanism or competency of transport during Pierce Canyon time.

Like loess, the Pierce Canyon siltstone contains a small amount of clay, which probably resulted largely from scarcity at the source and to a lesser extent from the ineffectiveness of wind alone to erode clay. Most clays originate from the chemical decomposition of feldspar or other aluminum silicates. The feldspar in this detritus is fresh (p. 71) and, except for minor sericitization, the grains show no evidence of chemical decay. Inasmuch as chemical decomposition requires water, this evidence suggests that the source was under the influence of an arid or semiarid climate, and probably little clay developed at the source during weathering.

Sedimentary Structures

Outcrop and thin-section examination shows that most of the detritus

was deposited as an intricate maze of very fine cross-laminae. Most of the crosslaminations are not apparent in hand specimen or on the outcrop and are visible only in thin section. The larger crossbeds are more obvious, for the length of their foreset beds ranges from a few millimeters to 4 to 5 feet. The smaller, more common, type of very fine crosslamination is illustrated in Figure 4 where the individual sets have resulted from formation as a rippled surface. This type is the result of gentle current eddies or small waves that heap the loose detritus, then spread it evenly as the turbulence recedes. Such waves and eddies are common in very shallow water where a light breeze ripples the surface and imparts to it a slight forward motion. A single wave or eddy may arrange the loose bottom material into a rippled surface while the following wave or eddy destroys or at least modifies it. The larger, more prominent crossbeds were measured on the outcrop. At Maroon Cliffs the crossbeds have a mean dip of 13° northwest, below the "blocky" sandstone, indicating a transport direction from south to north. The detritus must have been continually shifted by uniform and gentle currents, for elongate and platy minerals (including even quartz, some tourmaline and zircon and nearly all the mica) are well oriented with their longest dimension parallel to 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 to the crosslaminations.

Grain orientation is especially evident in the clayey zones where the mica flakes are concentrated. Similar orientation of elongate minerals occurs in the parallel beds, but parallel bedding is rare in the Pierce Canyon formation. Graded bedding, which might indicate different settling rates, is lacking.

The small amount of clay in the detritus is believed to have been flocculated by the salt water previous to deposition, and the flocculated clay was probably transported along the sea bottom together with the silt but was only rarely deposited with it because of its different hydraulic behavior. Some of the clay became aggregated by rolling during transport to form minute balls (Fig. 18), which were deposited with the heavy minerals in placers. At other brief intervals wave or current action was more intense as evidenced by the local distribution of rounded, granule- or pebble-size mud- or clay-balls in a matrix of silt and sand.

Two major transporting agents carried the Pierce Canyon detritus to the final depositional site. The first was the wind, which deflated the loess-size silt and sand as dust clouds from a relatively arid, nearly clay-free source, carrying the silt and rounding and frosting the sand, and deposited them in shallow saline water. The second transportation agent was the water, which received the wind-blown detritus, resorted it by means of gentle currents and small waves, and finally deposited it almost grain by grain in finely laminated crossbeds.

[illegible]. [illegible]ward view of preconsolidation slump folds in the Dewey Lake redbeds along Champion Creek, in Mitchell County, Texas; 4.2 miles south of Colorado City, [illegible] miles south-southeast of Seven Wells School and [illegible] west of Texas State Highway 208.

Fig. [illegible]. [illegible] structure in the Dewey Lake redbeds along Champion Creek, Mitchell County, Texas; same location as Figure 19.

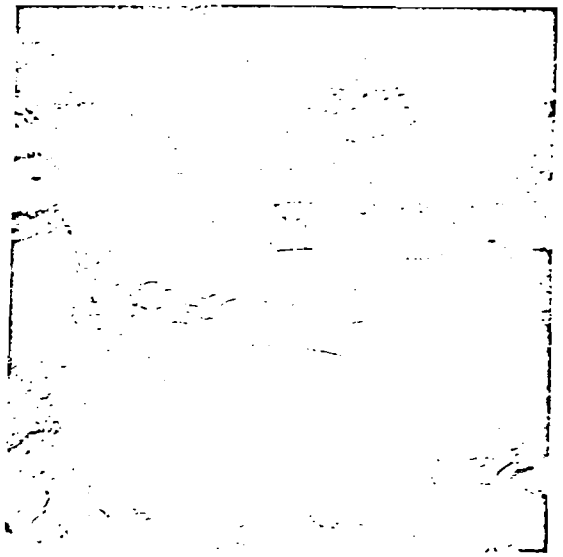


Fig. 19. Southward view of preconsolidation slump folds in the Dewey Lake redbeds along Champion Creek, in Mitchell County, Texas; 4.2 miles south of Colorado City, 0.8 miles south-southeast of Seven Wells School and 1.1 miles west of Texas State Highway 208.

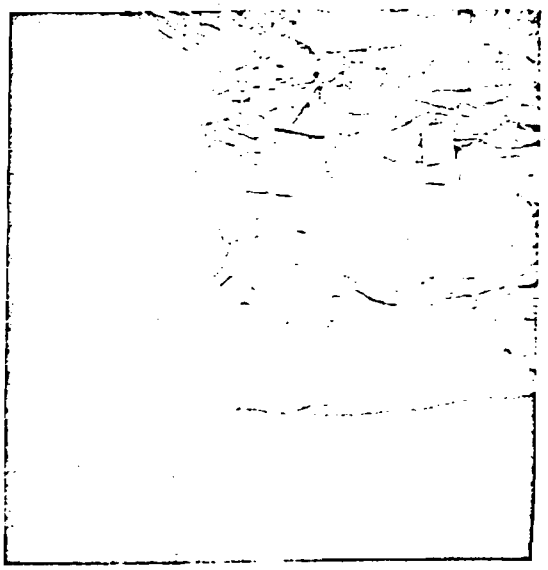


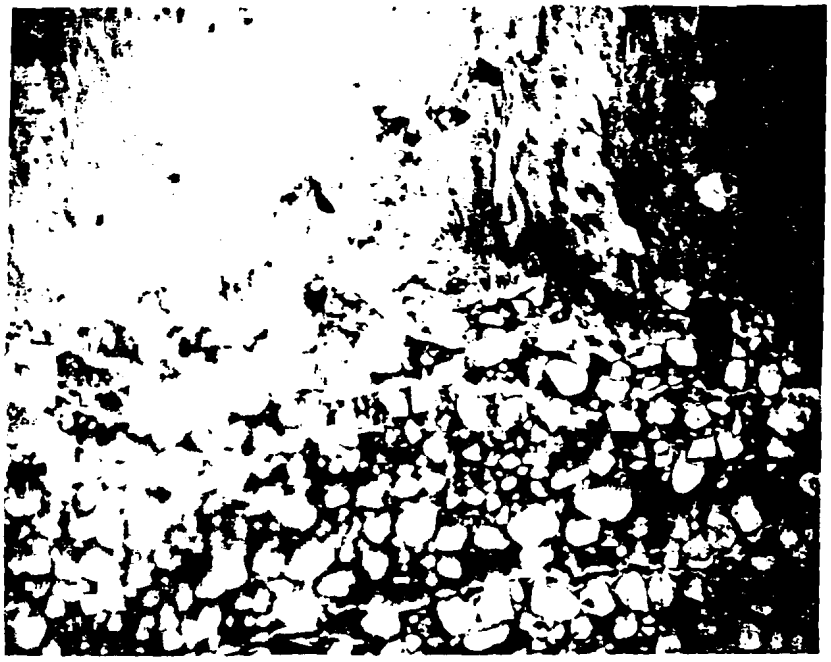
Fig. 20. Southward view of mushroom shaped slump structure in the Dewey Lake redbeds along Champion Creek, Mitchell County, Texas; same location as Figure 19.

Following deposition in the shallow saline sea the sediments were buried by the influx of more detritus. Differential settling and compaction resulted in local slump features in some zones. In a few places, such as the Dewey Lake outcrops near Colorado City, Texas, slumping has distorted the bedding into small folds and even mushroom-shaped domes as illustrated in Figures 19 and 20.

Much later, during the Cenozoic Era, the Pierce Canyon redbeds slumped as huge blocks into karst depressions that resulted from the removal of the underlying salt and gypsum. More or less contemporaneously with subsidence gypsum veins intruded permeable and fractured zones parallel to the bedding planes; and, as the crystals of gypsum grew, they spread the grains apart by the force of crystallization, and disrupted the bedding as shown in Figures 21 and 22.

Detrital Minerals

The detrital minerals of the Pierce Canyon red arkosic siltstone constitute a distinct and nearly homogeneous assemblage, which is similar to the detrital mineral assemblage of the Rustler formation below and unlike that of the Santa Rosa formation above. The areal extent of the formation is not fully known (Map 3[illegible]), but outcrop and subsurface samples from the Delaware and Midland Basins (including the Dewey Lake formation), more than 200 miles apart, have almost identical composition and texture.



[illegible] section No. [illegible] (X [illegible] plain light) of gypsum vein disrupting the bedding and displacing the grains, Eddy County, New Mexico.

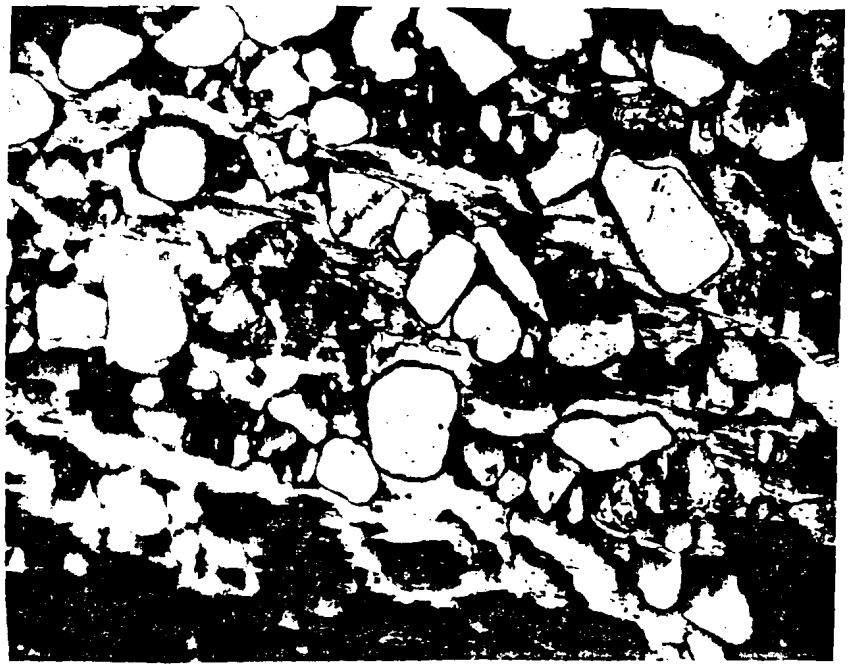


Fig. [illegible] Thin section No. [illegible] (X [illegible]) [illegible] detrital sand grains displaced by gypsum veins, Eddy County, New Mexico.

Fig. 21. Thin section No. 54 (X 12 plain light) of gypsum vein disrupting the bedding and displacing the grains, Eddy County, New Mexico.

Fig. 22. Thin section No. 54 (X 30 plain light) of detrital sand grains displaced by gypsum veins, Eddy County, New Mexico.

Quartz.- Quartz constitutes 60 to 80 per cent of the detrital mineral content in the Pierce Canyon formation. The grains range in size from 0.005 to 0.7 mm. and have a mean diameter of 0.04 mm. Grains less than 0.1 mm. in diameter, comprising the great bulk of the quartz, are typically subangular to angular (Fig. 24) with smooth surfaces. They are only moderately spherical because of their slightly elongate habit. Grains larger than 0.1 mm. but less than 0.4 mm. (fine and medium sand size) are typically subrounded with moderate to high sphericity; their surface is characteristically frosted by abrasion. A grain-size diameter of 0.4 mm. appears to mark the lower limit of well rounded quartz. Larger grains (Figs. 21 and 22) are well rounded and moderately to highly spherical with uniformly frosted surfaces; the frosted surfaces (caused by crescentic chatter marks) and high sphericities are the result of abrasion by impact with other grains during saltation while undergoing eolian transportation. Smaller grains, less than 0.1 mm. in diameter, lack frosted surfaces, because they were carried chiefly in suspension. No overgrowths were observed on any quartz grains in the Pierce Canyon detritus.

There are three types of quartz in the Pierce Canyon redbeds: grains consisting of a single crystal with straight or slightly undulose extinction (normal igneous or end-phase quartz of Krynine, 1940, p. 15) hereinafter referred to as plutonic quartz (Fig. 23); grains of grossly composite crystals with strongly undulose extinction (idem, p. 17)

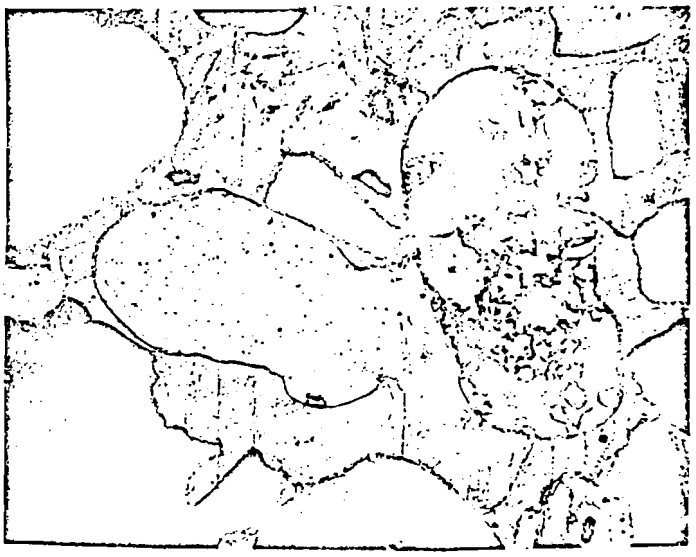


Fig. 23. Thin section No. 54 (X 75) with nicols crossed: Plutonic igneous quartz (left), a single crystal with straight extinction and a small number of vacuoles and microlites; metamorphic quartz (right), grossly composite with strongly undulose extinction, cemented with calcite.

hereinafter referred to as metamorphic quartz; and euhedral, dipyramidal quartz with embayed surfaces hereinafter referred to as volcanic quartz. More than 99 per cent of the quartz is monotonously uniform and classed as plutonic; and nearly all the grains have straight as opposed to slightly undulose extinction. This indicates that the source of the sediment was a granite with but few stressed portions, and that gneiss was either lacking or quite subordinate.

Most of the quartz grains contain a few vacuoles which are typically grouped in discontinuous subparallel lines or less commonly randomly distributed. Only a few grains contain abundant vacuoles such as are present in "milky" or vein quartz, and their occurrence does not appear to be related to grain size; thus there was little contribution from hydrothermal veins to this sediment.

Only about 20 per cent of the quartz grains contain mineral inclusions of euhedral apatite, tourmaline, zircon, and rutile needles, and these occur in different amounts. Pale blue tourmaline, the most conspicuous microlite, occurs in about 10 per cent of the grains as individual euhedral crystals. Colorless euhedral zircon occurs in 5 to 10 per cent of the grains in different amounts. Only a few grains contain an abundance of rutile needles; most of these grains have only a few randomly scattered needles. There is no patent relationship between microlite types and grain size.

The diameter of every metamorphic quartz grain is smaller than

0.07 mm. These grains were probably derived from minor stressed gneissic or schistose zones within the granite. Metamorphic quartz occurs only as traces although it is randomly distributed throughout the entire formation.

Volcanic quartz occurs only as traces 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.

Orthoclase.- Orthoclase grains range from 0.009 to 0.6 mm. with a mean grain size of 0.04 mm. They typically constitute from 20 to 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 traces. Orthoclase constitutes about 5 per cent of the total sand coarser than 0.4 mm.; thus there is a weak tendency for orthoclase to be concentrated in the finer sizes, yet its rounding is no better than the quartz. Authigenic overgrowths of orthoclase, which formed in the Pierce Canyon redbeds, are rare but these may account, at least in part, for the fresh surface on the larger grains.

Rare microlites of euhedral tourmaline, zircon, apatite, and rutile needles 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 showing a few vacuoles in parallel lines along cleavage planes. No surface alteration was detected. The absence of altered orthoclase and the abundance of fresh orthoclase is indicative of a granitic source in an arid or semiarid climate; the small amount of clay in the Pierce Canyon redbeds is in accord with this hypothesis. The modal silt size of this detritus and the flat-lying beds suggest that eolian distribution was assisted by low relief. The small amount of clay is probably due to mild weathering at the granitic source. It may have been altered to illite during marine diagenesis.

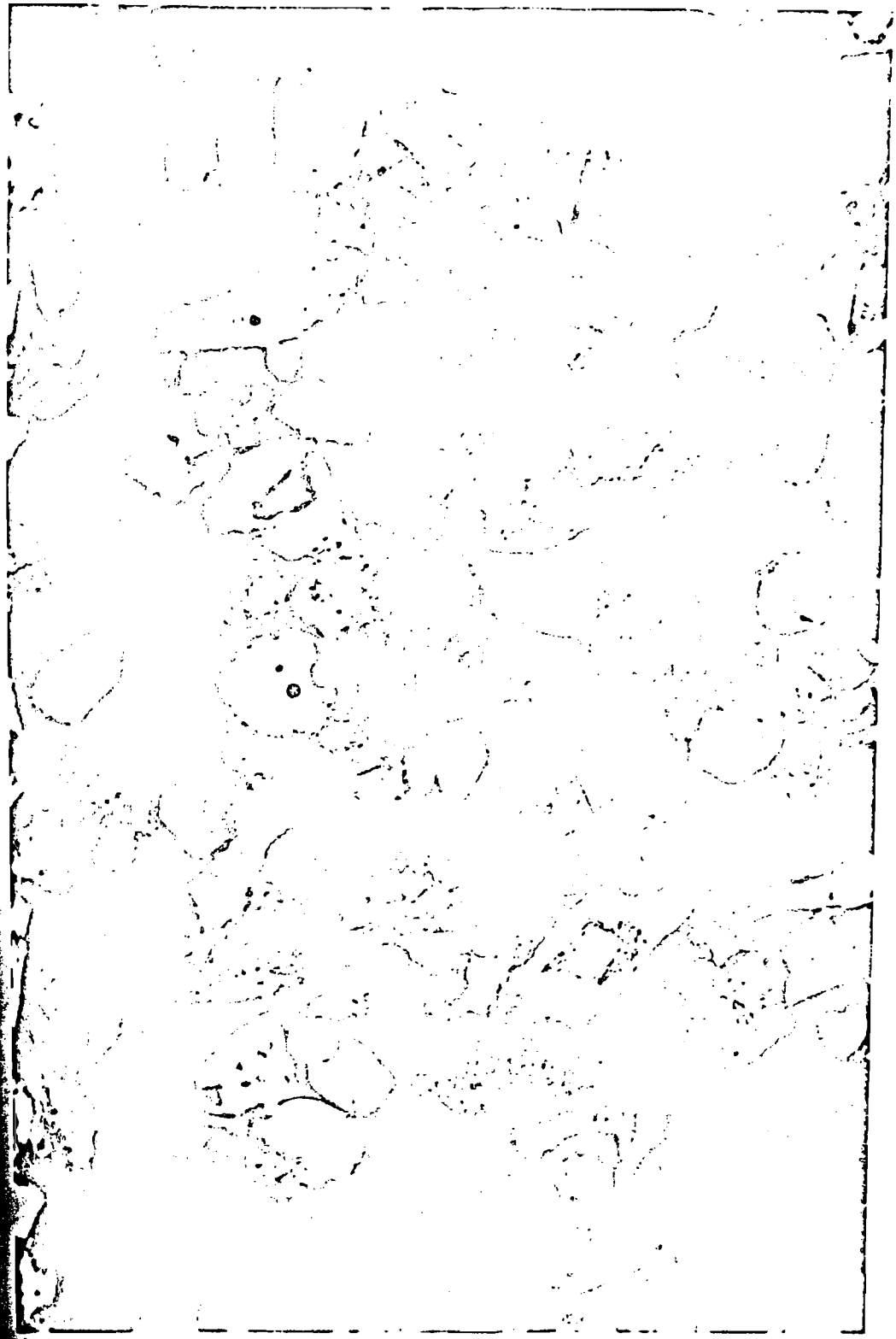
Microcline.- The diameters of most of the microcline grains are smaller than 0.09 mm.; hence their abundance is a function of texture. Microcline constitutes less than 5 per cent of the total detritus and is similar in its size distribution to orthoclase; it typically occurs as subrounded to well-rounded grains with moderate to high sphericity. The surfaces of the larger grains are frosted and like the orthoclase their interior is unaltered. Thin overgrowths have been detected. Most of the rare vacuoles are 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 to 0.14 mm. The grains are subrounded with moderate to high sphericity and their surfaces are corroded. Sanidine is sporadically distributed in the section. In some siltstone lenses it may constitute as much as 35 per cent of the detritus; in most of the samples it occurs only as traces.

Some of the sanidine is hollow. The cavities range in size from minute, slightly altered patches in the center of the grain to large holes that occupy more than 80 per cent of the grain volume. The cavities have irregular shapes and seem to be controlled by solution along cleavage planes rather than by solution within a crystal zone. The cavity typically occurs in the center of the grain and has a pattern similar to that shown in Figure 24. Some grains that do not contain a hole or cavity exhibit a faint, elusive central zone that has an optical orientation different from that of the outer crystal. Crystal zonation is more evident in the vicinity of the decomposed central cavity. Hsu (1954) has found that the cores of zoned sanidine from a dacite intrusion in the San Gabriel Mountains, California, are more potassic whereas the shells are more sodic. A similar composition may be the cause of solution of the sanidine cores in the Pierce Canyon redbeds.

Fig. 24. Thin section No. 29 (X 150, plain light) of two hollow sanidine grains in the Pierce Canyon detritus, Eddy County, New Mexico.



These holes or cavities in the sanidine grains from the Pierce Canyon redbeds are believed to have been formed after deposition, because many of the grains now are only fragile shells that would have been destroyed during transport, and because none of the holes is stained with hematite around the edges although a few do contain calcite or gypsum. Hence the holes in the sanidine must have formed after the hematite precipitation. The only connecting channels between the hollow interior and the fresh exterior are rare cleavage planes. It is believed that fluids penetrated the grain along similar planes and dissolved the less stable central zone which was probably of slightly different composition. Some of the cavities were later filled with gypsum or calcite, while others remained empty.

The small range in the modal size of the sanidine grains (0.12 to 0.14 mm.) plus the central location of the hole in most of the grains suggest that they were only slightly abraded during transport and that they are about the same size as the original crystals at the source. The hollow sanidine grains probably were deposited in a shower of volcanic ash, but may have come from erosion of a trachyte, or possibly some other eruptive or extruded rock.

So far as the writer knows, neither the Santa Rosa sandstone above, nor the Rustler evaporites and redbeds below the Pierce Canyon contain hollow sanidine; therefore it may be useful as a stratigraphic marker.

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 suggests that they received detritus from the same source. A more detailed description of these hollow sanidine grains is currently in press (Miller, 1955).

To check the relative abundance of sanidine, random samples were selected and 100 grains were examined in refractive index oils. The sanidine content ranged from traces to as much as 35 per cent of the material. In one particular set of samples from a fresh core (U. S. Potash Company shaft No. 3, SE$\frac{1}{4}$ Sec. 13, T. 20 S., R. 30 E., Eddy County, New Mexico) there is a marked change in sanidine content 140 feet below the surface which corresponds to a change in the cement in the Pierce Canyon redbeds. Below 140 feet, sanidine constitutes less than one per cent of the detritus in which the dominant cement is gypsum. Above 140 feet the sanidine content increases sharply to about 30 or 35 per cent and the dominant cement is calcite. Other than the change in the abundance of sanidine and the cement, there is no change in the texture or in the mineral assemblage. This change was not detected in any of the other cores or outcrop samples from nearby. A possible explanation may be that conditions favoring calcite cementation also favored better preservation of the sanidine.

Plagioclase.- Plagioclase grains are restricted to diameters of less than 0.13 mm. They constitute less than one per cent of the total

detritus and are typically subangular to subrounded and about 0.04 mm. long. Both the exterior and interior of the grains are unaltered, but corroded edges and small embayments are common. The grains are typically elongate, irregularly-shaped laths; hence their sphericity is somewhat less than that of the other feldspar grains. Vacuoles are abundant; although 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 because of their small size.

Chert.- Chert is restricted almost entirely to the silt-size detritus, where it occurs as well-rounded, slightly elongate (elliptic) grains sparsely and randomly distributed through the entire formation. The length of the grains ranges from 0.03 to 0.06 mm. The surfaces of the grains are pitted by randomly shaped, shallow depressions, as the result of impact with other grains during transportation.

Chert constitutes much less than one per cent of the total detritus but is significant because it indicates that at least a part of this material was derived from some pre-existing 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. Most of the calcite is sparry; the grains, composed of clear crystals about 0.01 mm. long, are moderately-rounded and have a

moderate to high sphericity with a median diameter of about 0.03 mm.

Detrital sparry calcite is rare in most sedimentary rocks because of its chemical instability. Its occurrence here suggests that it originated from the disaggregation of previously cemented material or chemically precipitated beds and was transported only a short distance to the depositional site. Reworking of the material probably occurred as the result of a periodically lowered water level, which exposed the newly deposited carbonate beds to wave action. The source of sparry calcite is discussed in more detail under the heading "Mineral Cement".

Muscovite.- Muscovite, its grain length averaging 0.07 mm., is a widespread constituent in the formation but comprises less than one per cent of the detritus. Flakes of muscovite up to 0.8 mm. long are twisted and bent between sand grains even in the coarsest detritus, but in most places the muscovite is much more concentrated in fine-silt and clay laminae. In the finer grain-sizes the flakes are typically so oriented that their long diameters almost perfectly parallel the bedding planes. The flakes are elliptical with well rounded edges, which may have resulted from eolian transport or from abrasion in the gentle currents of the Pierce Canyon sea.

Biotite.- The biotite content of this formation exceeds the muscovite content about two to one. Brown, pale green, and colorless

(leached) biotite altogether constitutes about one per cent of the detritus. Brown biotite is much more abundant than the green or colorless variety. 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 are elliptical with rounded edges similar to the muscovite; some of them occur as rather thick packets.

Chlorite.- Traces of chlorite are randomly dispersed in the fine detritus as pale blue green flakes about 0.08 mm. long. A few flakes have rounded edges as the result of abrasion. They may have been derived from a minor area of schist or gneiss associated with the granite, but more probably result from alteration of other ferromagnesian minerals.

Metamorphic-rock fragments.- Irregularly shaped rock-fragments with schistose or slaty structure constitute less than one per cent of the detritus. The fragments are small, about 0.04 mm. in diameter, and are randomly dispersed with the other detritus. Although their mineral content was not determined, most of them contain badly warped sericite and fine quartz. These fragments probably originated from small outcrops of schistose rock within the igneous source.

Glauconite.- Rare glauconite occurs as well-rounded grains with moderate sphericity. They are randomly distributed in the formation as silt-size grains 0.03 to 0.04 mm. long. In thin section the grains

appear pale "apple" green.

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

Magnetite-ilmenite is abundant in the heavy-mineral placers throughout the red oxidized parts of the rock; it occurs only as traces in the gray-green reduced spots or beds. Many heavy-mineral placers have been traced from the red portion of the rock on one side of a gray-green zone, across the zone, and into the red portion of the rock on the opposite side. Both red ends of the placer contain about the same amount of magnetite-ilmenite, leucoxene, tourmaline, zircon, and apatite; but, within the reduced gray-green zone the magnetite-ilmenite content drops to zero or a trace, whereas the other heavy minerals maintain about their same relative abundance. The abrupt decrease coincides with the color change. The magnetite-ilmenite originally present has been dissolved by the influence of reducing conditions and weak acids.

Where chemical reduction has resulted from leaching by ground water, the gray-green zones may contain magnetite-ilmenite partly altered to hematite; in these zones, the grains appear to be channeled by solution

or fragmented and the surrounding matrix is dark red because of authigenic hematite. In a few places where the leaching is incomplete, as indicated by the dark (red) patches in Figure 4, magnetite-ilmenite is still abundant. In the vicinity of the magnetite-ilmenite grains, in most of the gray-green zones, there is no evidence of alteration such as leucoxene or limonite rims or halos; neither is there any decrease in the size of the magnetite-ilmenite grains close to the reduction spots.

The presence of detrital magnetite-ilmenite in the red, oxidized parts of the rock indicates only that the source rock was rich in these minerals. The absence of detrital magnetite-ilmenite in the gray-green, reduced spots and beds indicates that these minerals have been dissolved. The causes of reduction and solution are discussed under the heading "Gray-green reduction zones".

The preceding remarks concerning the presence and absence of detrital magnetite are true of more than a hundred samples from widely separated geographical areas examined by Folk and the writer. The samples are from beds ranging in age from Cambrian to Tertiary, including most of the famous redbeds on the North American continent. Beds which have been enriched with hematite such as residual clays and soils are not represented. Abundant detrital magnetite-ilmenite in every red sample indicates that the source of the detritus was rich in these minerals. The significance of source rocks rich in magnetite-ilmenite, and their

relationship to the origin of redbeds has been discussed by Miller and Folk (1955), who concluded that the great sequences of redbeds in the geological column were derived predominantly from igneous or metamorphic sources and were not necessarily formed in a marine or nonmarine environment or under any specific climatic conditions.

Leucoxene.- Leucoxene, one of the most abundant heavy minerals, constitutes about one 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 0.05 mm. to 0.02 mm. and have a mean long diameter of 0.03 mm.

Leucoxene is a stable heavy mineral which results from the alteration of ilmenite. There are no partially altered ilmenite grains with leucoxene rims. There was hardly time for alteration after deposition and before burial. Alteration by ground water should have left rims. Hence, if the leucoxene grains are still in their first sedimentary cycle, the alteration from ilmenite probably took place at the source or during transport, not in the Pierce Canyon redbeds.

Tourmaline.- Subhedral and euhedral tourmaline grains are less common than leucoxene, composing less than one per cent of this detritus. Most of the grains are pale blue and may be indicative of pegmatites within the granitic source. Blue tourmaline ranges in size up to a maximum of about 0.6 mm., but typically its longest dimension is 0.03

to 0.04 mm. Most of these crystals are slightly rounded at the corners, and a few broken crystals are well-rounded. Elongate rectangular vacuoles and scattered rutile needes are the only inclusions. Pale pink and colorless tourmaline, which are much less abundant, contain the same inclusions and are about the same size as the blue variety. The largest tourmaline grain encountered was of the colorless variety and had a long dimension of 0.8 mm.

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, is one of the common heavy minerals. Most of it occurs as euhedral crystals with slightly rounded corners and an average grain diameter of about 0.03 mm. The scarce grains, 0.2 to 0.4 mm. long with well-rounded edges, were, like the tourmaline, probably derived from some other source or suffered longer abrasion. All the zircon is colorless.

Apatite.- The fact that subhedral apatite grains are abnormally abundant suggests that the apatite, the abundant biotite, and the volcanic quartz may have been derived from the same volcanic source. The crystals are slightly rounded on the corners 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 occur as pale yellow, near perfect squares with slightly rounded corners about 0.02 mm. long.

Fossils.- Only two fossils were recovered from this detritus, both of which were unidentifiable broken fragments about 0.03 mm. long and consist 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 believed to be representative of the vertical clay distribution at U. S. Potash Company's mine shaft No. 3, SE$\frac{1}{4}$ 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 content is homogeneously distributed in thin beds throughout the Pierce Canyon section and constitutes only 4 per cent of the detritus. There are only a few beds of claystone, and these are

only a few inches thick. The lateral distribution is similarly homogeneous. Most of the illite is completely stained with hematite, so that it is darker red than the coarse-grained material. All the illite is absorbent; it tends to swell to the point of dissaggregation when water is added.

Authigenic Minerals

Gypsum.- Clear fibrous gypsum is the predominant cement in the Pierce Canyon redbeds. It composes 10 to 20 per cent of the rock, occurring as subparallel, mosaic patches of fibrous crystals 0.01 to 0.03 mm. long. Some of the beds contain much larger crystals, which, as the result of their growth up to 0.7 or 0.8 mm., have slightly displaced the grains. The fact that nearly all the gypsum is clear and free of inclusions suggests that the crystals were precipitated in the interstices of the sediment after burial in highly saline sea water.

In a few places the fibrous crystals of gypsum enclose small patches of calcite, which may indicate that the gypsum was deposited around the edge of the interstice and that calcite later filled the central void space. In other parts of the same specimen the calcite is in contact with the hematite-stained grains. Hence there is no patent order of precipitation for calcite and gypsum, but both of them were deposited after the hematite. This is clearly shown by the fact that all the quartz silt-grains are coated with hematite, but the gypsum and

calcite overlie the hematite and are not themselves stained with it.

Veins of gypsum, which penetrated the formation during the Cenozoic Era as the result of slump in the basin, contributed additional cement to the lower half of the Pierce Canyon redbeds. These zones are discussed in more detail on page 20.

Calcite.- Sparry calcite cement constitutes approximately 5 per cent of the volume of the rock. In most of the beds the calcite content is less than one per cent, but in a few it may be as high as 30 per cent. Sparry cement occurs as individual crystalline patches 0.01 to 0.02 mm. long, many of which are surrounded by fibrous gypsum, but in many places the calcite is in direct contact with the hematite-stained grain. All the calcite patches are clear; none contain inclusions of hematite or gypsum.

Calcite crystals enlarged perhaps by precipitation from ground water are most abundant in the upper part of the Pierce Canyon section. They are also prevalent in the gray-green beds where ground water has permeated a stratum dissolving hematite and precipitating calcite. A few of these enriched zones contain small calcite mosaics in which the individual crystals, 0.02 mm. long, are in optical orientation with adjacent crystals.

Sand-crystal calcite is present in a few localized zones on the outcrops. These zones are completely cemented with a mosaic of patchy calcite whose individual crystals are in optical orientation over an

area of about 1 square centimeter and each crystal encloses hundreds of sand grains. Little of the boundary between the large crystal zones is straight, and in most places the zones seem to grade or feather into each other. There is no difference in the size of the individual calcite crystals within the larger sand-crystals and those in other parts of the rock. Smaller calcite mosaics, similar to sand-crystal calcite, were observed in one core sample only. 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; and only one core sample of sand-crystal calcite was obtained. Sand crystals are possibly the 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. Since rocks containing sand-crystals have more calcite than the adjacent rock, it is assumed that the addition of calcite is a necessary prerequisite to its formation. Hence, the added calcite must have come from a source outside the area enclosed by sand crystals. The reason for the concentration of calcite into crystals of nearly uniform size is not evident.

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$\frac{1}{4}$ 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. This increase in calcite corresponds to an abrupt increase in the sanidine content in this core, but the increase of neither the calcite cement nor the sanidine was detected in other stratigraphic sections in the vicinity.

Anhydrite.- Anhydrite constitutes less than one per cent of this formation and in most places occurs only as traces. It occurs most frequently 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. The anhydrite is considered to be a chemical precipitate.

Dolomite.- Dolomite occurs only as traces in a few of the samples. The crystals are typically 0.02 to 0.03 mm. long; in most places they exhibit a rhombic zonation.

Hematite.- The red color of this formation results from a thin hematite coating on the surface of the sand and silt grains and from disseminated hematite-stained clay. Hematite, which constitutes less than

5 per cent of the rock, was deposited as a chemical (hydrosol) precipitate that formed at or near the site of deposition 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. The hematite stain is thickest in the corners between two or more grains where it accumulated on the greater surface area and thinnest along the mutual boundary between two touching grains.

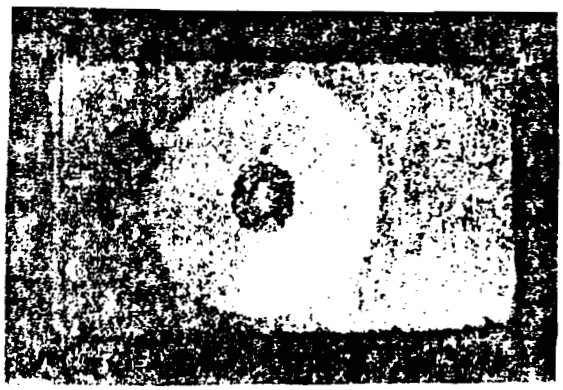
This type of hematite accumulation is described as post-depositional but essentially penecontemporaneous with deposition by Krynine (1950, p. 143); this description assumes that the source of the iron lies outside the basin of deposition and that the iron was transported to the basin and precipitated during or immediately following the deposition of the detritus.

The predominant occurrence of quartz and orthoclase, the abundance of magnetite-ilmenite, and the other accessory minerals strongly suggest that this is a first-cycle sediment derived from a granitic source in an arid climate. As evidenced by the abundance of magnetite-ilmenite and probably part of the abnormally high biotite content, the granitic source 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 all the hornblende and pyroxene and part of the magnetite-ilmenite. As both hornblende and pyroxene are unstable in oxidizing environments, it is not unlikely that they should have been destroyed at or near the source. Magnetite and ilmenite, which are more stable in an oxidizing environment, survived the erosion and transport.

The iron was probably transported by water to the site of deposition in several forms, the most important of which was as a ferric-oxide hydrosol. A much smaller amount was probably transported in solution as ferrous-bicarbonate. After reaching the Pierce Canyon sea these materials were slowly precipitated over a period of several days (Moore and Maynard, 1929, p. 278) in the gently agitated saline water which was winnowing and distributing the detritus. Then, as is characteristic of nearly all colloids and most chemical precipitates, the iron oxide was precipitated on the largest and most available surfaces, the grains. This process probably continued for a short time after burial. The minor amounts of flocculated clay received more iron proportionately than the silt and sand grains as the result of its larger surface area.

The Pierce Canyon detritus was buried and compacted predominantly as red sediment, although there may have been a few local gray or green zones or beds resulting from local reducing conditions caused by accumulations of organic matter or bacteria, but there is no direct evidence of this in the slides. Many of the reduced gray-green zones that are



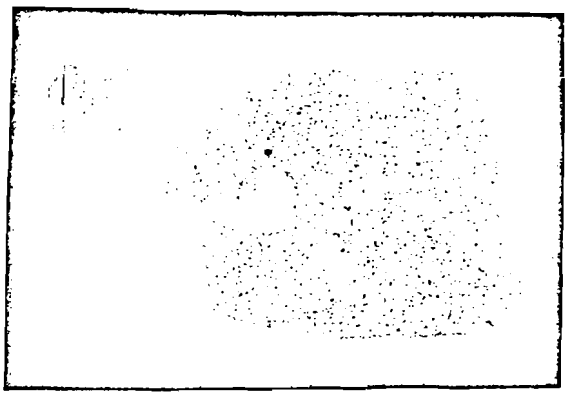


Fig. 25. Thin section No. 12 (X 1.5) of sub-spherical reduction spot with dark central sphere of authigenic biotite, SW$\frac{1}{4}$ Sec. 14, T. 22 S., R. 30 E., Eddy County, New Mexico.

present today, however, are the result of post-depositional processes.

Biotite.- Dark brown 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 (Fig. 25). The dark-brown flakes are extremely thin and have a maximum length of about 0.05 mm. The origin of this mineral is discussed under the paragraph heading "Gray-green reduction zones".

Biotite does not ordinarily form authigenically in sedimentary rock, although Curry and Curry (1954, p. 2141) have reported concentrations of authigenic biotite from the Cretaceous Muddy formation of Wyoming. The first identification of authigenic biotite in the Pierce Canyon redbeds was made with the petrographic microscope by Folk. E. J. Weiss, Department of Ceramic Engineering, The University of Texas, confirmed Folk's identification by X-ray.

Post-Depositional Alteration

In the preceding section the minerals were discussed separately for the purpose of easy reference. In order to set forth a probable paragenetic order here, it will be necessary to refer to the section on "Mineralogy" for details.

The sediments that now compose the Pierce Canyon formation were deposited in a saline environment (p. 84) which is believed to have been

mildly oxidizing and slightly basic, similar to normal marine water (James, 1954, p. 240). Hematite was the first chemical precipitate to form at the depositional site (p. 89) and probably accumulated on the grains during and immediately after deposition. In some places the hematite has been dissolved along with the magnetite-ilmenite. A few of these reduction zones may have formed immediately after or during deposition, others are the result of vadose or groundwater leaching. Subsequent deposition buried the loosely packed hematite-stained detritus which was still saturated with sea water. The interior of the sanidine grains was then dissolved after the precipitation of the hematite (p. 74) and before the precipitation of the gypsum and calcite. There is no manifest order of crystallization for the predominant gypsum (p. 84) and the lesser amount of calcite (p. 85) 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. In most specimens the gypsum is in contact with the hematite-stained grains, and in a few it surrounds patches of sparry calcite. In a few places sparry calcite is in direct contact with the hematite-stained grains (p. 85), but calcite has never been detected completely surrounding gypsum; this may indicate that the gypsum was precipitated before calcite. In one set of core samples (p. 87), the uppermost 100 feet of section is completely cemented with sparry calcite. Both the relative order and relative abundance of gypsum and

calcite presumably depend on fluctuations in the composition of the water saturating the sediment, with gypsum indicating more evaporitic conditions. Traces of anhydrite have been detected (p. 87) in a few samples, its local and sporadic distribution and its association with the hematite-stained grains suggests that it formed as a chemical precipitate at about the same time as the gypsum. Traces of dolomite (p. 87) have also been detected in a few places. Every dolomite rhomb is surrounded by a sparry calcite mosaic. Since consolidation the redbeds have been fractured and jointed (p. 20); some of these fractures and joints have been filled with fibrous gypsum.

Gray-green reduction zones.- There are numerous gray-green reduction spots and zones in the Pierce Canyon redbeds. They 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 gray-green color in similar beds has been attributed by Keller (1953, p. 5) to the illite content.

The presence in general, of more gray-green reduction zones on the outcrop than in the subsurface, shows that at least part of the reduction is the result of surface leaching. 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 groundwater leaching; other smaller, nearly spherical, reduction spots may have resulted from the oxidation of local accumulations of organic matter. Many of these reduced spots have been

cut and separated by gypsum veins (Fig. 7), indicating that the hematite was dissolved before veining. Most of the reduction spots and zones are devoid of detrital magnetite-ilmenite, because these minerals have been dissolved along with the hematite (p. 89).

A few of the reduction spots are spheroidal and have sharply defined, smoothly rounded borders and contain a dark central nucleus or core (Fig. 25). They typically range from 3 to 10 mm. in diameter, although a few are as large as 2.5 cm. in diameter. The following description is that of a typical spheroidal, gray-green, reduction spot which contains a dark gray nucleus.

(1) The center of the spot (Fig. 25) consists of typical Pierce Canyon detritus — quartz, feldspar, and mica cemented with pale gray fibrous gypsum; this central core shows on the illustration as a small, light colored circle, inside the dark circle. (2) The next spherical zone consists of the same detrital minerals and gypsum cement as the core, but it also contains abundant dark-brown flakes of authigenic biotite about 0.05 mm. long, disseminated between the fibers of the gypsum. All the biotite flakes are neatly arranged in a near perfect sphere around the core, parallel to the gypsum crystals. Most of the feldspar grains in this ring have corroded surfaces and show more internal alteration along the cleavage planes than is normal in the red part of the rock. In many places authigenic biotite is disseminated in the corroded cleavage planes of the feldspar. The detrital biotite in

this ring is fresh. (3) The next larger sphere is just slightly darker than (4) the gray-green outer part of the reduced spot. All the previously mentioned detrital minerals are present here, in about their same relative abundance, and gypsum is the dominant cement. The slightly darker color of this zone (3), which does not show in Figure 25, is caused by a little disseminated authigenic biotite between the gypsum crystals. (5) The outer boundary of the reduction spot is an abrupt color change from gray-green to red.

The biotite is known to be authigenic because of its (1) concentration in a small sphere and (2) different size and shape from that of the detrital biotite, and because (3) bedding planes pass through the sphere of concentrated biotite; hence it could not be a coprolite.

Most of the gray-green reduction spots are markedly deficient in detrital magnetite-ilmenite (p. 79). There is one other difference between the detrital minerals in the red and gray-green zones. Only a small percentage of the orthoclase grains in this formation have overgrowths; where present they are extremely thin and barely cover the edges and corners of the grains. Within these reduced spots, however, there are characteristically a small number of orthoclase grains which have thick overgrowths. The thickness of the overgrowths in many places is about half the width of the detrital grains.

Any attempt on the part of the writer to explain the origin of the authigenic biotite would undoubtedly have many shortcomings. Any explanation concerning this type of chemical reduction must also explain: 1)

the spheroidal shape of the spots, 2) the abrupt color change along the smoothly rounded border, 3) the alteration of the feldspar grains inside the reduced zone, 4) the abnormally large overgrowths on a few feldspar grains, 5) the dissolving of hematite and the magnetite-ilmenite, and 6) the precipitation of authigenic biotite.

The origin of the red color in redbeds has been aptly discussed by Von Houten (1948), Krynine (1937, 1949, and 1950), James (1954) and a host of others mentioned in the reference lists of these recent articles. Krumbein and Garrells (1952), Zobell (1946), and others have studied the stability limits of iron oxides and provided additional references on the chemistry of oxidation-reduction in Recent sediments. None of these investigations provide information which can be readily applied to the removal of hematite, magnetite-ilmenite, and the formation of authigenic biotite and authigenic feldspar. Presumably the spot contained potassium- and silica-rich solutions which caused the ferric iron oxide (hematite, magnetite, and ilmenite) to be reduced and then dissolved. A small part of the iron recombined with the potassium and silica to form biotite.

Geological Interpretation of Pierce Canyon Redbeds

Modern methods of sedimentary petrology show that a great amount of geological information which can help to solve many stratigraphic problems has been neglected in the past. Geology, like all other physical sciences, will continue to progress as fast as new parameters can be found to permit the comparison of data. The fundamental approach to comparative study depends almost exclusively upon observation and measurements, hence the trend in sedimentary petrology today is toward more detailed examination of the physical differences in minerals. Mineral descriptions alone are not sufficient until they have been compared to similar studies and incorporated into a broad, overall geological interpretation. The step from pure descriptive matter to its geological significance calls for conclusions on the part of the writer and, in sedimentary petrology, calls for answers to four fundamental questions: 1) What was the source rock and where was it located? 2) How was the sediment transported? 3) What were the climatic conditions at that time and how did they influence the source rock and the transportation of the sediment? and 4) What were the environmental conditions of the basin of deposition? The answers to these questions depend to a large extent on the presence or absence of some physical character of the mineral assemblage. Therefore, before proposing the conclusions it is necessary to review briefly the general character of the Pierce Canyon redbeds.

Lithology.- A typical sample of the Pierce Canyon redbeds is a moderate reddish brown (10R4/6) slightly sandy or slightly clayey siltstone. Small gray-green reduction zones or spots are common, but are most abundant in the coarser grained part of the rock. The rare sand grains greater than 0.4 mm. in diameter are well rounded and frosted, but the rest of the detritus is subangular or subrounded. Most of the detritus is arranged in thin, parallel sets of very fine crosslaminations less than one inch thick. Dark gray or black heavy-mineral placers, a grain or two thick, parallel the bedding. Dry samples are moderately well indurated but wet samples tend to disaggregate. This material is classed as a submature to mature arkose or subarkose (Folk, 1954, p. 354) because of the high quartz and feldspar content and the deficiency in metamorphic constituents. The detrital minerals are composed of 70 to 80 per cent plutonic (igneous) quartz with straight extinction. Almost all the quartz contains a few liquid and gas-filled vacuoles, and about 10 per cent of the quartz contains inclusions of pale blue tourmaline and colorless zircon. Approximately 25 to 30 per cent of the detritus is fresh feldspar, which consists predominantly of orthoclase with lesser amounts of microcline, sanidine, and plagioclase. The abnormally high biotite content exceeds the muscovite content about two to one. Both these micas are more abundant than chlorite. Schist and phyllite fragments, considered here as undifferentiated metamorphic-rock fragments, constitute less than one per cent of the detritus.

Chert is rare and occurs as well rounded, slightly elongate grains. The heavy-mineral placers are rich in black magnetite-ilmenite, dull white leucoxene, pale blue tourmaline, pink garnet, colorless zircon, and apatite. Rutile and glauconite are rare. There is little or no magnetite-ilmenite in the gray-green reduced zones and spots. The predominant mineral cement is fibrous gypsum; sparry calcite is also present but is much less abundant, and hematite occurs as a coating on the grains. Gypsum veins both cut and parallel the bedding.

Location and composition of source.- The uniform distribution, monotonous uniformity, and relative abundance of the quartz, feldspar, and accessory minerals in the Pierce Canyon redbeds suggests that almost all the detritus was derived from the same source. The fact that two minerals, quartz and orthoclase, constitute more than 90 per cent of the detritus indicates that these minerals were abundant at the source. This material is predominantly a first-cycle sediment, which was probably derived from an igneous source. Evidence of this granitic source is shown by the persistence and abundance of colorless, plutonic (strain-free) quartz, and the virtual lack of any strained or composite grains which might indicate derivation from some other, perhaps metamorphic, source. Almost all the quartz contains the same type and amount of vacuoles, some of which contain liquid, and microlites; this predominance could not have been obtained if the detritus had been derived from a mixture of reworked older sediments. The absence of milky or smoky vein quartz and

the 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 zone of an igneous body where hydrothermal veins and pegmatites are more abundant. The fresh and unaltered feldspar grains indicate that there was little chemical alteration of the feldspar at the source and further suggest a first-cycle sediment. Most of the accessory minerals were also derived from the same source. Magnetite-ilmenite and leucoxene, for example, probably came from the same source as did the quartz and orthoclase, because their relative abundance is about the same throughout the formation. Pale blue tourmaline is another example of an accessory mineral with a uniform distribution that suggests a single mutual source.

In most sediments that have been reworked from older sedimentary rock one can expect to find an assortment or mixture of mineral types: i.e., mixtures of quartz types; various types and stages of alteration in the feldspar; and erratic and possibly localized heterogeneous mixtures of accessory minerals such as chert, tourmaline, zircon, garnet, rutile, kyanite, hornblende, and many others. For example Krynine (1950, p. 24) reported many varieties of tourmaline and other minerals from the Triassic sediments of Connecticut which indicated a multiple source. Swineford and Frye (1951, p. 314) reported all stages of alteration in the feldspar, in all the samples from the Kansas loess deposits, which were indicative of reworked sedimentary material and probably multiple

source-areas. In the Pierce Canyon redbeds, only a few minerals like sanidine range in abundance from plentiful to scarce independently of the persistent quartz and feldspar; these few will be discussed at the close of this section. Furthermore, the uniform angularity and lack of rounded grains in the silt sizes favors a primary source.

In order for basement rocks to become exposed over a large region, there must have been an uplift followed by a prolonged period of erosion. There was such an uplift (King, 1942, p. 731) south of the Delaware Basin where pre-Permian mountains and the Marathon folded belt were progressively eroded during the Permian period. King referred to Wolfcamp and Leonard clastic beds in the Glass Mountains, which contain fragments that can be matched with rocks from the folded belt to the south. Moreover middle and upper Guadalupe beds in the Midland Basin contain thin layers of bentonite and volcanic ash which thicken southward, indicating a volcanic source to the south. From this we can gather three important facts which have to do with the location of a possible source: 1) that there probably was a structural complex south of the Permian Basin, in northern Mexico; 2) that there was volcanic activity south of the basin; and 3) that the wind was from the south, during at least part of Permian time.

The Pierce Canyon redbeds are believed to have been derived from a granitic source in northern Mexico, south of the Marathon folded belt. The source was probably a granitic mass that was subjected to prolonged

erosion.

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. King (1934) and others. They all agree 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 followed shortly after folding as part of an orogeny in the late Paleozoic. Kellum et al. (1936, Table 1) have listed the Permian igneous rocks at Las Delicias as lavas and fine-grained granite. They have stated that hornblende granite, quartz porphyry, and fine-grained diorite are unconformably overlain by Cretaceous rocks. They have also stated 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 hardly a question that can be settled until more extensive work has been done in northern Mexico.

Pre-Cretaceous arkose has been described (Imlay, 1944, p. 1111) from the subsurface of northern Coahuila. Kellum et al. (1936, p. 978-979)

and R. King (1934, p. 103-104) have also mentioned post-Permian arkose south of Cuatro Ciengas, 70 miles northeast of Las Delicias. At least the upper part of this arkose is thought (Kellum, et al., 1936, p. 978) to be of Jurassic age. Probably the arkose is younger than the Pierce Canyon redbeds, but it may have been derived from the same source area.

By Pierce Canyon time the source was probably denuded to low, barren hills of fresh granite. As erosion continued, the detritus was swept northward by the southerly winds (p. 101). Northwest-dipping crossbeds in the Pierce Canyon formation show that the water currents, probably wind-driven, transported the material northward within the basin of deposition. The prevailing wind of this region would have been from sea to northern shore much as it is today along the present Gulf of Mexico.

Less than 2 per cent of the Pierce Canyon detritus was derived from eruptive or extruded volcanic rocks. This source is proven by the sanidine and supported, in part, by the abnormally high apatite and biotite content and the traces of volcanic quartz. The volcanic source was probably nearer the site of deposition than the granitic source because these chemically unstable volcanic minerals have undergone little alteration or abrasion. The sanidine especially suggests a nearby trachyte or dacite source or contributions from ash falls. All this material was probably derived from a source south of the basin of deposition.

Metamorphic rocks contributed about 2 per cent of this detritus, and sedimentary rocks less than one per cent that is surely identifiable. The

metamorphic contributions include strained composite quartz and schist and phyllite fragments. Sedimentary contributions include a trace of chert from outside the basin and reworked sparry calcite from inside the basin of deposition. Older arkosic sediments may have contributed material to the Pierce Canyon detritus but these contributions were probably small as evidenced by the homogeneity of the composition, as previously discussed.

Climate.- Climatic conditions at the site of deposition were probably warm, arid, and windy. Evidence of the warm climate is the great thickness and wide distribution of salt, gypsum, anhydrite, and other evaporites of the underlying Rustler formation as well as the gypsum and calcite cement of the Pierce Canyon redbeds.

Aridity at the source is evidenced 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. Less than 5 per cent of the orthoclase shows alteration and most of this is the result of illitization along cleavage planes. Bubbly alteration (Folk, 1955, p. 356-357) is even less common and there is no indication of kaolinization. The other feldspars are equally fresh, even the large (0.5 mm.) rounded and frosted grains. If there had been even moderate rainfall and a little vegetation, part of the feldspars would show some sign of decay (Krynine, 1950, p. 20). Hence, the freshness and abundance of the feldspars and the low clay content, as previously described, were

probably brought about by an arid or semiarid climate. This is confirmed by grain size, surface features of large sand grains, and gypsum cement.

In an arid or semiarid climate chemical weathering of crystalline rocks is accomplished mostly by hydrolysis. Hydrolysis loosens the crystals at or near the surface leaving them susceptible to transport.

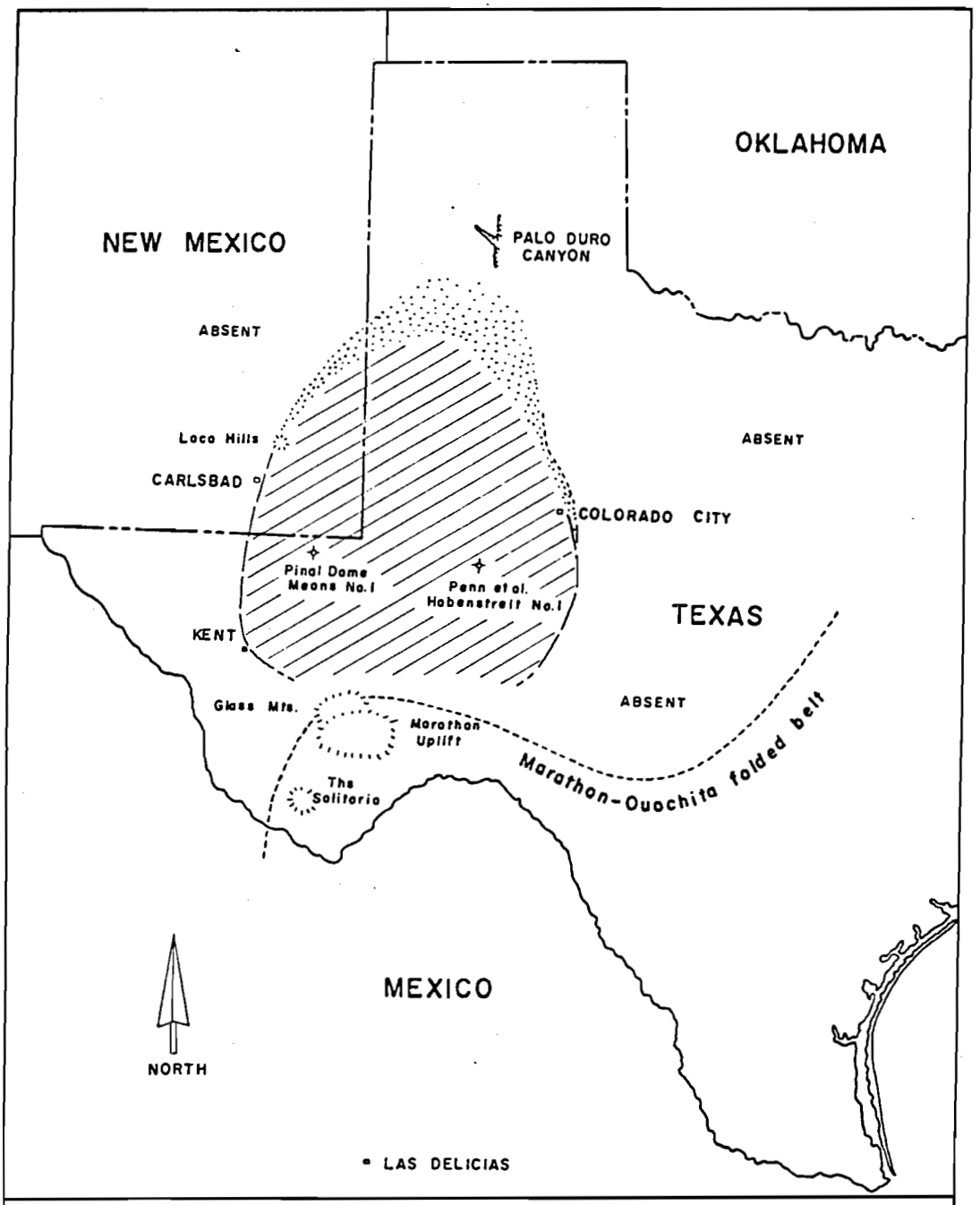
Transport.- Most of the detritus that was weathered from the granitic source was transported to the basin of deposition by the wind. A lesser portion was carried by water. Eolian transportation is evidenced by the uniform grain-size distribution throughout the Pierce Canyon section over more than 15,000 square miles in west Texas and southeastern New Mexico. If it were not for its intricate crossbedding and crosslaminations, i.e. had this material not been deposited under water, this siltstone might well be a loess deposit, because like loess, these grains have a small range in size around a median of 4.5ϕ (0.035 mm.). Almost all the material is coarse-silt, indicating that the transportation agents were competent to move material of this median grain-size. At times the competency of the wind was greater than that necessary to transport silt, times when fine, medium, and even a little coarse sand were transported; but these periods occurred rarely because less than 10 per cent of the detritus is of sand size. The small amount of medium and coarse sand is well rounded and has frosted surfaces as the result of the greater impact, and lack of protective water film, that are characteristic of wind abrasion. Most of the detritus is fine-skewed.

Fine-skewness here, indicates that when the wind was competent to sort and move coarse silt, it was also competent to transport a little finer material.

All the detritus could not have been transported by the wind alone. These sediments are coated with hematite, which is also believed to have been derived from a granitic source with a normal iron content. The abundance of magnetite-ilmenite, and probably part of the biotite, suggests the presence of other iron-bearing minerals like pyroxene and hornblende at the source, but pyroxene and hornblende are lacking in the thin sections and heavy-mineral slides. Chemical decomposition of unstable minerals like pyroxene and hornblende was probably induced by an oxidizing environment and a small amount of water which later flowed into the basin.

Judged from the extent of pre-Pierce Canyon deposits, the relief of the region must have been low; hence, it does not seem out of place to conclude that the streams which carried the dissolved and suspended material were probably broad and shallow, with possibly braided and silt-choked channels.

Environment of deposition.- The Pierce Canyon sediments were deposited in a broad, shallow, almost landlocked arm of the sea which covered at least the eastern part of the Delaware Basin (Pl. 3). The sea extended north at least to Loco Hills in northeastern Eddy County, New Mexico, and eastward across the Central Basin Platform into the south



DISTRIBUTION OF
PIERCE CANYON REDBEDS

Present — Possibly present

Scale 0 — 100 miles

Presence or absence in Texas Panhandle and adjacent Oklahoma not determined

1955

D. N. MILLER JR.

DEPARTMENT OF GEOLOGY, THE UNIVERSITY OF TEXAS

half of the Midland Basin.

The basin of deposition was almost flat by the end of Rustler time; the marginal land to the north and east probably sloped gently upward from the shallow saline sea. Small changes in sea level probably resulted in the submergence or emergence of this vast region around the basin. As the youngest Rustler deposits in the basin are gypsiferous dolomite and anhydrite, it is probable that the basin was not completely isolated from the sea at the beginning of Pierce Canyon time.

The contact between the highest Rustler evaporites and the overlying Pierce Canyon siltstone is an abrupt lithologic change; there is no evidence of lithologic gradation. Hence, the oldest Pierce Canyon detritus could not have accumulated at the same place in the basin while the youngest Rustler beds were being precipitated. The contact between the two formations is possibly a disconformity or diastem, a hiatus when virtual cessation of chemical precipitation may have been caused by an influx of sea water from the south. The addition of sea water would have diluted the highly saline Rustler sea, and caused a minor transgression to the north. Such an influx of water could have resulted from a slight subsidence of the region between the basin and the open sea, and may have been the indirect cause of the prevailing south wind which transported Pierce Canyon detritus northward as the shore line moved northward in this embayment. Inasmuch as most of the Rustler formation is composed of chemical rocks and not silt or other windblown detritus,

some change of this sort was necessary before the Pierce Canyon detritus began to accumulate. Hence, as a working hypothesis, we can assume that as the plutonic igneous rocks in northern Mexico became exposed to erosion, part of the silt was swept out over the shallow sea while more of the material was being blown across the flat, marginal lands south of the basin. Wind-driven waves and gentle uniform currents sorted the silt and deposited it in broad, crosslaminated sheets as the detritus slowly filled the basin. The volume of water was slowly reduced again by evaporation just as it had been reduced at irregular intervals all through Rustler time, and as the basin filled with sediment, the water was forced back to the southeast and into the open sea. As the result of desiccation the mineral concentration of the water increased, but its rate of concentration was never rapid enough to exceed the influx of sediment and no beds of gypsum, anhydrite, limestone, or salt were formed. The salinity was high enough, however, to cause the flocculation and precipitation of the iron-oxide hydrosol on the surfaces of the grains, and to cause precipitation of gypsum and calcite after burial.

The saline environment of the Pierce Canyon sea and the land adjoining it was probably not well suited to the preservation of organic remains. Only two fossils were found by the writer, neither of which were complete enough to permit identification. No other fossils have been reported from this formation.

COMPARISON WITH OTHER PERMIAN AND TRIASSIC FORMATIONS

Redbeds in Rustler Formation

The evaporites of the Rustler formation are interbedded with red sandy claystone which is similar mineralogically to the Pierce Canyon redbeds. In most places the primary fabric of the claystone has been destroyed during Cenozoic slumping but the detrital minerals have undergone little or no change.

The detritus of the Rustler redbeds consists of 60 to 95 per cent clay-size material and 5 to 40 per cent silt and sand. The silt-and-sand fraction ranks as a subarkose or orthoquartzite (Folk, 1954, p. 354). Quartz constitutes about 90 per cent of the silt and sand in the Rustler redbeds. About 10 per cent of the quartz is probably of plutonic igneous origin because it occurs as single crystals with straight extinction and has a few vacuoles in train. Approximately 5 per cent of these grains contain microlites of tourmaline, zircon and rutile needles. The mean grain-size of the plutonic quartz is about 0.05 mm. Nearly all of the sand size quartz is moderately rounded; grains larger than 0.4 mm. are typically well-rounded and frosted as the result of abrasion. The size, optical character, and inclusions of the plutonic quartz grains in the Rustler redbeds matches the plutonic quartz grains in the Pierce Canyon redbeds. Approximately 90 per cent of the quartz consists of reworked euhedral, dipyramidal crystals about 0.22 mm. long (Fig. 26).

Fig. 26. Thin section No. 30 (X 450) with nicols crossed: Reworked, euhedral, dipyramidal, quartz grains in the Rustler redbeds of Eddy County, New Mexico. Notice the large void (black) spaces, and the shape of the hematite-stained clay and vacuoles.

Fig. 26. Thin section No. 30 (X 450) with nicols crossed: Reworked, euhedral, dipyramidal, quartz grains in the Rustler redbeds of Eddy County, New Mexico. Notice the large void (black) spaces, and the shape of the hematite-stained clay and vacuoles.

The crystals are typically colorless although a few contain pale red cloudy inclusions of hematite-stained clay; they also contain a few randomly dispersed colorless vacuoles. The surfaces of these crystals have an adamantine luster and the corners and edges are sharp. None of the quartz crystals shows abrasion. If they had been transported far they should be abraded. Because the plutonic quartz grains do not have overgrowths of silica and because they are concentrated with the sand-size detritus, these crystals probably formed authigenically in the vicinity and were reworked and transported over the clayey bottom to this site of deposition without undergoing abrasion.

Orthoclase constitutes about 5 per cent of the silt and sand as subrounded grains with moderate sphericity; its median grain size is 0.04 to 0.05 mm. About 99 per cent of the orthoclase has been slightly decomposed by illitization or sericitization along the cleavage planes; only about one per cent is completely fresh. These grains are more altered than the orthoclase in the Pierce Canyon redbeds and have probably been reworked within the basin of deposition.

Microcline makes up less than one per cent of the detritus and has the same physical characteristics as the orthoclase. Plagioclase occurs only as traces and has a mean grain-size of about 0.01 mm.

Muscovite and biotite, common in these redbeds, occur most frequently as fresh elongate flakes about 0.04 mm. long. Muscovite is more

abundant than biotite and together they form about one per cent of the detritus.

Detrital calcite is present as traces in a few places just as it is in the Pierce Canyon redbeds. 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. Detrital sparry calcite is rare in sediments because of its instability during transport; its presence here indicates that it was reworked contemporaneously from carbonate deposits in the vicinity.

Fibrous gypsum is also a rare detrital constituent in these redbeds. In most places it occurs only as traces of well rounded grains about 0.07 mm. long. Like the sparry calcite, detrital gypsum is unstable during transport, hence it was probably derived along with the calcite from a nearby source under the influence of an arid or semiarid climate.

The only heavy minerals in the red claystone of the Rustler formation are an occasional rounded zircon or tourmaline.

Most of these redbeds are cemented and veined with colorless, fibrous gypsum. Sparry calcite cement is much less abundant than gypsum and together they make up less than 5 per cent of the rock. The calcite occurs as small clear crystals about 0.003 mm. long and is most abundant in the silt-and-sand-size detritus. Gypsum and calcite also occur as pseudomorphs after halite.

The lower part of the Rustler formation contains a few silty and

sandy beds of limestone, which are not directly associated with redbeds. The limestone contains 30 to 40 per cent silt and fine sand and 60 to 70 per cent sparry calcite. The detrital mineral assemblage consists of 80 to 90 per cent colorless, plutonic igneous quartz, 2 to 4 per cent orthoclase, one per cent microcline, traces of plagioclase, and 2 per cent muscovite and biotite, and is, with the exception of a few unstable minerals like calcite and gypsum, almost identical with the mineral assemblage of the redbeds.

The silt-and-sand-size detritus is the same in both the redbeds and the limestone; with the exception of the authigenic quartz, it originated in an igneous source, although it may have been reworked many times in the basin of deposition before it was deposited as part of the Rustler formation.

Comparison with Yates Sandstone

Mineralogical differences show that the rounded and frosted sand grains of the Pierce Canyon redbeds and the Yates sandstone were probably from different sources.

Practically all detrital quartz, whether it is of igneous, metamorphic, or sedimentary origin, has about the same specific gravity and durability during transportation. Approximately 50 to 60 per cent of the Yates sandstone is detrital quartz; of this, about 80 per cent is colorless with straight extinction and is believed to be of plutonic

igneous origin. Most of the grains contain a moderate amount 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 to 4) crystals with sweeping extinction; almost all are devoid of microlites. About 5 per cent of the quartz grains are grossly composite similar to Figure 23. These grains are made up of a mosaic of smaller crystals which have parallel elongation and sweeping (undulose) 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. Only a very few grains of this type are present in the Pierce Canyon redbeds. These quartz types cannot be differentiated with the binocular microscope.

Both quartz and chert have about the same specific gravity and durability; hence if the quartz was reworked from the Yates sandstone the chert would have been reworked with it. The Yates sandstone contains 5 to 7 per cent chert whereas only traces of chert occur in the Pierce Canyon redbeds.

Approximately 20 per cent of the Yates sandstone is made up of feldspar grains (orthoclase, microcline, and plagioclase); practically all of it has been at least partly decomposed. Almost all the feldspar in the Pierce Canyon redbeds is brilliantly fresh; it could not have

been derived from the altered feldspar of the Yates sandstone.

Judged from the differences in quartz types, chert content, and degree of alteration of the feldspars as just described, the Yates sandstone probably did not contribute any significant material to the Pierce Canyon redbeds.

Upper Triassic Redbeds

That the redbeds of the Upper Triassic were not derived from the same source as the Pierce Canyon redbeds is evidenced by the difference in their detrital minerals. Moreover, differences suggest that the climate was more humid during Upper Triassic than in Pierce Canyon time. These 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.

Santa Rosa sandstone.- The Santa Rosa sandstone is a feldspathic subgraywacke (Folk, 1954, p. 354) consisting of 50 to 70 per cent quartz. About 10 per cent of the quartz is composite (Fig. 27) with strongly undulose extinction; it was probably derived from a metamorphic source. About 5 per cent of the quartz is milky or white because it contains abundant vacuoles some of which are filled with liquid; it probably was derived from pegmatites or veins. Colorless, plutonic igneous quartz grains containing a moderate amount of vacuoles, abundant rutile needles, and sparse tourmaline and zircon microlites, make up the other 85 per

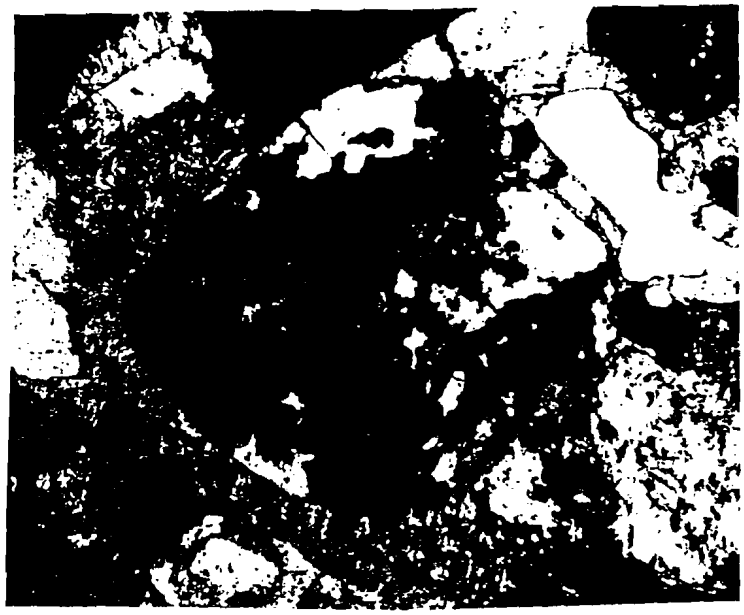


Fig. 27. Thin section No. 28 (X 120) with nicols crossed: metamorphic quartz grain, grossly composite with strong undulose extinction, from the Santa Rosa sandstone of Eddy County, New Mexico.

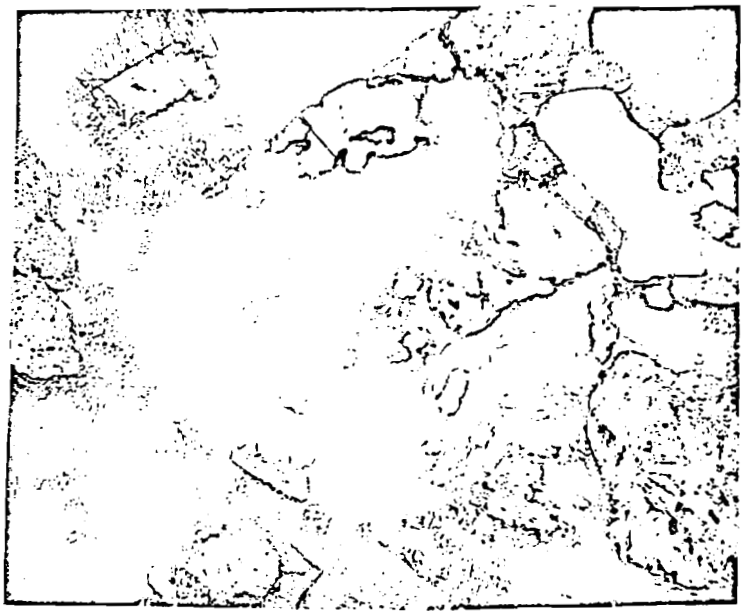


Fig. 27. Thin section No. 28 (X 120) with nicols crossed: metamorphic quartz grain, grossly composite with strong undulose extinction, from the Santa Rosa sandstone of Eddy County, New Mexico.

cent. Commonly the metamorphic-quartz grains are smaller than the plutonic-igneous and vein-quartz grains, suggesting derivation from different sources. Almost all the quartz of sand size was severely abraded during prolonged transportation, as indicated by the moderate-to-well-rounded shapes and frosted surfaces of the grains.

Approximately 10 per cent of the detritus is orthoclase, 50 per cent 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. The microcline grains are slightly larger than the orthoclase grains; the microcline may have been derived from pegmatites or from a more coarsely crystalline part of the granite. About one 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) has reported that most of the feldspar in the Santa Rosa is altered or weathered.

Chert is a common constituent in the Santa Rosa sandstone and makes up from 5 to 25 per cent of the detritus. The grains are typically well rounded and elongate because of abrasion; they were probably derived from older sedimentary rocks. As there is only a meager amount of chert in the Pierce Canyon redbeds, the chert in the Santa Rosa sandstone must have been derived from some other sedimentary source.

Muscovite, biotite, and chlorite are all abundant in the Santa Rosa sandstone, but altogether they constitute only about one per cent of the detritus. The mica is most abundant in the silty beds, wherein the majority of the flakes are oriented parallel to the bedding planes. This type of grain orientation suggests deposition in water by gentle currents. Muscovite and biotite are equally abundant in the Santa Rosa sandstone, whereas in the Pierce Canyon redbeds the biotite content exceeds that of the muscovite about two to one. Most of the Santa Rosa mica is fresh, but many of the flakes have been rounded by abrasion.

Approximately 10 per cent of the detritus consists of metamorphic-rock fragments, which include metaquartzites and mineral aggregates with schistose or slaty structure. In most of the rock fragments the minerals are elongate and subparallel. These fragments were probably derived from the same metamorphic source as the composite (metamorphic) quartz; together they show that at least 10 to 15 per cent, and possibly much more, of the sediment was derived from a source rich in metamorphic material.

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, because it was dissolved during the leaching. Almost all the grains are well rounded and fresh, although a few have been partly altered to a red iron-oxide, probably hematite, when leaching is not complete. Leucoxene is abundant and occurs as slightly elongate, rounded grains presumably as an alteration

product of ilmenite. Zircon and tourmaline are also 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. In a few places the calcite cement was precipitated after the hematite had been leached. Authigenic quartz is also common but is much less abundant than calcite. In most places the 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 define the old abraded surface. Mosaics of interlocking quartz crystals have resulted from the merger of overgrowths wherever the silica was more abundant. 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-sized material are:

1) The Santa Rosa sandstone contains 10 to 15 per cent metamorphic-rock fragments and metamorphic (composite) quartz, whereas the Pierce Canyon contains less than 2 per cent.

2) White or milky vein-quartz constitutes about 5 per cent of the Santa Rosa detritus; this type of quartz occurs only as trace in the

Pierce Canyon redbeds.

3) The Santa Rosa sandstone contains 5 to 25 per cent chert. The Pierce Canyon redbeds contain only trace of chert.

4) The feldspar content of the Santa Rosa sandstone makes up 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 at least a small amount of 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 in contrast to the quartz grains in the Pierce Canyon redbeds which do not have overgrowths.

8) The Pierce Canyon redbeds are predominantly cemented with 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, were probably derived from older sediments. This

analysis suggests that about a third of the detritus was reworked from older sediments, a third was derived from a metamorphic source because of the high percentage of metamorphic constituents, and a third was derived 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 humid and semiarid conditions after studying the petrography and paleontology of the Dockum Group.

Chinle shale.- No attempt was made to conduct a complete mineral study of the Chinle formation. Nevertheless, from the few samples available it is evident that the Chinle shale and the Santa Rosa sandstone have much in common. The Chinle shale ranks as a feldspathic subgraywacke (Folk, 1954, p. 354) in southeastern New Mexico. It contains about 80 to 85 per cent quartz of which all but about 5 per cent is of plutonic origin. About 2 per cent of the plutonic-quartz grains contain rutile needles or more rarely small tourmaline or zircon microlites. Vacuoles, some of which are liquid filled, are randomly arranged in most of the grains. About 5 per cent of the quartz is composite with strongly undulose extinction and is believed to be of metamorphic origin. Almost all the quartz grains have thick silica overgrowths and in some places the grains and cement form a solid mosaic of interlocking crystals. Feldspar makes up about 5 per cent of the detritus. Orthoclase is far

more abundant than either plagioclase or microcline. Less than 5 per cent of the feldspar is fresh; the remaining 95 per cent is moderately to intensely altered by sericitization, probably owing to a humid climate at the source. Thus, the feldspar in the Chinle shale shows even more alteration than the feldspar in the Santa Rosa formation. Chert is less abundant here than in the Santa Rosa sandstone and makes up only about 5 per cent of the detritus, possibly in part because of the grain-size difference in the two formations. Metamorphic-rock fragments composed of strained composite quartz, clay, and mica, constitute 10 to 15 per cent of the material and in this respect indicate that the Chinle shale, like the Santa Rosa sandstone, received sediments from a source rich in metamorphic material. Sidwell (1945, p. 53) has stated that the same heavy minerals are present in both the Santa Rosa sandstone and the Chinle shale. He has suggested (p. 54) that both of these formations are similar lithologically to the other Upper Triassic sediments and may have been derived from the Pre-Cambrian outcrops to the northwest. The similarity between the altered feldspar, chert content, and metamorphic constituents in the Santa Rosa and Chinle formations shows that their sources were lithologically similar. Together they indicate that in contrast with the Pierce Canyon redbeds the Upper Triassic sediments were derived from an entirely different source containing metamorphic materials and sedimentary rocks and that the climate of the Upper Triassic source area was probably more humid during Upper Triassic time than the

climate of the Pierce Canyon source area.

Dewey Lake Redbeds of Midland Basin

In order to study the lithology of the Dewey Lake redbeds for comparative purposes, thin sections were prepared from cable-tool cuttings of the subsurface type section in R. R. Penn's Habenstreit No. 1 (dry hole) in Glasscock County, Texas. Surface samples were also obtained from a thin-bedded red-and-white gypsiferous siltstone that crops out beneath the Santa Rosa sandstone along Champion Creek, 4.2 miles south of Colorado City (0.8 miles south-southeast of Seven Wells School and 1.1 miles west of Texas State Highway 208) in Mitchell County, Texas (DeFord, 1941, p. 56). Approximately 50 feet of red siltstone is exposed along Champion Creek from the single span wooden bridge westward. DeFord has stated that the lithology of the red siltstone which underlies the Santa Rosa sandstone at this outcrop is identical with that of the Dewey Lake redbeds.

Detailed petrographic analysis of these samples shows that the red siltstone at the Dewey Lake type section and the red siltstone at the Champion Creek outcrop are essentially identical in texture and mineral composition. Because they occupy the same stratigraphic position beneath the Santa Rosa sandstone they are believed to be part of the Dewey Lake formation. Furthermore, the texture and composition of the Dewey Lake redbeds are essentially identical to 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, referred to as "Tecovas", from the subsurface. This light-colored zone may be the upper leached part of the Pierce Canyon redbeds similar to the 50-foot leached zone beneath the Cretaceous rocks described from Red Point, Texas.

Quartermaster and Tecovas shales of Palo Duro Canyon.- In order to justify the use of the name "Tecovas" in this work the writer sampled the Tecovas formation in Palo Duro Canyon (now Palo Duro Canyon State Park), 13 miles east of Canyon in Randall County, Texas. Gould (1907, p. 26) described and named the Tecovas formation from outcrops along Tecovas Creek but mentioned that good exposures are to be found all 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 shale, separated from it by an unconformity, is a pebble-conglomerate that grades upward into sand and multicolored shale that are parts of the Tecovas formation (Upper Triassic). The contact between the Quartermaster and Tecovas shales is very conspicuous along the west wall of the canyon where the more resistant conglomerate forms a nearly vertical cliff 6 to

15 feet high above the uniformly sloping shales of the Quartermaster. The Tecovas formation is about 200 feet thick (Gould, 1907, p. 23) at Palo Duro Canyon 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 lithologically similar to the Pierce Canyon redbeds of the Delaware Basin and to the Dewey Lake redbeds of the Midland Basin. The Quartermaster shale 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 to 75 per cent plutonic quartz with tourmaline, zircon, and occasionally apatite microlites, and a moderate amount of vacuoles some of which are filled with liquid. Feldspar, chiefly orthoclase, makes up about 20 per cent of the detritus; microcline, plagioclase, and sanidine are also present and altogether 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 as a first-cycle sediment. The freshness of the feldspar also suggests an arid or semiarid climate. Sanidine is especially significant here because the grains are hollow just as they are in the Pierce Canyon formation to the south. The holes in the sanidine are the result of selective internal

decomposition in zoned crystals originally derived from a volcanic source. Of the Upper Permian and Upper Triassic sediments investigated by the writer, the Quartermaster shale is the only formation, other than the Pierce Canyon and Dewey Lake redbeds, that contains hollow sanidine grains. Only traces of chert were detected. Muscovite and biotite constitute less than one per cent of the detritus; both minerals are equally abundant. Chlorite occurs only as traces.

The heavy minerals of the Quartermaster shale 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 Quartermaster shale is mineral cement. Fibrous gypsum makes up 85 to 90 per cent of the cement and occurs here as colorless crystals and as microscopic veins. Sparry calcite and hematite constitute the remaining 10 to 15 per cent.

The mineralogic similarity between the Quartermaster and Pierce Canyon formations -- specifically the preponderance of plutonic quartz, the freshness of the feldspar, the presence of hollow sanidine, the virtual absence of metamorphic constituents and the low chert content — strongly suggests that these two formations were derived from the same or similar sources, under the influence of an arid or semiarid climate and deposited in a similar environment rich in calcium sulphate. Whether or not the two formations are stratigraphically equivalent remains an

open question until more detailed correlations become available.

Samples of the Tecovas shale from the outcrop at Palo Duro Canyon are mineralogically similar to the other Upper Triassic redbeds farther south. The predominant grain size of the Tecovas shale 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 to 95 per cent of which is plutonic; the other 5 to 10 per cent is metamorphic. Orthoclase and traces of microcline constitute about 10 to 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 makes up 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 of the writer that magnetite-ilmenite, tourmaline, zircon, garnet and rutile are all present.

Permian Versus Triassic Lithology

Throughout the foregoing descriptive matter an effort was made to delineate the lithologic differences between uppermost Permian and Upper Triassic rocks at three widely spaced localities. The fundamental

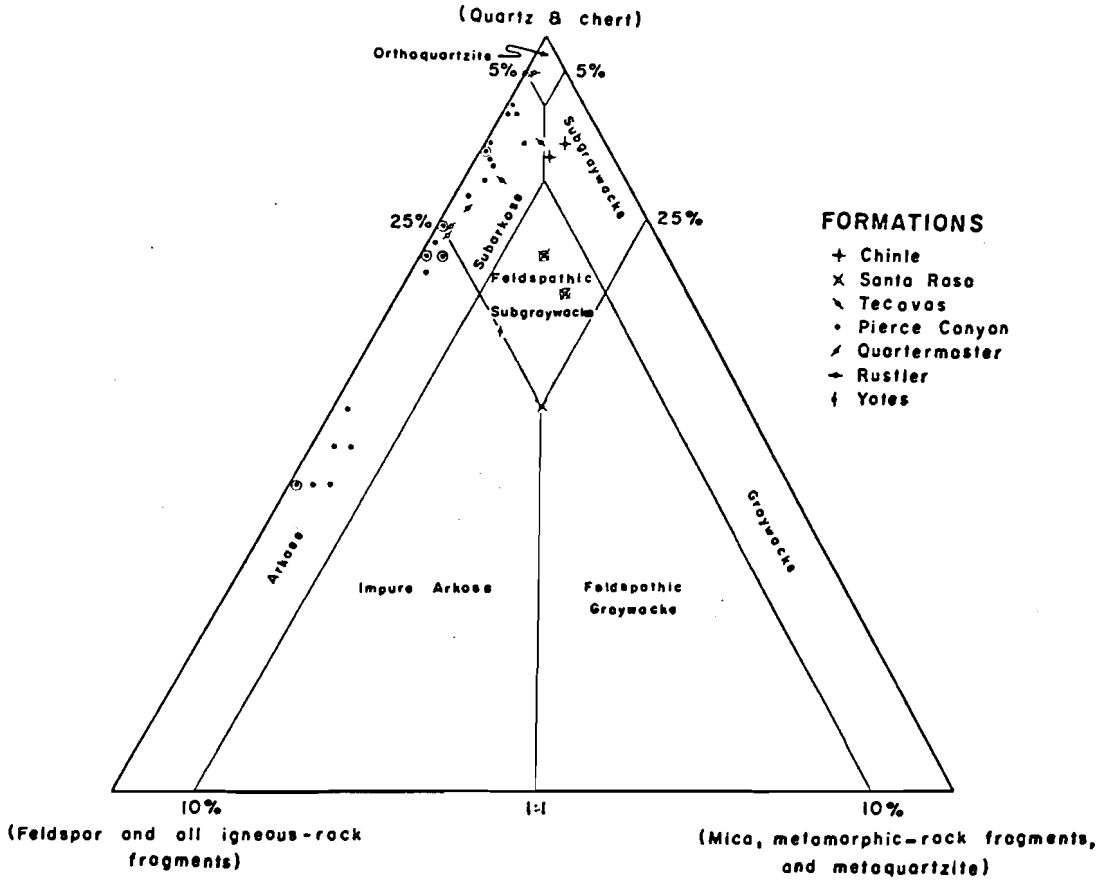


Fig. 28. Rock composition diagram (Folk, 1954): each vertex represents 100%, the corresponding base represents 0%. Double circles indicate 2 samples with that composition.

differences in the minerals of the formations are sufficient 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 shales of Palo Duro Canyon in the north end of the Texas Panhandle. The eight mineralogic differences described on page 120 as a practical means of differentiating the Pierce Canyon redbeds from the Santa Rosa sandstone are applicable to all the Upper Permian and Upper Triassic formations described under "Petrology" in this report. They show that the Upper Permian sediments were composed of minerals derived from an igneous source, deposited in sulphate-rich water under the influence of an arid or semiarid climate. They also show that the Upper Triassic sediments contained a significant amount of minerals derived from reworked sedimentary rocks and metamorphic rocks under the influence of a moderately humid climate in the source area and were deposited in carbonate- and silica-rich water.

These eight mineralogic differences prove that the Pierce Canyon redbeds are more nearly like the Rustler formation below than like the Santa Rosa or Tecovas formations above.

The Permian-Triassic boundary is a time horizon. Its position in the Permian Basin will depend on its position in a type locality, a matter that is not yet entirely settled. Its identification in the Permian Basin will then depend on correlation, which is subject to error.

Meanwhile the tentative assignment of the Pierce Canyon redbeds to the Permian relates them to genetically similar underlying formations and separates them from genetically dissimilar overlying strata.

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Stratigraphic Petrography Collection, Department of Geology
The University of Texas

D. N. Miller, Jr., 1955

1) Sand-crystal calcite in Pierce Canyon float boulder, 30 ft. below Santa Rosa contact, NE$\frac{1}{4}$ Sec. 5, T. 21 S., R. 30 E., Maroon Cliffs, Eddy County, New Mexico.

2) Anhydrite from the Rustler formation, shaft sample 365-373 ft. U. S. Potash Co., shaft No. 3, NE$\frac{1}{4}$ SE$\frac{1}{4}$ Sec. 13, T. 20 S., R. 30 E., Eddy County, New Mexico.

3) Same locality as thin section 2, depth 357-358 ft.

4) Vertical section, base of Pierce Canyon redbeds, 1 inch above Rustler contact, depth 357 ft., U. S. Potash Co. shaft No. 3, (same locality as thin section 2).

5) Vertical section, calcitized zone of Dewey Lake redbeds from creek bed, 200 ft. west of single span bridge on Champion Creek, 4.2 miles south of Colorado City, Mitchell County, Texas.

6) Horizontal section, same locality as thin section 5.

7) Pierce Canyon sample, 30 ft. below Santa Rosa contact, NE$\frac{1}{4}$ SE$\frac{1}{4}$ Sec. 5, T. 21 S., R. 30 E., Maroon Cliffs, Eddy County, New Mexico.

8) Reduced zone in Pierce Canyon redbeds, sampled 7 ft. below thin section 7.

9) (a) Ocotillo redbeds, from base of road-cut (U. S. Hwy. 285) 4.5 miles north of Carlsbad city limits, SW$\frac{1}{4}$ SW$\frac{1}{4}$ Sec. 22, T. 21 S., R. 26 E., Ocotillo Hills, Eddy County, New Mexico.

9) (b) Gypsum vein, Pierce Canyon redbeds, 100 yards north of road, SW$\frac{1}{4}$ SW$\frac{1}{4}$ Sec. 14, T. 22 S., R. 30 E., Livingstone Ridge, Eddy County, New Mexico.

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11) (a) and (b) same locality as thin section 9b.

12) Same locality as thin section 9b.

13) Same locality as thin section 9b.

14) Vertical section, calcitized Pierce Canyon redbeds from the gypsum vein zone, Livingstone Ridge, same locality as thin section 9b.

15) Vertical section, ripple marks, Pierce Canyon redbeds, from Red Point, 35 ft. above valley floor, NW$\frac{1}{4}$ Sec. 20, Blk. 59, T. 7, T&P RR Co. Surv., Culberson County, Texas.

16) Vertical section, Santa Rosa sandstone from Barstow Quarry, 4 ft. above base of quarry, Barstow, Ward County, Texas.

17) Samples 17 to 21 across Rustler - caliche - Gatuña boundary from Southwest Potash Company pilot hole No. 6A, SE$\frac{1}{4}$ SE$\frac{1}{4}$ Sec. 9, T. 19 S., R. 30 E., Eddy County, New Mexico. Sample 17 from 214-216 ft.

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19) Same locality as thin section 17, depth 218-221 ft.

20) Same locality as thin section 17, depth 221-228 ft. from lower part of this interval.

21) Same locality as thin section 17, depth 221-228 ft. from upper part of this interval.

22) Vertical section, leached zone in Pierce Canyon redbeds, 2 ft. below Santa Rosa contact NW$\frac{1}{4}$ SE$\frac{1}{4}$ Sec. 5, T. 21 S., R. 30 E., Maroon Cliffs, Eddy County, New Mexico.

23) Vertical section, Pierce Canyon-Santa Rosa contact (gray coarse grained zone is Santa Rosa) NE$\frac{1}{4}$ NE$\frac{1}{4}$ Sec. 5, T. 21 S., R. 30 E., Maroon Cliffs, Eddy County, New Mexico.

24) Horizontal section, basal Santa Rosa, 1 inch above Pierce Canyon contact, Maroon Cliffs, same locality as thin-section 23.

25) Vertical section, same as thin-section 24.

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28) Vertical section, Santa Rosa conglomerate, at bridge, same locality as thin-section 27.

29) Horizontal section, base of blocky sandstone and about 130 ft. below Santa Rosa contact in Pierce Canyon redbeds, SE$\frac{1}{4}$ SE$\frac{1}{4}$ Sec. 5, T. 21 S., R. 30 E., Maroon Cliffs, Eddy County, New Mexico.

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33) (a) Vertical section, Pierce Canyon redbeds, random sample, Sec. 26, Blk. 53, PSL Culberson County, Texas, (See University of Texas M.A. thesis, W. L. Hall, 1952, for exact location).

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39) Vertical section, Pierce Canyon redbeds, NE$\frac{1}{4}$ Blk. 91, PSL, Culberson County, Texas, (See University of Texas M.A. thesis, Seely, 1952).

40) Vertical section, Yates sandstone, 1 ft. below Tansill contact, NE$\frac{1}{4}$ NW$\frac{1}{4}$ Sec. 16, T. 22 S., R. 26 E., Eddy County, New Mexico.

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52) Vertical section, 332-337 ft.

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60) Pierce Canyon redbeds, 2 ft. below Cretaceous contact at Red Point, Culberson County, Texas. (Same location as thin section 15).

61) Cutting of Pierce Canyon redbeds from the type locality, Pinal Dome Oil Co. No. 1 Means, dry hole, SE$\frac{1}{4}$ Sec. 23, Blk. C-26, PSL, Loving County, Texas; depth 240 ft.

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74) Rustler silty clay, from shaft sample, U. S. Potash Company shaft No. 1, depth 420-427 ft., S$\frac{1}{2}$ Sec. 12, T. 29 S., R. 21 E., Eddy County, New Mexico.

OUTCROPS OF PIERCE CANYON REDBEDS

Maroon Cliffs: 23 miles northeast of Carlsbad, Secs. 5, 6, 9, 11, 14, 15, 16, T. 21 S., R. 30 E., Eddy County, New Mexico.

The uppermost 210 feet of Pierce Canyon section is exposed at this locality from the bottom of Nash Draw (alluvium) to the upper contact with the Santa Rosa sandstone (NE$\frac{1}{4}$ SE$\frac{1}{4}$ Sec. 5, T. 21 S., R. 30 E.). Throughout Maroon Cliffs the Pierce Canyon formation is a reddish brown, gypsiferous and calcareous siltstone with parallel bedding planes. The unconformable contact with the Santa Rosa is at the base of a 1-foot gray (leached), clay zone containing reworked pebbles from the Pierce Canyon redbeds. The Santa Rosa can be readily identified by its sandy texture and calcite cement. Approximately 80 feet of Santa Rosa sandstone overlies the Pierce Canyon redbeds in Secs. 5 and 6, T. 21 S., R. 30 E.

Livingstone Ridge: 7 miles southeast of Maroon Cliffs, Secs. 11, 14, 15, 22, T. 22 S., R. 30 E., Eddy County, New Mexico.

About 30 to 40 feet of Pierce Canyon section are exposed along the dissected escarpment shown on topographic sheet Nash Draw Quadrangle (1943 ed. U. S. Geol. Surv.). Neither the upper nor lower contact is exposed at this locality. Gypsum filled joints cut the parallel bedded Pierce Canyon redbeds approximately 100 yards northeast

of the road connecting the Crawford Ranch headquarters and Hill Tank at the escarpment.

Southeastern Eddy County, New Mexico: 2 miles north of the Texas state line, along the east side of the Pecos River valley, Sec. 22, T. 26 S., R. 29 E.

About 30 feet of Pierce Canyon section was reported from this locality by Leve (1952) as red gypsiferous siltstone.

Red Bluff Lake, Texas: Northwest corner of Loving and northern end of Reeves Counties, Texas, Secs. 2, 3, 11, 12, 13, and 14, Blk. 57, T. 1, T&P RR Co.

Komie (1952) has reported a maximum thickness of 110 feet for the Pierce Canyon redbeds and described them as thin-bedded gypsiferous, red siltstone. Neither the upper nor lower contact is exposed.

Eastern Culberson and northwestern Reeves Counties: 15 miles south-southwest of Red Bluff Lake dam, Secs. 3, 10, 23, 26, and 35, Blk. 45, PSL.

The Pierce Canyon redbeds are exposed at these localities as small, low (10- to 15-foot), hills that consist of thin-bedded, dark red, gypsiferous and calcareous, sandy siltstone. Neither the upper

nor lower contacts are exposed. The location and accessibility of these outcrops has been illustrated by Hall (1952).

Red Point: 10 miles north of Kent, Culberson County, Texas, NW¼ Sec. 20, Blk. 59, T. 7, T&P RR Co.

About 140 feet of Pierce Canyon section is exposed from the valley floor (talus) to the base of the Cretaceous conglomerate, 30 feet below the top of the cliff. The lowermost 90 feet of section is dull, moderate reddish brown, thin-bedded sandstone. The uppermost 50 feet of Pierce Canyon redbeds is light brown to pale red, thin- to thick-bedded, silty fine grained sandstone. The contact with the overlying Cretaceous is about 5 feet above the base of a nearly vertical, gray cliff 30 feet below the top of Red Point.

Southeastern Culberson County, Texas: Southeastern Culberson County, Texas, NW¼ NW¼ Sec. 5, Blk. 91, PSL.

About 45 feet of Pierce Canyon section crops out at this locality on the south side of a large hill, along the north bank of a large draw. The exposure is moderate brownish red, thin-bedded, gypsiferous, silty sandstone. The exact location of this outcrop has been illustrated by Travis (1951).

Near Seven Heart Gap: In the SW¼ NE¼ Blk. 87, PSL, Culberson County, Texas, approximately 25 miles northwest of Kent, DeFord (oral

communication) has reported a sinkhole filling containing fragments of Pierce Canyon redbeds.

REFERENCE LIST

Adams, J. E., 1929, Triassic of West Texas: Bull. Amer. Assoc. Petrol. Geol., Vol. 13, p. 1045-1055.

_____ 1935, Upper Permian Stratigraphy of West Texas Permian Basin: Bull. Amer. Assoc. Petrol. Geol., Vol. 19, p. 1010-1022.

_____, Cheney, M. G., DeFord, R. K., Dickey, R. I., Dunbar, C. O., Hills, J. M., King, R. E., Lloyd, E. R., Miller, A. K., and Needham, C. E., 1939, Standard Permian Section of North America: Bull. Amer. Assoc. Petrol. Geol., Vol. 23, p. 1673-1681.

_____ 1944, Upper Permian Ochoa Series of Delaware Basin, West Texas and Southeastern New Mexico: Bull. Amer. Assoc. Petrol. Geol., Vol. 28, p. 1596-1625.

Böse, E., 1923, Vestages of an Ancient Continent in Northern Mexico: Amer. Jour. Sci., 5th Ser., Vol. 6, p. 127-136.

Bretz, J. H. and Horberg, L., 1949a, The Ogallala Formation west of Llano Estacado: Jour. of Geol., Vol. 57, No. 5, p. 477-490.

_____ and _____ 1949b, Caliche in Southeastern New Mexico: Jour. of Geol., Vol. 57, No. 5, p. 491-511.

Cartwright, L. D., Jr., 1930, Transverse Section of Permian Basin, West Texas and Southeastern New Mexico: Bull. Amer. Assoc. Petrol. Geol., Vol. 14, p. 969-981.

Curry, W. H., Jr., and Curry, W. H. III, 1954, South Glenrock, A Wyoming Stratigraphic Oil Field: Bull. Amer. Assoc. Petrol. Geol., Vol. 38, p. 2119-2156.

Darton, N. H., 1921, Geologic Structure of Parts of New Mexico: U. S. Geol. Surv., Bull. 726E, p. 173-276.

DeFord, R. K., 1941, in Fort Worth to Midland, Texas: West Texas Geol. Soc. guidebook, May, p. 56.

_____ 1942, Halfway Pool: The Oil and Gas Resources of New Mexico, New Mexico School of Mines, Bull. 18, p. 216-219.

_____ and Wahlstrom, E. A., 1932, Hobbs Field, Lea County, New Mexico: Bull. Amer. Assoc. Petrol. Geol., Vol. 16, p. 51-90.

_____, Wills, N. H., Riggs, G. D., 1940, Eddy County, New Mexico: West Texas Geol. Soc. guidebook, September.

Dickey, R. I., 1940, Geologic Section from Fisher County through Andrews County, Texas, to Eddy County, New Mexico: Bull. Amer. Assoc. Petrol. Geol., Vol. 24, p. 37-51.

Fitzpatrick, J. E., 1950, Geology of Kent Draw, Culberson County, Texas: M. A. thesis, The University of Texas, Austin, Texas.

Folk, R. L., 1954a, The Distinction Between Grain Size and Mineral Composition in Sedimentary-Rock Nomenclature: Jour. of Geol., Vol. 62, No. 4, p. 344-359.

_____ 1954b, Syllabus for Geology 370K, Introductory Sedimentation: The University of Texas, Austin, Texas.

_____ 1955, Note on the Significance of "Turbid" Feldspars: Amer. Mineralogist, Vol. 40, Nos. 3 and 4, p. 356-357.

Gould, C. N., ~~1954~~ 1907, Western Portion of the Panhandle of Texas: U. S. Geol. Surv., Water Supply and Irrigation Paper No. 191, Document 76, p. 1-70.

Green, F. E., 1954, The Triassic Deposits of Northwestern Texas: Ph. D. dissertation, Texas Technological College, Lubbock, Texas.

Griffths, J. C., 1951, Size Versus Sorting in Some Caribbean Sediments: Jour. of Geol., Vol. 59, p. 211-243.

Hsu, K. J., 1954, A Study of the Optic Properties and Petrologic Significance of Zoned Sanidine: Amer. Jour. Sci., Vol. 252, p. 441-443.

Hughston, E. W., 1950, Geology of Northern Half of Salt Draw Quadrangle, Culberson County, Texas: M. A. thesis, The University of Texas, Austin, Texas.

Imlay, R. W., 1944, Cretaceous Formations of Central America and Mexico: Bull. Amer. Assoc. Petrol. Geol., Vol. 28, p. 1077-1195.

James, H. L., 1954, Sedimentary Facies of Iron Formation: Jour. Econ. Geol., Vol. 49, No. 3, p. 235-293.

Keller, W. D., 1953, Illite and Montmorillonite in Green Sedimentary Rocks: Jour. Sed. Petrology, Vol. 23, No. 1, p. 3-9.

Kellum, L. B., Imlay, R. W., and Kane, W. G., 1936, Evolution of the Coahuila Peninsula, Mexico: Bull. Geol. Soc. of Amer., Vol. 47, p. 969-1007.

Kelly, W. A., 1936, Evolution of the Coahuila Peninsula, Mexico: Part II, Bull. Geol. Soc. of Amer., Vol. 47, p. 1009-1038.

King, P. B., 1942, Permian of West Texas and Southeastern New Mexico: Bull. Amer. Assoc. Petrol. Geol., Vol. 26, p. 535-763.

Komie, E. E., 1952, Geology of Red Bluff Lake Area, Loving and Reeves Counties, Texas: M.A. thesis, The University of Texas, Austin, Texas.

Krumbein, W. C. and Garrels, R. M., 1952, Origin and Classification of Chemical Sediments in Terms of pH and Oxidation and Reduction Potentials: Jour. of Geol., Vol. 60, p. 1-33.

_____ and Pettijohn, F. J., 1938, Manual of Sedimentary Petrography, Appleton - Century - Crofts, Inc., New York.

Krynine, P. D., 1937, Western Redbed Sedimentation: Geol. Soc. of Amer., Proc. Abst., p. 96.

_____ 1940, Petrology and Genesis of the Third Bradford Sand: The Pennsylvania State College, Bull. 29, State College, Pennsylvania.

_____ 1949, The Origin of Redbeds: New York Acad. of Sci., Trans., Ser. II, Vol. 2, p. 60-68.

_____ 1950, Petrology, Stratigraphy, and Origin of the Triassic Sedimentary Rocks of Connecticut: The Pennsylvania State College, Bull. 73, State College, Pennsylvania.

Lang, W. B., 1935, Upper Permian Formation of Delaware Basin of Texas and New Mexico: Bull. Amer. Assoc. Petrol. Geol., Vol. 19, p. 262-270.

_____ 1937, The Permian Formations of the Pecos Valley of Texas and New Mexico: Bull. Amer. Assoc. Petrol. Geol., Vol. 21, p. 833-898.

_____ 1938, Geology of the Pecos River Between Laguna Grande de la Sal and Pierce Canyon: in State Engineer of New Mexico, 12th and 13th Biennial Reports, 1934-1938, p. 80-86.

_____ 1942, Basal Beds of Salado Formation in Fletcher Potash Core Test, Near Carlsbad, New Mexico: Bull. Amer. Assoc. Petrol. Geol., Vol. 26, p. 63-79.

_____ 1947, Triassic Deposits of Pecos Valley, Southeastern New Mexico:

Bull. Amer. Assoc. Petrol. Geol., Vol. 31, p. 1673-1674.

Leve, G. B., 1952, Geology of the Red Bluff Area, Eddy County, New Mexico: M.A. thesis, The University of Texas, Austin, Texas.

Maley, V. C. and Huffington, R. M., 1953, Cenozoic Fill and Evaporite Solution in the Delaware Basin, Texas and New Mexico: Bull. Geol. Soc. of Amer., Vol. 64, p. 539-546.

Miller, D. N., Jr., 1955, Hollow Sanidine Grains: Stratigraphic Marker for the Pierce Canyon Formation, West Texas and Southeastern New Mexico: in press for September 1955, Jour. Sed. Petrology.

_____ and Folk, R. L., 1955, Occurrence of Detrital Magnetite and Ilmenite in Red Sediments: New Approach to Significance of Redbeds: Bull. Amer. Assoc. Petrol. Geol., Vol. 39, p. 338-395.

Moore, E. S. and Maynard, J. E., 1929, Solution Transportation and Precipitation of Iron and Silica: Jour. of Econ. Geol., Vol. 24, p. 272-303.

Page, L. R. and Adams, J. E., 1940, Stratigraphy, Eastern Midland Basin, Texas: Bull. Amer. Assoc. Petrol. Geol., Vol. 24, p. 52-64.

Richardson, G. B., 1904, Report of a Reconnaissance in Trans-Pecos Texas North of the Texas and Pacific Railway: The University of Texas, Bull. 23, p. 38-45.

Sayre, N. A., Lang, J. W., and Dennis, P. E., 1942, Groundwater in the Pecos River Basin in Texas: in The Pecos River Joint Investigations, Reports of Participating Agencies, p. 76-101, U. S. Govt. Printing Office.

Sidwell, R., 1945, Triassic Sediments in West Texas and Eastern New Mexico: Jour. Sed. Petrology, Vol. 15, No. 2, p. 50-54.

_____ and Gibson, D., 1940, Mineral Study of Santa Rosa Sandstone in Guadalupe County, New Mexico: Jour. Sed. Petrology, Vol. 10, No. 1, p. 5-7.

Swineford, A. and Frye, J. C., 1951, Petrography of the Peoria Loess in Kansas: Jour. of Geol., Vol. 59, No. 4, p. 306-322.

Theis, C. V. and Sayre, N. A., 1942, Geology and Ground Water: in The Pecos River Joint Investigations, Reports of Participating Agencies, p. 27-75, National Resources Planning Board, U. S. Govt. Printing Office.

Travis, E. J., 1951, Areal Geology of Harral Quadrangle, Culberson County, Texas: M.A. thesis, The University of Texas, Austin, Texas.

Von Houten, F. B., 1948, Origin of Red-Banded Early Cenozoic Deposits in Rocky Mountain Region: Bull. Amer. Assoc. Petrol. Geol., Vol. 32, p. 2083-2126.

Zobell, C. E., 1946, Studies on Redox Potential of Marine Sediments: Bull. Amer. Assoc. Petrol. Geol., Vol. 30, p. 477-513.

CHEMICAL ANALYSES

U. S. Potash Co. shaft No. 3, NE¼ SE¼ Sec. 13, T. 20 S., R. 30 E., Eddy County, New Mexico: depth 47 - 52 ft.

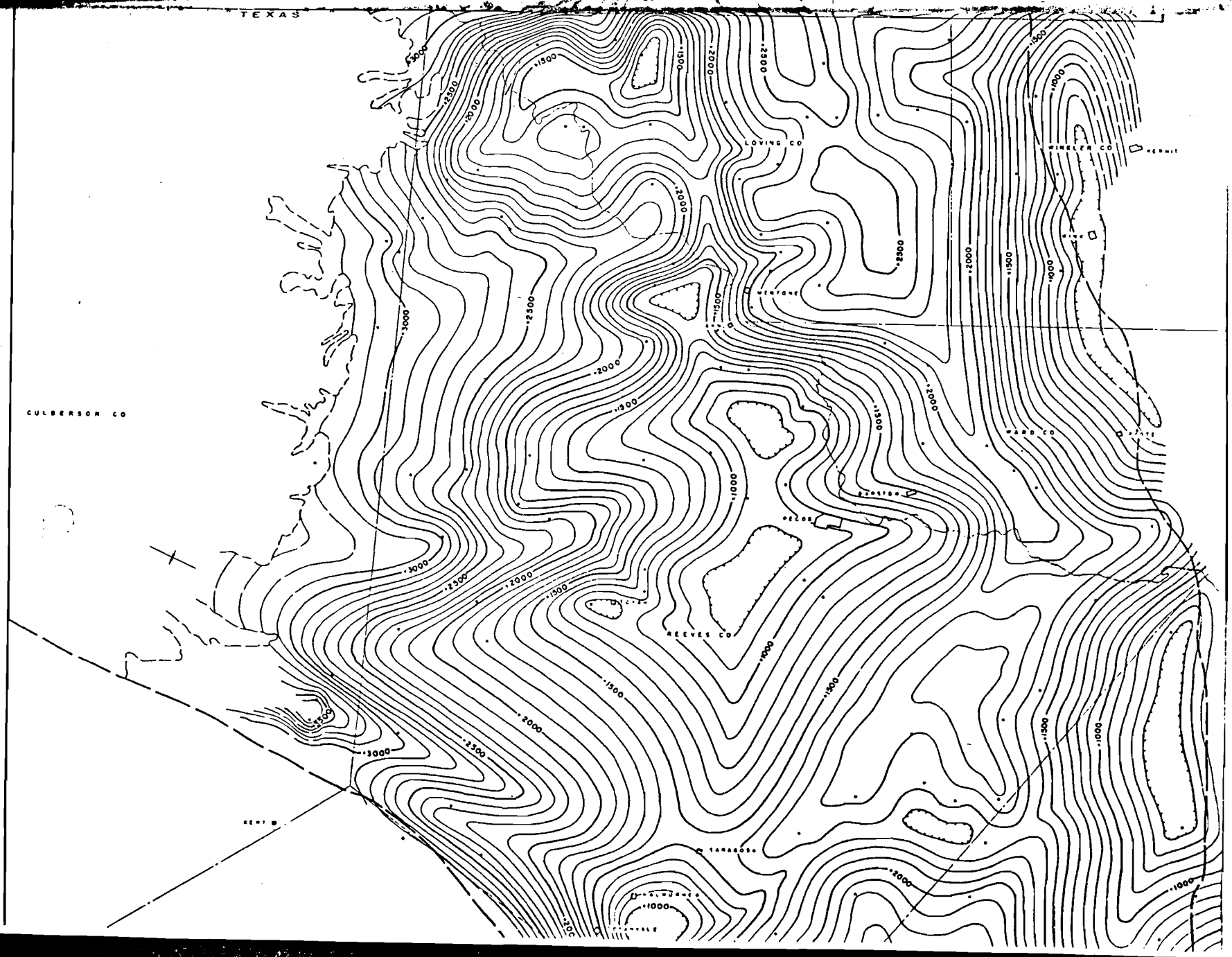
	Sample No. 1 (red)	Sample No. 2 (white)
SiO_2	59.01	76.52
Fe_2O_3	5.84	1.87
CaO	4.57	0.36
MgO	5.19	0.76
Na_2O	1.14	1.33
K_2O	5.32	6.52
S	0.0x	
CO_2	5.22	
Al_2O_3	11.95	13.40
TiO_2	0.75	0.81

VITA

Daniel N. Miller, Jr. was born August 22, 1924, in St. Louis, Missouri, the son of Daniel N. and Glaphia M. Miller. He attended the public elementary and high schools in Ferguson, Missouri, and enrolled at Missouri School of Mines and Metallurgy, Rolla, Missouri in September, 1942. In February, 1943, he joined the Army Air Force and served as a combat pilot in B-29 type aircraft in the Pacific Theater of Operations. His initial interests in geology developed during this period while stationed on Tinian and later in the Phillipines. After discharge in August, 1946, he enrolled at Southeastern Missouri State College and in September, 1947 returned to Missouri School of Mines. He received the degrees of Bachelor of Science in geology from that institution in August, 1949, and of the Master of Science in geology in February, 1951. He was married in September, 1950 to Esther Faye Howell of Columbia, Missouri. As a graduate student he was awarded the Missouri School of Mines Research Fellowship in Geology for ecological studies of Recent foraminifera and sediments under the supervision of Professor Don L. Frizzell. From February, 1951 to 1952 he was employed as a subsurface geologist by the Stanolind Oil and Gas Company at the district office in Corpus Christi, Texas. He enrolled in Graduate School of The University of Texas in September, 1952, as the recipient of the Stanolind Oil and Gas Research Fellowship in Geology.

Permanent Address: 7 Kings Court, Ferguson, Missouri.

NEW MEXICO
TEXAS
LEA CO
EUNICE
JAL
CARLSBAD
NEW MEXICO
TEXAS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PECOS
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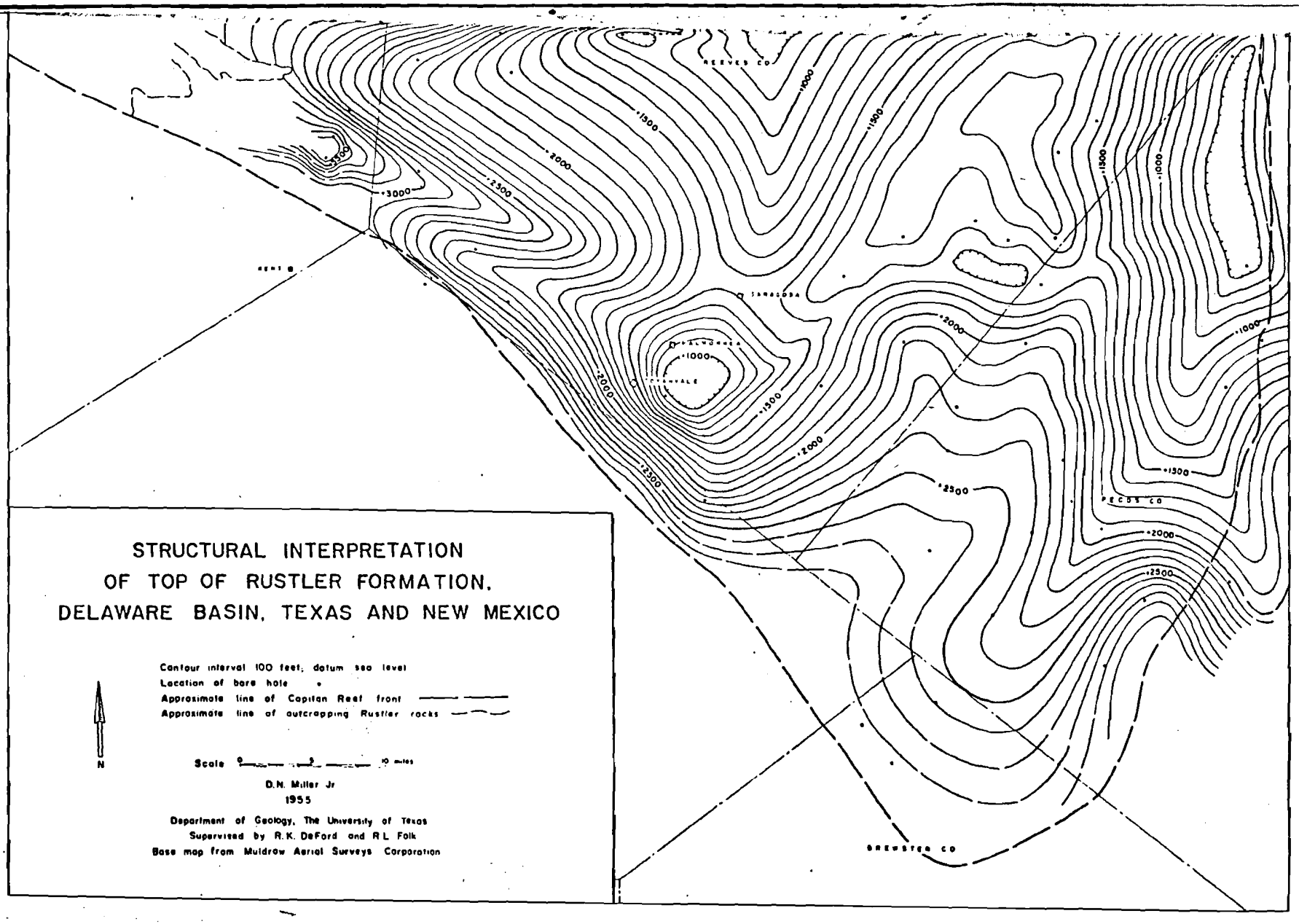
STRUCTURAL INTERPRETATION
OF TOP OF RUSTLER FORMATION,
DELAWARE BASIN, TEXAS AND NEW MEXICO
Contour interval 100 feet; datum sea level
Location of bore hole
Approximate line of Capitan Reef front
Approximate line of outcropping Rustler rocks
N
Scale 0 5 10 miles
D.N. Miller Jr
1955
Department of Geology, The University of Texas
Supervised by R.K. DeFord and R.L. Folk
Base map from Muldrow Aerial Surveys Corporation
REEVES CO
PECOS CO
BREWSTER CO
SANGLORA
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+1500
+2000
+2500
+3000