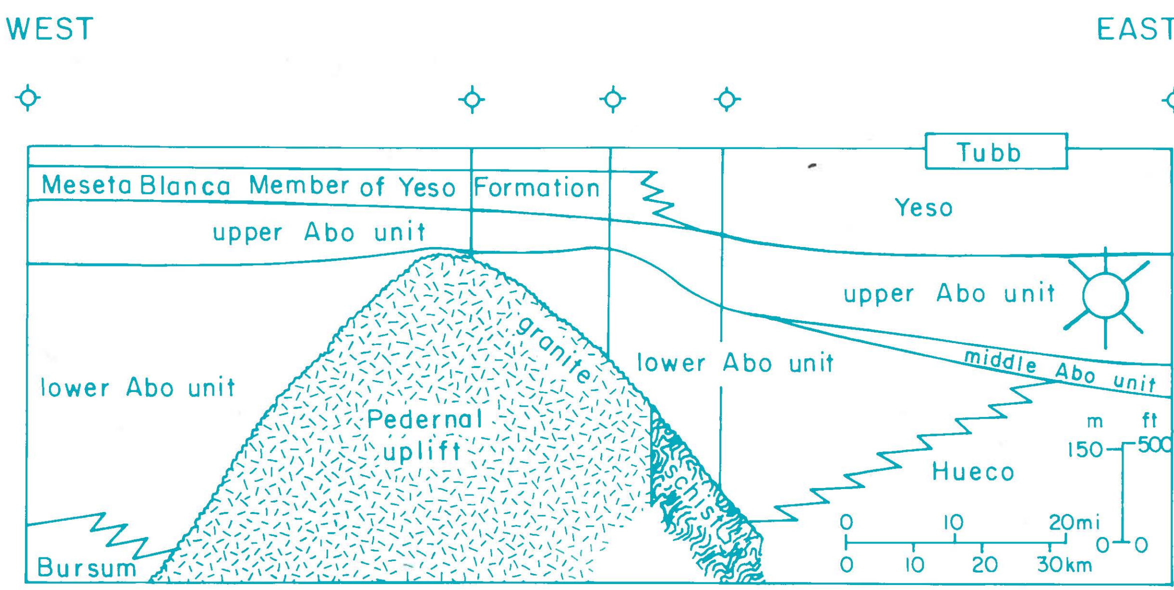
Stratigraphically controlled gas production from Abo red beds (Permian), east-central New Mexico

by Ronald F. Broadhead



CIRCULAR 183 New Mexico Bureau of Mines & Mineral Resources 1984
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COVER—West–east stratigraphic cross section from Lincoln County to Chaves County showing internal stratigraphy of Abo red beds and stratigraphic occurrence of gas in the Abo red beds.

Circular 183

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SOCORRO 1984

First Printing, 1984

Published by Authority of State of New Mexico, NMSA 1953 Sec. 63-1-4
Printed by University of New Mexico Printing Plant, April 1984

Available from New Mexico Bureau of Mines & Mineral Resources, Socorro, NM 87801

Preface

The Abo red beds in the subsurface of Chaves County, New Mexico, have become some of the most important targets of natural-gas drilling in New Mexico. Abo red-bed gas was discovered in 1977, and drilling boomed in 1980 after the Abo red beds were designated as a "tight gas sand" by the Federal Energy Regulatory Commission. The tight-sand designation allows producers to sell gas at a higher regulated price than allowed for gas produced from formations not designated as tight gas sands. At the higher prices, gas can be produced economically from the Abo red beds. Gas production is confined presently to northern Chaves County, but several wildcats drilled to the north in De Baca and Guadalupe Counties have encountered encouraging shows of hydrocarbons in the Abo red beds.

This report maps and analyzes geologically the Abo red beds of east-central New Mexico. Emphasis is placed on the lithologic characteristics of productive Abo sandstones. Stratigraphy and structure have been mapped in both producing and nonproducing areas in order to compare stratigraphic and structural characteristics of the Abo in producing areas with stratigraphic and structural characteristics of the Abo in areas where Abo red-bed gas has not yet been found. Producing Abo sandstones also were studied and characterized petrographically and petrophysically.

Detailed lithologic descriptions of Abo cores and drill cuttings are presented in this report. These descriptions should prove useful to petroleum geologists who are exploring for gas in the Abo red beds of east-central New Mexico. The stratigraphic analysis of the Abo places the lithologic descriptions in a useful framework. The sedimentologic interpretation should help geologists with the prediction of porosity trends. The petrographic and petrophysical analyses will help geologists interpret borehole logs and also should help geologists and reservoir engineers gain insight into the reservoir characteristics of the Abo gas sands.

I would like to thank Frank E. Kottlowski, Director of the New Mexico Bureau of Mines and Mineral Resources, for suggesting and steadfastly supporting this study. Sam Thompson III, Robert A. Bieberman, and Greg Mack thoroughly reviewed the manuscript and offered constructive advice and criticism. Todd Stephenson of AMOCO Production Company kindly arranged for me to log cores from the two AMOCO wells used in this study, and he also provided a suite of borehole logs from each well; Todd also lent me thin sections of core samples. Art Bowsher and Ray Beck of Yates Petroleum Corporation allowed me to log and sample cores from the Yates Papalote and Thorpe wells. George Scott III provided the drill cuttings from the Mesa No. 1 Gallo State; Joseph W. Jeffers of Mesa Petroleum Company arranged for early release of logs from that well. Dave Boneau, an engineer with Yates Petroleum Corporation, provided the compositional analyses of Abo gas. Larry Brooks of the New Mexico Oil Conservation Division provided the permeability data. George Scott, Jr., President of Los Siete Exploration, Inc., provided much stimulating and knowledgeable discussion of the Pecos Slope Abo gas field. Marla Adkins-Heljeson and Deborah Shaw edited the manuscript and Lynne McNeil patiently typed it.

Socorro, New Mexico
March 4, 1983

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Contents

TABLES

FIGURES

APPENDICES

Abstract

Red-bed sandstones of the Abo Formation (Permian: Wolfcampian to Leonardian) currently produce natural gas from the Pecos Slope Abo field in northern Chaves County, New Mexico. The Pecos Slope Abo field is located on the Northwest shelf of the Permian Basin. Production currently comes from an approximately 700 mi² area. The Abo has been designated a "tight gas sand," thus Abo gas can be sold for as much as $5.41 per MCF (thousand ft³), $2.60 more than the regulated ceiling price of gas produced from formations not designated as tight. The tight-sand designation greatly stimulated drilling, and more than 350 wells have been drilled since field discovery in 1977. Because of low permeability, wells must be artificially fractured to obtain economic production. Initial calculated open flow rises from a few tens of MCFGPD (thousand ft³ of gas per day) before fracturing to an average of approximately 2,200 MCFGPD after fracturing. The Abo red beds are subdivided vertically into three informal lithologic units on the Northwest shelf of the Permian Basin: a lower unit of "granite wash," a middle unit of mudstone, and an upper unit of interbedded sandstone and mudstone. The lower unit of "granite wash" is more than 800 ft (244 m) thick in some places and is composed of interbedded, coarse-grained arkosic sandstones and arkosic conglomerates. This unit rings Abo-age uplifts of Precambrian granitic basement and intertongues basinward with marine limestones of the Hueco Formation. The middle unit is approximately 100 ft (30 m) thick and conformably overlies the clastic facies of the lower unit or the Hueco limestone facies. The middle unit is composed of calcareous, sparsely fossiliferous, argillaceous mudstone and minor fine-grained sandstone. It is a shallow-marine shelf deposit. The upper unit is approximately 600 ft (183 m) thick and is composed of interbedded mudstones and lenticular sandstones. It conformably overlies the middle unit and is disconformably overlain by the dolostones, anhydrites, and fine-grained sandstones of the Yeso Formation (Permian–Leonardian). The upper unit intertongues southward with lagoonal dolostones; a shelf-margin reef facies lies south of the lagoonal dolostones. Sandstone lenses are generally 10 ft (3 m) to 20 ft (6 m) thick. Sandstones are very fine grained, arkosic, and hematitic. The upper unit was deposited as a fluvial-deltaic system which prograded southward over the marine mudstones of the middle unit. Gas is produced from sandstones of the upper unit. Primary porosity has been reduced by compaction to values near zero and is present mostly as submicroscopic pores. The average in situ matrix permeability of Abo sandstones is only 0.0067 millidarcies. Such small amounts of matrix porosity and permeability probably do not contribute greatly to production. The Abo wells tap a gas-filled natural fracture system, and mudstones seal the fractured sandstone reservoirs. Because fluvial-deltaic deposits extend almost 100 mi (160 km) north of present production, the area underlain by potential Abo sandstone reservoirs is at least five times greater than the area that is currently productive.

Introduction

Red-bed sandstones of the Abo Formation (Permian) currently produce natural gas from the Pecos Slope Abo field in northern Chaves County, New Mexico (Figs. 1, 2; Wheatley, 1981; Broadhead, 1982a, p. 18). The productive area of the field currently covers approximately 700 mi² (1,800 km²). First production from the Abo red-bed facies was obtained in 1977 by the Yates Petroleum Corp. No. 1 McConkey located in sec. 10, T. 9 S., R. 26 E., Chaves County (Table 1, Figs. 2, 9). The Yates well was a workover of the Honolulu Oil Corp. No. 1 McConkey Estate, originally abandoned as a dry hole in 1951. Yates tested the Ellenburger Group (Ordovician) and the Devonian and Pennsylvanian Systems without success. The Abo red beds were then tested to verify gas detected by crossover of the neutron-porosity and density-porosity logs. After acidization and artificial fracturing were done, an 18-ft- (5.5-m-) thick sandstone bed in the Abo produced 2,550 MCFGPD (thousand ft³ of gas per day) and 1 BCPD (bbl of gas condensate per day). The discovery prompted operators to drill a few more wells in the area to specifically test the red beds. These additional wells confirmed the discovery. Drilling continued at a slow pace until 1980. In that year the Abo red beds were designated a "tight gas sand" by the Federal Energy Regulatory Commission. That designation raised the ceiling price at which producers could sell gas from $2.81 to $4.92 per thousand ft³ (MCF) of gas. The ceiling price has subsequently been raised to $5.41 per MCF. At these higher prices, gas can be produced economically from the tight Abo sandstones. Since the tight-sand designation, more than 350 gas wells have been drilled and completed in the Abo red beds.

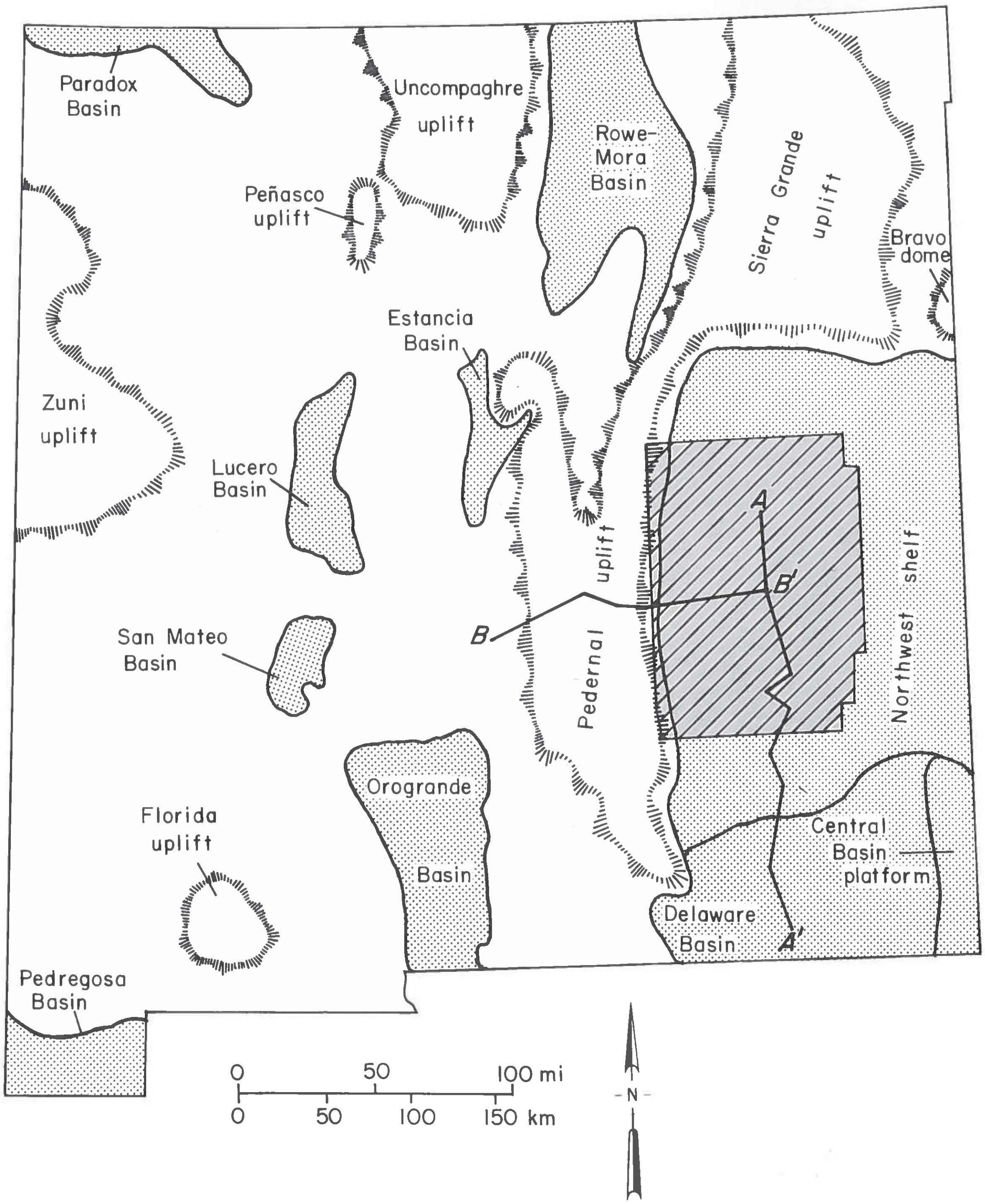

FIGURE 1—Report area (shaded), major late Paleozoic uplifts (hachured) and basins (stippled), and lines of cross sections A–A′ (Fig. 5) and B–B′ (Fig. 6).

The purpose of this report is to map the Abo red beds in the subsurface of east-central New Mexico in order to determine stratigraphic and structural controls on Abo gas production. This report expands on an earlier preliminary report (Broadhead, 1982b). Wheatley (1981), Scott (1982), and Scott and others (1983) also have recently reported on the gas-producing Abo red beds of Chaves County.

The petrographic classification used in this report is derived from the classification of Grabau (1924, pp. 285–297). The term mudstone is used for rocks composed of more than 50% detrital clay and silt-size grains; argillaceous mudstone contains more clay than silt and silty mudstone contains more silt than clay. Sandstones are terrigenous detrital rocks composed of at least 50% sand-size grains and less than 10% gravel. Conglomeratic sandstones contain 10–50% gravel-size clasts, and conglomerates contain more than 50% gravel-size clasts. Anhydrite rock contains more than 50% of the mineral anhydrite, although in some cases this mineral may be gypsum or hemihydrite because distinguishing anhydrite, gypsum, and hemihydrite from each other in drill cuttings is difficult with a binocular microscope. Limestones are

TABLE 1—Key wells used in this study; see Fig. 2 for locations. Wells prefixed with letter **A** have detailed descriptions of drill cuttings in appendix A; wells prefixed with letter **B** have detailed descriptions of cores in appendix B; geophysical logs were information source for wells prefixed with letter **C**. See Figs. 8–19 for summary descriptions of key wells. **TD** = total depth; **OWWO** = old well worked over; **MCFGPD** = thousand ft³ of gas per day; **BCPD** = bbl gas condensate per day; **IPCAOF** = initial potential calculated open flow.

Well	Operator, well no., lease, location (section–township–range, county)	Completion date (mo/yr)	TD (ft)	Remarks
A1	Humble Oil and Refining Co. No. 1 State U, 10–12S–27E, Chaves	8/23/48	7,851	D & A. Did not test Abo. Used in cross section of Roswell Geological Society (1953). See Appendix A, Table A–1 and Fig. 8 for descriptions, also Fig. 5.
A2	Yates Petroleum Corp. No. 1 McConkey (OWWO) 10–9S–26E, Chaves	9/6/77	6,371	Discovery well. Initial production 2,550 MCFGPD + 1 BCPD through perforations from 4,764–4,782 ft. See Appendix A, Table A–2 and Fig. 9 for descriptions. Originally Honolulu Oil Corp. No. 1 McConkey Estate. See Fig. 5.
A3	Yates Petroleum Corp. No. 1 Willow Creek unit 16–4S–25E, Chaves	1/4/80	6,670	D & A. Tested Abo through perforations from 3,800–3,807 ft, 4,030–4,042 ft, 4,158–4,162 ft, 4,204–4,210 ft with no show. See Appendix A, Table A–3 and Fig. 10 for descriptions, also Figs. 5 and 6.
A4	Spartan Drilling Co. No. 1 Bonner & Thompson 25–5S–29E, Chaves	12/23/50	8,911	D & A. Did not test Abo. See Appendix A, Table A–4 and Fig. 11 for descriptions.
A5	Mesa Petroleum Co. No. 1 Gallo State 3–5S–18E, Lincoln	12/29/81	3,185	D & A. Abo wildcat test. No reported shows from Abo. See Appendix A, Table A–5 and Fig. 12 for descriptions, also Fig. 6.
A6	J. D. Sandefer III No. 1 Vaughn State 21–1S–26E, De Baca	7/16/74	5,800	D & A. Did not test Abo. See Appendix A, Table A–6 and Fig. 13 for descriptions.
A7	Clayton W. Williams No. 1 Salado Dome 11–4N–19E, Guadalupe	4/14/77	4,766	D & A. Did not test Abo. See Appendix A, Table A–7 and Fig. 14 for descriptions.
A8	Abercrombie & Hawkins No. 1 Nappier 22–5N–26E, De Baca	10/4/49	5,560	D & A. Did not test Abo. See Appendix A, Table A–8 and Fig. 15 for descriptions.
B1	Yates Petroleum Corp. No. 1 Papalote OI State 16–7S–25E, Chaves	2/2/81	4,475	Abo production through perforations from 4,052–4,062 ft. IPCAOF 1,050 MCFGPD. See Appendix B, Table B–1 and Fig. 16 for descriptions.
B2	Yates Petroleum Corp. No. 2 Thorpe MI Federal 3–7S–25E, Chaves	2/23/81	4,150	Abo production through perforations from 3,958–3,964 ft. IPCAOF 1,068 MCFGPD. See Appendix B, Table B–2 and Fig. 17 for descriptions.
B3	AMOCO Production Co. No. 1 GK State 32–1N–26E, De Baca	1/12/80	4,900	D & A. Abo wildcat test. No reported shows from Abo. See Appendix B, Table B–3 and Fig. 18 for descriptions.
B4	AMOCO Production Co. No. 1 GM State 16–6N–29E, Quay	9/11/79	6,400	D & A. Abo wildcat test. No reported shows from Abo. See Appendix B, Table B–3 and Fig. 19 for descriptions.
C1	Texam Oil and Gas Co. No. 1 Welsh Federal 11–9S–20E, Lincoln	5/21/55	3,562	D & A. Did not test Abo.
C2	Magnolia Petroleum Co. No. 1 Bert Federal 5–8S–30E, Chaves	8/10/52	8,015	D & A. Did not test Abo.
C3	Tidewater Assoc. Oil Co. No. 1 Grady Best 27–2S–29E, Roosevelt	10/19/51	7,277	D & A. Did not test Abo.
C4	Southern Union Gas Co. No. 1 Lucas 5–2N–30E, Roosevelt	4/2/46	7,155	D & A. Did not test Abo.

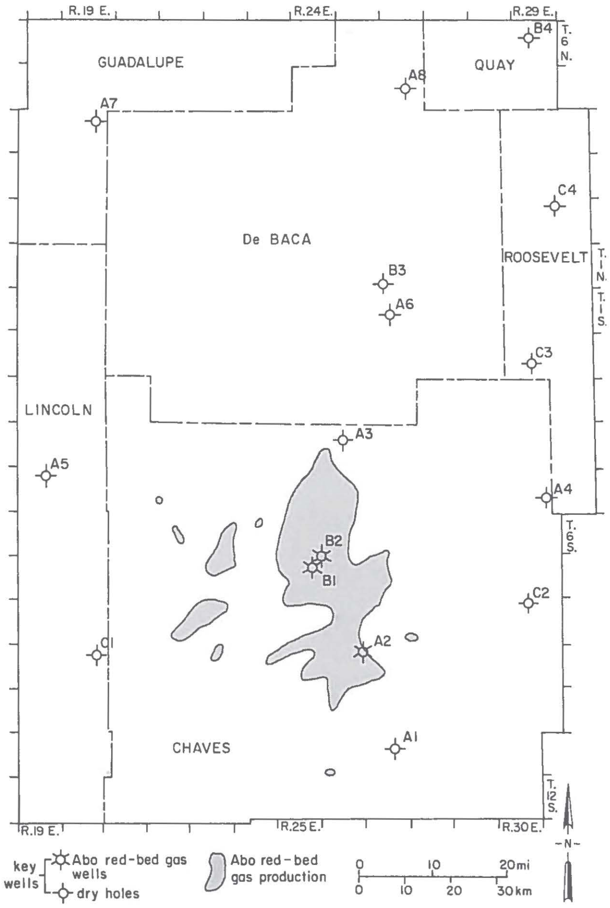

FIGURE 2—Study area, Abo red-bed gas production (shaded), and key wells used in study (see Table 1).

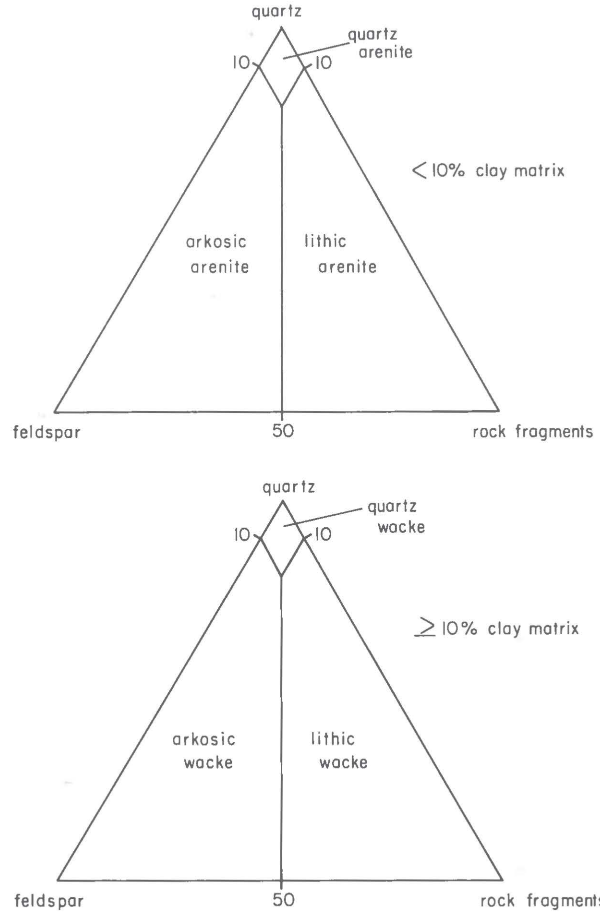

FIGURE 3—Sandstone classification used in this study; modified from Dott (1964).

sedimentary carbonate rocks in which the dominant mineral is calcite; dolostones are sedimentary carbonate rocks in which the dominant mineral is dolomite. Sandstones are subdivided on the basis of clay-matrix content and mineralogy of the framework grains with a classification modified from Dott (1964; Fig. 3). Limestones are subdivided according to the classification of Dunham (1962).

Regional setting

The area of current gas production from Abo red beds lies on the northwest part of the Northwest shelf of the Permian Basin (Fig. 2). Both the Permian Basin and its Northwest shelf were geomorphic features during the Permian. Structurally, the area lies on the broad Pecos slope, east of the Pedernal uplift.

The Pedernal uplift (Fig. 1) is a buried north-trending positive element with Precambrian and lower to middle Paleozoic rocks in its core. Uplift began in early Pennsylvanian time when a fault-bounded mountain range rose out of the Paleozoic seas (Thompson, 1942, pp. 12–13; Meyer, 1966, pp. 69–74, 93; Kottlowski, 1969). Uplift continued into Wolfcampian (early Permian) time. During the late Pennsylvanian and early Permian, the dominantly granitic terrain of the Pedernal uplift debouched vast quantities of arkosic gravels, sands, and muds into the Paleozoic seas present on the east and west flanks of the uplift. The Pedernal uplift formed a major barrier to the Paleozoic seas and exhibited a strong control on depositional facies. Uplift of the Pedernal mountains culminated in Wolfcampian time. By the late Wolfcampian, the Pedernal uplift was almost completely buried in its own debris. This burial resulted in onlap of lower Permian strata onto the eastern and western flanks of the uplift.

The Pecos slope (Kelley and Thompson, 1964, pp. 110–111; Kelley, 1971, p. 38) is the gently eastward-dipping homocline that occurs over much of the report area. The crest of the Pecos slope is in central Lincoln County, west of the report area. From there, rocks that range in age from Precambrian to Triassic dip eastward into the Permian Basin at an overall angle of one-half degree to one degree. The Pecos slope is a Laramide-age structure. Numerous smaller scale structures are superimposed on the Pecos slope (Kelley, 1971, pp. 37–57).

Regional stratigraphy

Red beds of the Abo Formation (Permian: Wolfcampian to Leonardian) are present over a large part of New Mexico from McKinley County in the northwest part of the state to Sierra County in the southwest part to Chaves County in the southeast part (Fig. 1). Abo outcrops have been studied in the Rio Grande valley, west of the Pedernal uplift. The Abo Formation was first named by Lee (Lee and Girty, 1909, pp. 20–21) for the interbedded red to purple sandstones, conglomeratic sandstones, and mudstones that crop out in Abo Canyon at the southern end of the Manzano Mountains, Socorro and Torrance Counties, New Mexico. The type section was later moved a few miles east to better exposures near Scholle, New Mexico, and described in more detail (Needham and Bates, 1943, pp. 1,654–1,657; Bates and others, 1947). According to Needham and Bates, the Abo is composed of approximately 40% arkosic sandstone and 60% mudstone at its type section. Myers (1977) mapped the type locality in detail and described the stratigraphic section.

Characteristic sedimentary features of the Abo outcrops in and adjacent to the Rio Grande valley include crossbedding, symmetric and asymmetric ripple marks, desiccation cracks, casts of halite crystals, plant fossils, fish fossils, and bones and tracks of amphibians and land-dwelling reptiles (Needham and Bates, 1943, p. 1,657; Kottlowski, 1963, p. 50; Kelley and Northrop, 1975, p. 50; Cappa, 1975). Many of the Abo sandstone bodies are lens-shaped channel fills. In the San Andres Mountains of south-central New Mexico, conglomerates of the Abo are generally thin, sheetlike deposits and are not channel fills (Kottlowski and others, 1956, p. 52). In the northern parts of the state, the Abo seems to have been deposited in a nonmarine, generally fluvial environment; in the southern part of the state, the Abo intertongues with the marine limestones and mudstones of the Hueco Formation (Permian: Wolfcampian) and probably was, at least in part, deposited in a marine environment (Kottlowski and others, 1956, pp. 49–53; Pray, 1961, pp. 96–106; Kelley and Northrop, 1975, p. 49; Seager and others, 1976, p. 12).

At the type section, the Abo Formation conformably overlies the limestones, arkosic sandstones, and mudstones of the Bursum Formation (Permian: Wolfcampian). The conformable contact with the Bursum has been documented in many places (Kottlowski, 1963, pp. 45, 46, 47; Kottlowski and Stewart, 1970, p. 23). Locally, the contact of the Abo with the Bursum may be erosional and unconformable (Bachman, 1968, p. 29). The Bursum is considered by some workers to be a northern facies of the marine deposits of the Hueco Formation, but other workers consider the Bursum to be a chronostratigraphic unit of earliest Wolfcampian age (Kottlowski and Stewart, 1970, p. 23). Bursum limestones bear a marine fauna. On higher parts of the west flank of the Pedernal uplift, the Bursum is absent in many places, and the Abo rests unconformably on folded and faulted pre-Permian Paleozoic sedimentary rocks (Pray, 1949; Pray, 1954, p. 101; Pray, 1961, p. 97). Along even higher parts of the Pedernal uplift, the Abo rests unconformably on Precambrian basement rocks (Kottlowski, 1963, p. 51; Perhac, 1964, p. 87; Kottlowski and Stewart, 1970, pp. 23, 27, 31).

The Yeso Formation (Permian: Leonardian) overlies the Abo (Needham and Bates, 1943, p. 1,657; Kottlowski, 1963, p. 56; Kelley and Northrop, 1975, p. 50) in most places but unconformably onlaps Precambrian rocks on the highest parts of the Pedernal uplift (Kelley, 1971, p. 7; Kelley, 1972, p. 9) where the Abo either was never deposited or was deposited and then later eroded. The Yeso is composed primarily of orange fine-grained sandstone, anhydrite (gypsum in outcrop), limestone, and dolostone. The percentage of each of these lithologies varies vertically and areally within the Yeso, and this variation is the basis on which the Yeso Formation is subdivided into four members (Bieberman and Kottlowski, 1963; Hunter and Ingersoll, 1981). A basal interval composed almost entirely of sandstone has been named the Meseta Blanca Member by Wood and Northrop (1946).

The age of the Abo Formation on the west side of the Pedernal uplift has been the subject of much debate. The Abo appears to be primarily of Wolfcampian age (Kottlowski, 1963, p. 51). In western and northern New Mexico, the Abo may be of late Pennsylvanian age (Wood and Northrop, 1946; Kottlowski, 1963, p. 47). The upper part of the Abo may be of early Leonardian age (Kottlowski, 1963, pp. 50–51, 54). Read (*in* Bachman and Hayes, 1958) considered the Abo west of the Pedernal uplift to be Leonardian in age on the basis of paleobotanical studies.

Local stratigraphy

Sixteen key wells were used to help construct a stratigraphic column, regional cross sections, and fence diagrams of the Abo on the Northwest shelf (Figs. 4–7; Tables 1, 2). Detailed descriptions of drill cuttings from eight wells (Figs. 8–15; Tables A1–A8), core descriptions from four wells (Figs. 16–19; Tables B1–B4), and geophysical logs and less rigorous sample examinations from four additional wells (labeled C in Table 1) were used to describe lithologically the Hueco, Abo, and Yeso Formations on the Northwest shelf of the Permian Basin. Appendices A and B contain detailed descriptions of the cuttings and cores. Figs. 8–19 are summary descriptions of the cuttings and cores plotted against gamma-ray and resistivity borehole logs. Procedures used in description of cuttings and cores are outlined in the introductions to Appendices

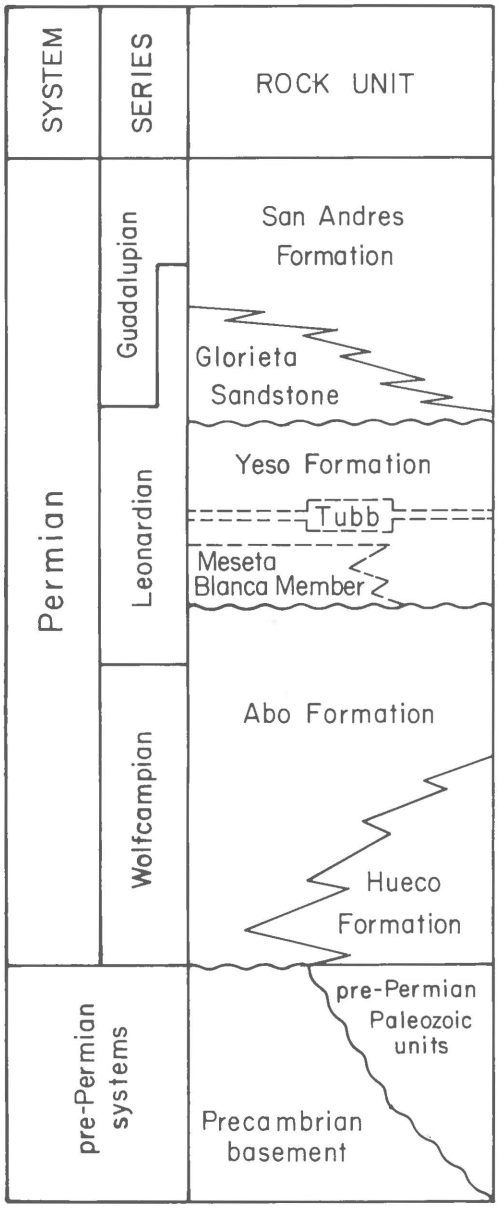

FIGURE 4—Generalized stratigraphic column of Lower Permian and older rocks on Northwest shelf of Permian Basin.

TABLE 2—WELLS USED IN SECTION OF FIG. 5. **TD** = total depth; **OWWO** = old well worked over; **OWDD** = old well drilled deeper. The term formation is used informally.

Well	Operator, well no., lease, location (section–township–range, county)	Completion date (mo/yr)	TD (ft)	Formation at TD
1	Hawkins No. 1 Myrick 17–2N–25E, De Baca	6/30/49	6,174	Precambrian
2	Yates Petroleum Corp. No. 1 Willow Creek unit 16–4S–25E, Chaves	1/4/80	6,670	Pennsylvanian
3	Yates Petroleum Corp. No. 1 McConkey (OWWO) 10–9S–26E, Chaves	9/6/77	6,371	Precambrian
4	DeKalb Agricultural Assoc. No. 1 Lewis 13–10S–25E, Chaves	6/30/59	5,650	Precambrian
5	Honolulu Oil Corp. No. 1 Texas Co. State 13–11S–27E, Chaves	4/8/50	6,933	Precambrian
6	Humble Oil and Refining Co. No. 1 State U 10–12S–27E, Chaves	8/23/48	7,851	Precambrian
7	Continental Oil Co. No. 1 Royce Langford 2–14S–26E, Chaves	10/10/47	8,099	Precambrian
8	Richfield No. 1 Trigg 35–14S–27E, Chaves	1/15/48	9,983	Precambrian
9	Continental Oil Co. No. 1 Thurman 11–16S–27E, Eddy	6/27/51	10,770	Precambrian
10	John M. Kelley No. 1 McMillan (OWDD) 36–20S–26E, Eddy	7/15/54	7,834	Hueco
11	Humble Oil & Refining Co. No. 1 Federal Wiggs 31–24S–27E, Eddy	2/8/50	14,865	El Paso

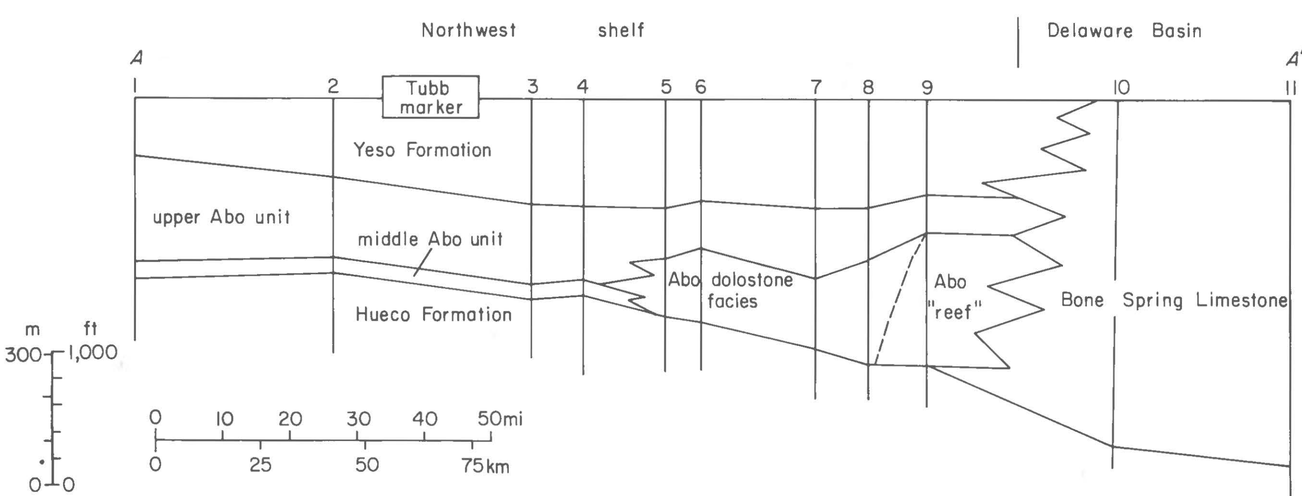

FIGURE 5—North–south cross section from Northwest shelf to Delaware Basin; datum is top of Tubb marker. See Fig. 1 for location and Table 2 for well data; numbers refer to wells listed in Table 2; modified from Roswell Geological Society (1953).

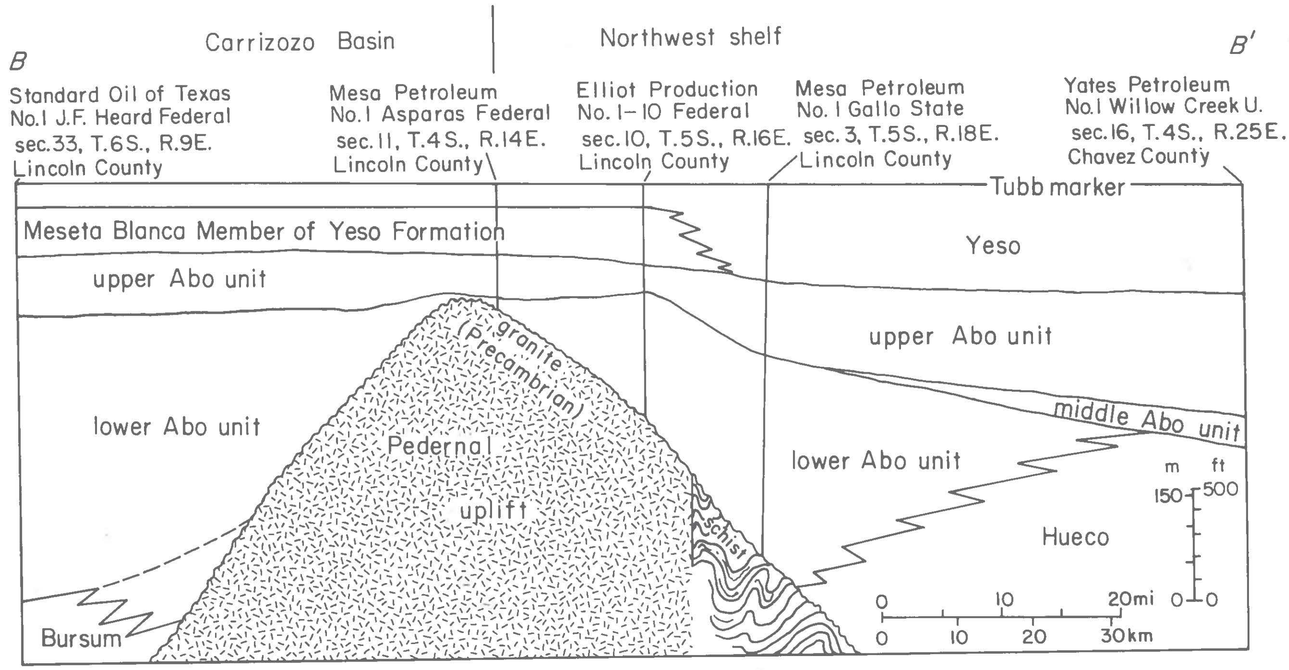

FIGURE 6—East–west cross section across Pedernal uplift; datum is top of Tubb marker. See Fig. 1 for location.

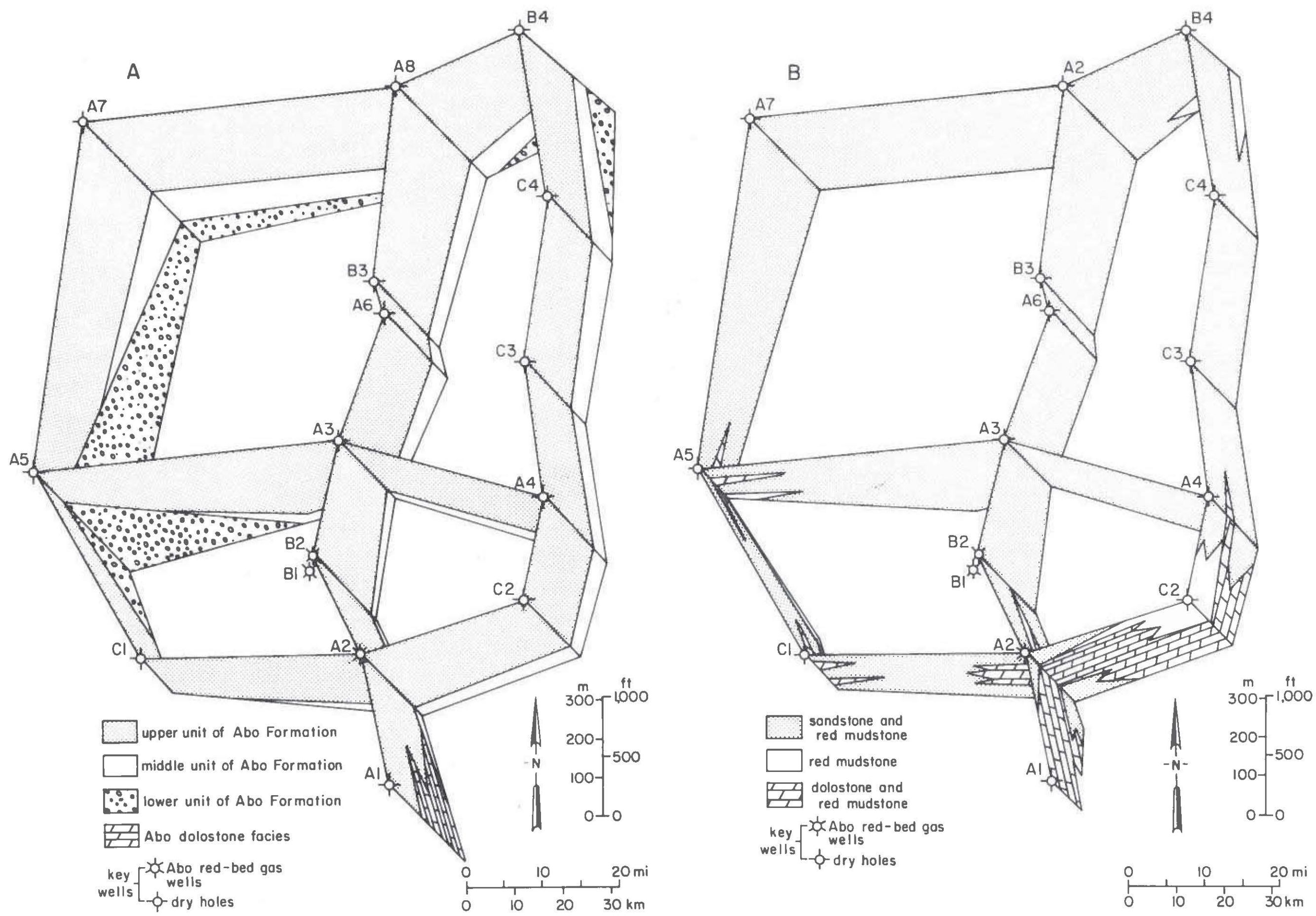

FIGURE 7—**A**, Fence diagram of Abo Formation on Northwest shelf of Permian Basin. **B**, Fence diagram of upper unit of Abo Formation on Northwest shelf of Permian Basin. See Table 1 for well locations; see Figs. 8–19 and Appendices A and B for lithologic descriptions; letters and numbers refer to wells.

A and B. Appendix C contains petrographic data from 59 thin sections prepared from cores and drill cuttings.

Hueco Formation (Permian: Wolfcampian)

The Hueco Formation conformably underlies the middle mudstone-rich unit of the Abo in all wells studied except the Humble No. 1 State U, the Mesa No. 1 Gallo State, and the AMOCO No. 1 State GM. In the Humble well, the Hueco conformably underlies Abo dolostones that are equivalent to the middle unit. In the Mesa well, the Hueco limestones are absent, having intertongued with and graded laterally into the lower "granite wash" unit of the Abo somewhere basinward of the well (Fig. 6). In the AMOCO well, the lower unit grades downward into the Hueco. The following description of the upper 200–300 ft (60–90 m) of the Hueco is based on analyses of cores, drill cuttings, and geophysical logs.

The Hueco is composed dominantly of interbedded limestone and mudstone; beds of sandstone and conglomerate are present near the Wolfcampian-age uplifts of Precambrian basement (AMOCO No. 1 State GM). The Hueco core from the AMOCO No. 1 State GM is composed chiefly of conglomeratic sandstone and contains only minor amounts of red mudstone, intraclastic limestone, and microcrystalline dolostone. Elsewhere, the Hueco is composed of subequal amounts of limestone and red to gray mudstone. Sandstone is dominant to the north and northwest in the Abercrombie & Hawkins No. 1 Nappier and in the Clayton Williams No. 1 Salado Dome. Where the sandstone and conglomerate are absent, Hueco cuttings are generally 80% mudstone and 20% limestone. Most, but not all, of the mudstone is caved Abo; this is indicated by the abundance of highly resistive "limestone peaks" on resistivity logs in the Hueco and also is indicated by the 80% limestone and 20% mudstone present in the Hueco core from the AMOCO No. 1 State GK. Except where the sandstones and conglomerates are abundant, the cuttings, cores, and geophysical logs indicate that the mudstone/limestone ratio does not vary greatly in the Hueco and is generally less than 1:1.

Thick limestone beds and bundles composed of limestone beds separated by thin mudstones are 10–30 ft (3–9 m) thick and are tabular. They can be traced 50 mi (80 km) or more in the subsurface. These thick limestone beds and bundles thin slightly to the north.

Hueco limestones are black (N1) to olive gray (5Y4/1) to white (N9) when wet and are microcrystalline, fossiliferous, and well indurated. Individual beds are typically 0.5–10 ft (0.2–3 m) thick. Fossils range from a trace to 50% or more of the rock; Hueco fossils are foraminifers, fusulinids, brachiopods, disarticulated crinoid columnals, ostracods, gastropods, coralline algae, and bryozoans. Some fossils are whole individuals, but most are only broken fragments. Many fossils have been micritized by endolithic algae. Most fossils are supported by a microcrystalline calcite matrix (micrite). Common types of Hueco limestones are (Figs. 20e, f): lime mudstones, fusulinid wackestones and

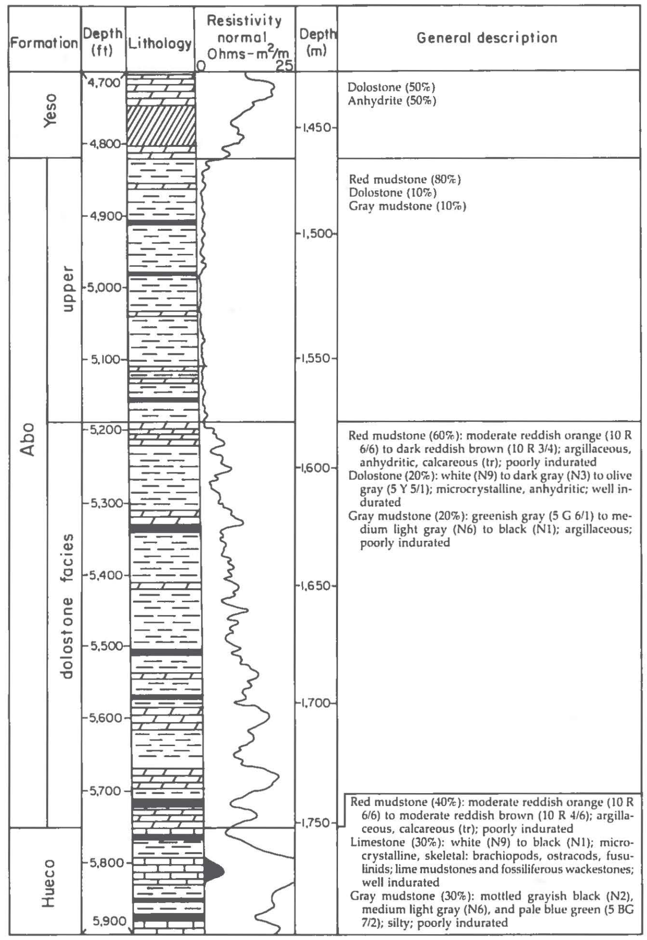

FIGURE 8—Generalized lithologic description of drill cuttings plotted against resistivity borehole log, Humble Oil and Refining Co. No. 1 State U, sec. 10, T. 12 S., R. 27 E., Chaves County, New Mexico. See Table 1 for well-completion information and Appendix A, Table A–1 for detailed lithologic descriptions.

packstones, crinoidal wackestones, foraminifer wackestones and packstones, and brachiopodal-ostracodal wackestones and packstones. Some lime mudstones are pelleted. Many of the limestone beds contain from 50 to 100% intraclasts of the aforementioned limestones. The intraclasts are angular to rounded and granule to cobble sized. The limestones may be classified as intraclastic packstones and grainstones. Syneresis cracks are common in the limestones; some of the syneresis cracks are filled with dark gray to red siliciclastic mudstone. Many of the intraclasts probably were formed during syneresis. Many of the limestones are intraclastic near contacts with interbedded siliciclastic mudstones and grade vertically into the mudstones; the vertically adjacent mudstones contain limestone intraclasts. Other limestones have sharp contacts with the mudstones.

Most Hueco mudstones are grayish black (N2) to medium dark gray (N4) when wet; a subordinate number are dark reddish brown (10R3/4) to moderate reddish orange (10R6/6). The gray mudstones are argillaceous, calcareous, thinly fissile, and fossiliferous; some fossils are fragments of brachiopods and crinoids, and others are unidentifiable recrystallized fragments. Some of the mudstones contain angular to rounded limestone intraclasts. The red mudstones are argillaceous and thinly fissile to nonfissile. Most are calcareous, but only a few contain fossils; fossils are brachiopods and fusulinids. Mudstone beds are typically 0.1–6 ft (0.03–1.8 m) thick. As with the limestones, individual bundles of mudstone beds separated by thin limestones are tabular and can be traced 50 mi (80 km) or more in the subsurface.

Abo Formation (Permian: Wolfcampian to Leonardian)

Lower Permian red beds commonly correlated with the Abo Formation contain the gas reservoirs on the Northwest shelf of the Permian Basin. These red beds do not crop out in the Pecos slope area because they are buried beneath younger Permian strata. Lloyd (1949, pp. 28–31) and the Roswell Geological Society (1956) correlated these red beds on the eastern side of the Pedernal uplift with the Abo Formation, implying that they are mostly of Wolfcampian age with the upper part possibly Leonardian. Kottlowski (1963, fig. 14) tentatively correlated a lower unit of red beds with the Abo Formation and an upper unit of red beds with the Meseta Blanca Member of the Yeso Formation; that correlation would indicate a Wolfcampian to possible Leonardian age for the lower Abo unit and a Leonardian age for the upper unit. Kottlowski's

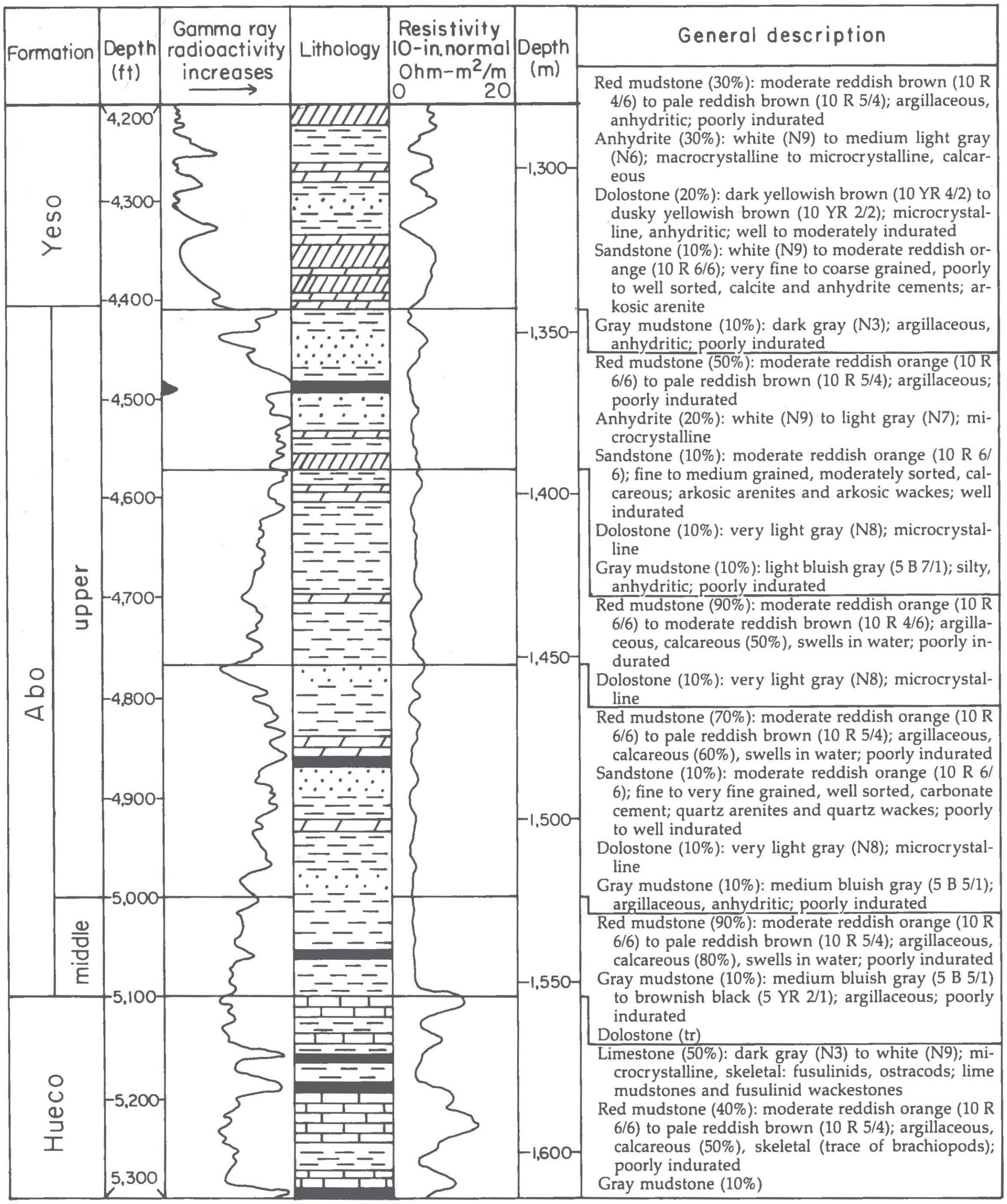

FIGURE 9—Generalized lithologic description of drill cuttings plotted against gamma-ray and resistivity borehole logs, Honolulu Oil Corp. No. 1 McConkey Estate, sec. 10, T. 9 S., R. 26 E., Chaves County, New Mexico; worked over by Yates Petroleum Corp. to become Pecos Slope Abo field discovery well. See Table 1 for well-completion information and Appendix A, Table A–2 for detailed lithologic descriptions.

correlation was made in Eddy County approximately 40 mi (60 km) south of the Pecos Slope Abo field. A cross section published by the Roswell Geological Society (1953) indicates that the gas-producing red beds of the Pecos Slope Abo field correlate with the upper part of these red beds. In yet a third correlation, Meyer (1966, p. 71) and Mazzulo (1982, fig. 3) correlated the red beds east of the uplift with the Wichita Formation (Leonardian) of Texas. According to Meyer, the Wichita separates the Hueco Formation (Meyer's "Wolfcampian") from the Yeso Formation. Meyer envisioned the Wichita as a wedge of red beds that pinches out westward between the converging Hueco and Yeso.

Biostratigraphic age determinations of the gas-producing Abo red beds point to a Leonardian age. Lloyd (1949, pp. 30–31) and the Roswell Geological Society (1953) lithostratigraphically correlated the red beds with the Abo reef (LeMay, 1961) of northern Eddy County and the Bone Spring Limestone of central Lea and Eddy Counties (Fig. 5). The Bone Spring was assigned a Leonardian age on the basis of fusulinids by Lloyd (1949, p. 31), Dunbar (1953, p. 799), Meyer (1966, p. 71), and Ross (1963, p. 46). Lloyd (1949, p. 30) reported Leonardian fusulinids from Abo dolostones in Lea County.

In this report, the gas-producing red beds east of the Pedernal uplift are subdivided vertically into three lithostratigraphic units: an upper unit of interbedded fine-grained sandstone and mudstone, a middle unit of mudstone, and a lower "granite wash" unit of interbedded conglomerate, sandstone, and mudstone. The upper unit is correlated with the Abo Formation on the west side of the Pedernal uplift; the middle unit onlaps and pinches out on the eastern side of the Pedernal uplift; the lower unit intertongues with and is correlated with the Hueco Formation (Figs. 5, 6). This correlation indicates a Wolfcampian to Leonardian age for the middle and upper units and a Wolf-

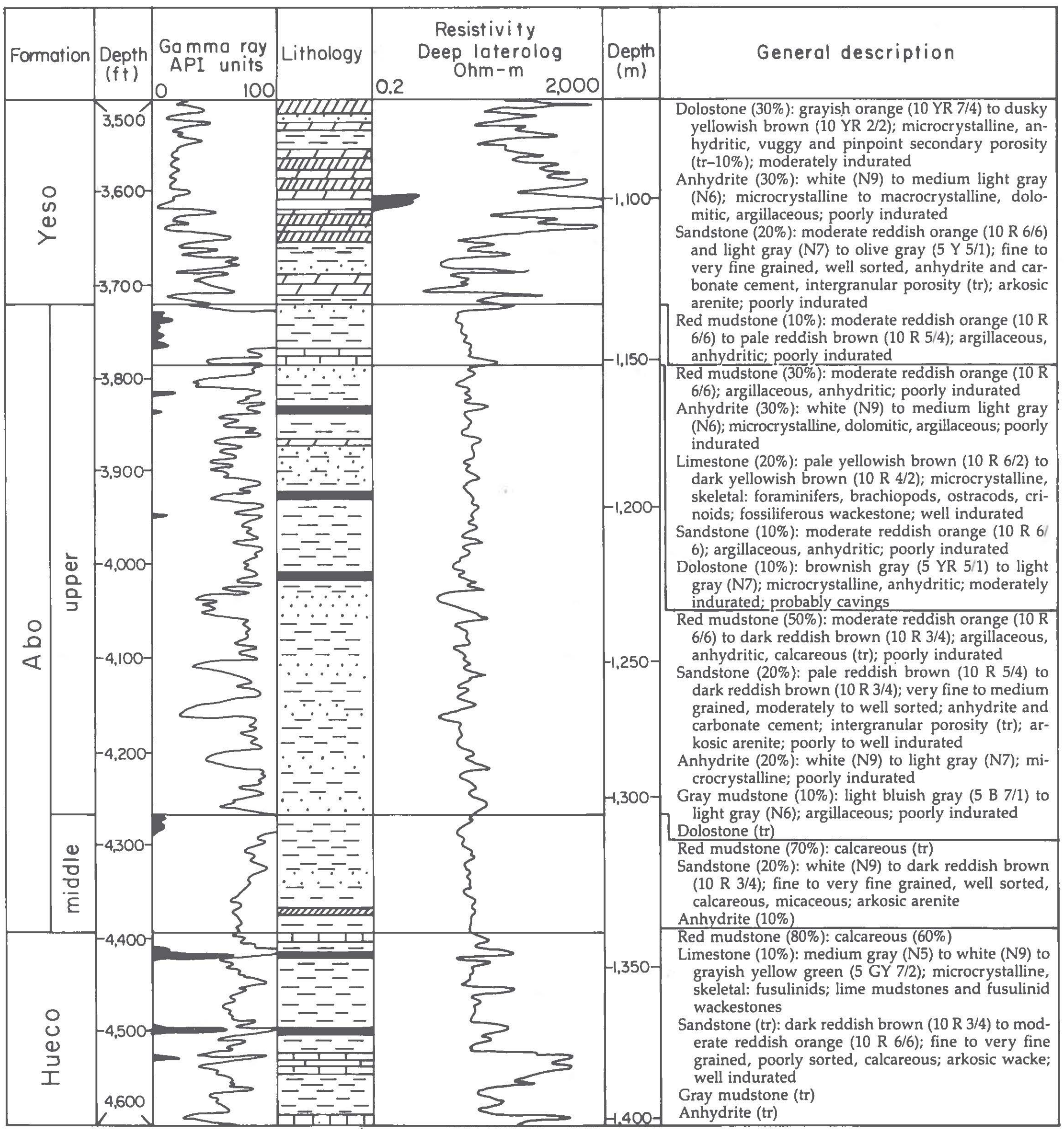

FIGURE 10—Generalized lithologic description of drill cuttings plotted against gamma-ray and resistivity borehole logs, Yates Petroleum Corp. No. 1 Willow Creek Unit, sec. 16, T. 4 S., R. 25 E., Chaves County, New Mexico. See Table 1 for well-completion information and Appendix A, Table A–3 for detailed lithologic descriptions.

campian age for the lower unit. Because of lithologic similarity with the Abo, and to avoid conflict with established usage, the entire red-bed section east of the Pedernal uplift is termed Abo. The upper and middle units grade southward into the dolostone facies of the Abo reef and back-reef lagoon. The lower unit grades eastward into the Hueco. The top of the Abo is picked at the top of the thick red-bed section that coincides with the base of the anhydrites, dolostones, and orange sandstones of the Yeso Formation. The base of the Abo is picked at the highest marine limestone (not dolostone) bed; that limestone marks the top of the Hueco. The highest marine limestone bed appears to be a laterally continuous stratigraphic marker. Where the Hueco is absent, the base of the Abo rests on granitic and metamorphic rocks of the Precambrian basement and possibly rests locally on pre-Permian Paleozoic rocks. The correlations made in this report are supported by stratigraphic data obtained from recently drilled wells.

The Abo is approximately 1,550 ft (472 m) thick in the Standard of Texas No. 1 Heard (Fig. 6). The normal thickness of the Abo is usually only a few hundred feet on the western side of the Pedernal uplift. Dipmeter log readings of only 5° or 6° dip in the Abo of the Heard well indicate that the 1,550 ft (472 m) is approximate true stratigraphic thickness. The anomalously large Yeso thickness of approximately 4,265 ft (1,300 m) in the well (Foster, *in* Griswold, 1959, p. 110) has been attributed to the presence of halite beds not present in outcrop sections as well as to discordant folding within the Yeso (Kottlowski and others, 1956, p. 59).

Fig. 7A shows that the principal lithologic variation within the Abo on the Northwest shelf of the Permian Basin is the transition from red-bed clastics in the

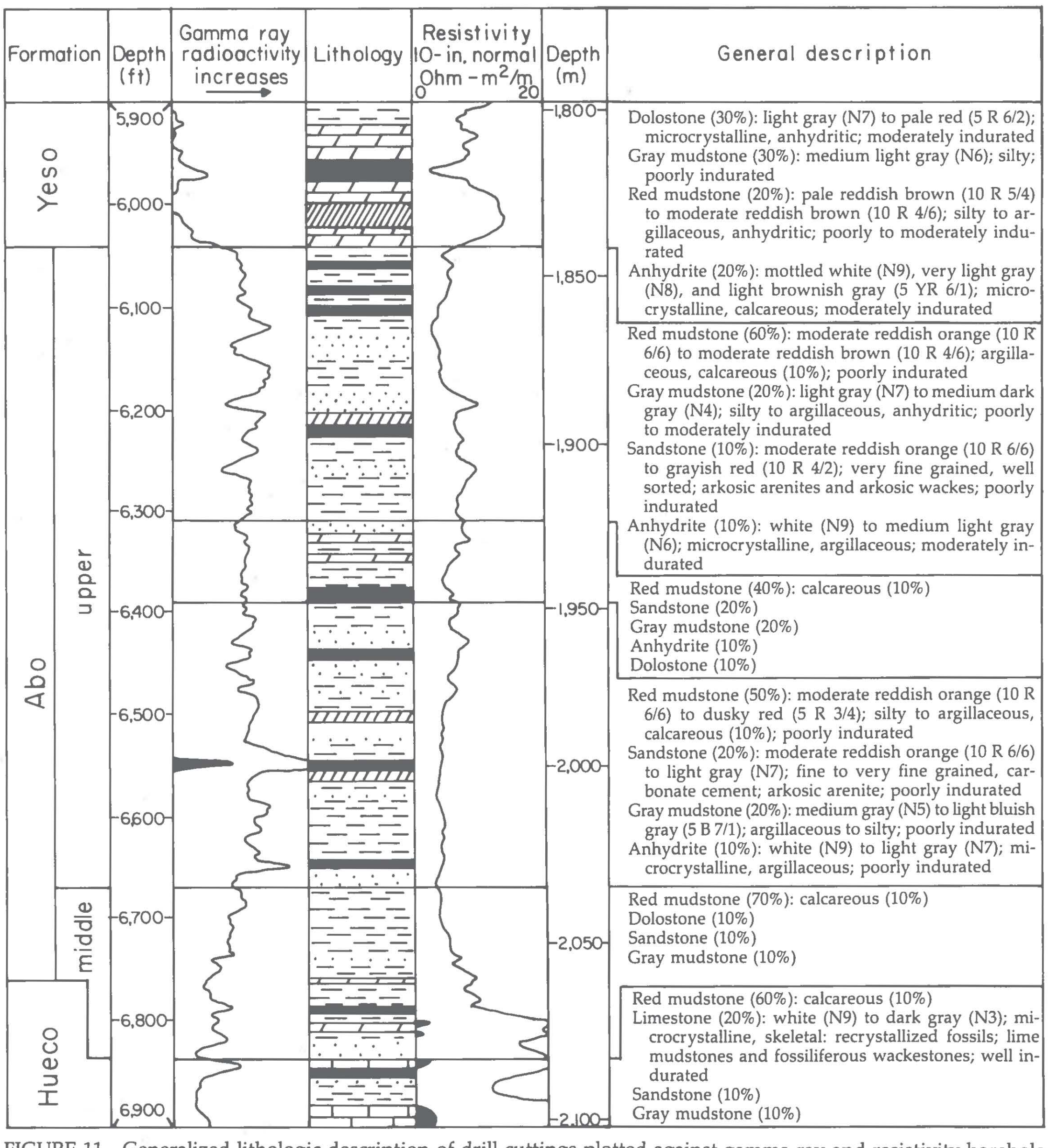

FIGURE 11—Generalized lithologic description of drill cuttings plotted against gamma-ray and resistivity borehole logs, Spartan Drilling Co. No. 1 Bonner & Thompson, sec. 25, T. 5 S., R. 29 E., Chaves County, New Mexico. See Table 1 for well-completion information and Appendix A, Table A–4 for detailed lithologic descriptions.

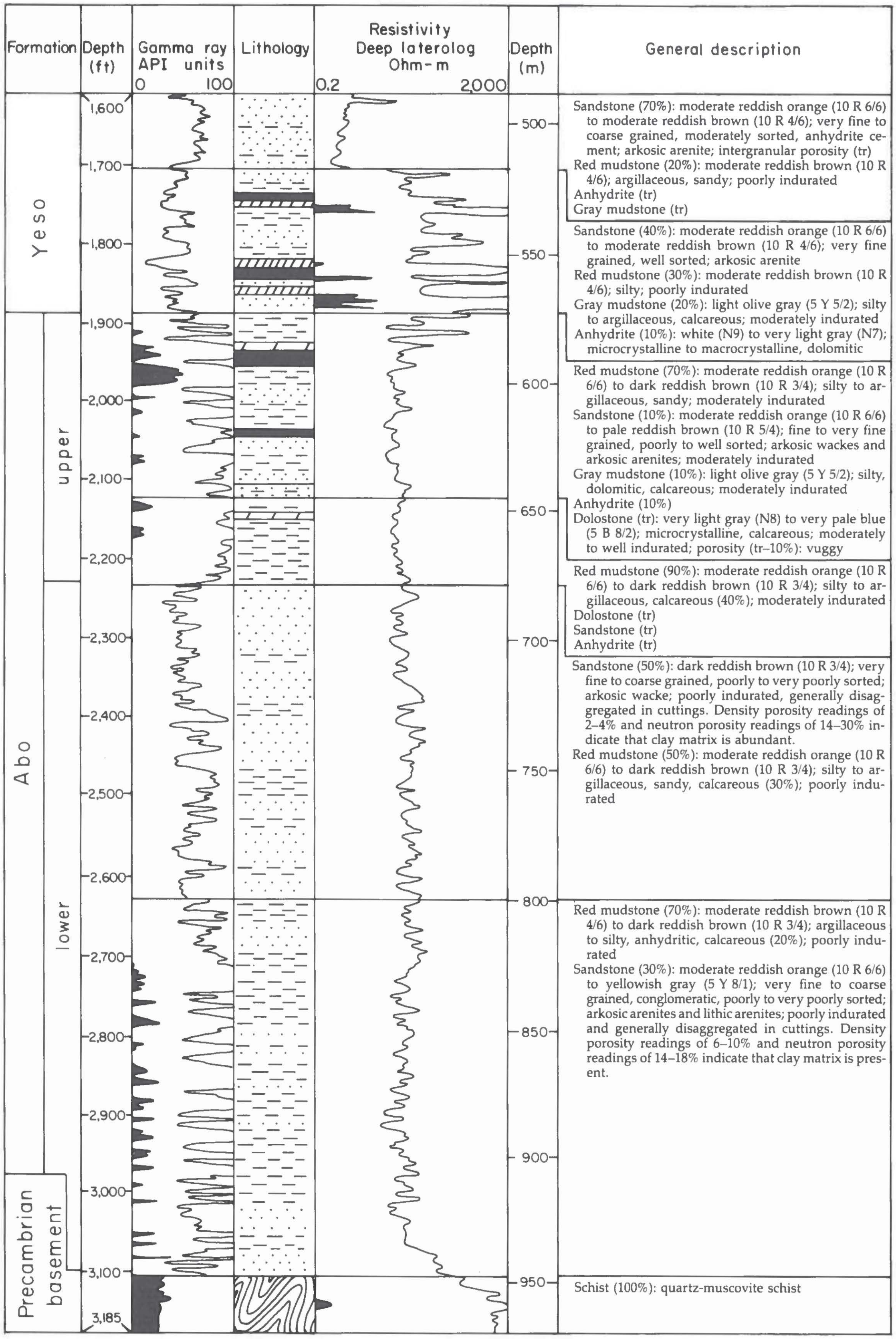

FIGURE 12—Generalized lithologic description of drill cuttings plotted against gamma-ray and resistivity borehole logs, Mesa Petroleum Co. No. 1 Gallo State, sec. 3, T. 5 S., R. 18 E., Lincoln County, New Mexico. See Table 1 for well-completion information and Appendix A, Table A-5 for detailed lithologic descriptions.

north to dolostones and interbedded red mudstones in the south. Significant amounts of dolostone are intercalated with the red beds in the Spartan Drilling Co. No. 1 Bonner & Thompson, in the Honolulu No. 1 McConkey Estate, and in the Mesa No. 1 Gallo State. A few thin dolostones are present in the Yates No. 1 Papalote (Fig. 16) and as far north as the Yates No. 1 Willow Creek (Fig. 10). Dolostones are present throughout the vertical extent of the Abo in the Humble No. 1 State U but are less abundant in the uppermost 370 ft (113 m; Fig. 8).

The Abo dolostones (Fig. 20A) are white (N9) to dark gray (N3) when wet and are microcrystalline and well indurated. They generally are composed entirely of dolomite or are mostly dolomite with traces of microcrystalline anhydrite. No porosity was observed in cuttings, cores, or thin sections of the dolostones; typical porosities obtained from formation density logs range from 0 to 2%. To the south in Eddy County, Abo dolostones are porous at the shelf edge and produce significant quantities of oil. The mudstones interbedded with the dolostones are moderate reddish orange(10R6/6) to dark reddish brown (10R3/4) when wet and are argillaceous, anhydritic, and poorly indurated. Some of the mudstones are calcareous.

North of the red bed–dolostone transition the Abo can be subdivided vertically into three units, as previously mentioned. The three units are referred to as the lower "granite wash" unit, the middle unit, and the upper unit. They are discussed below in detail.

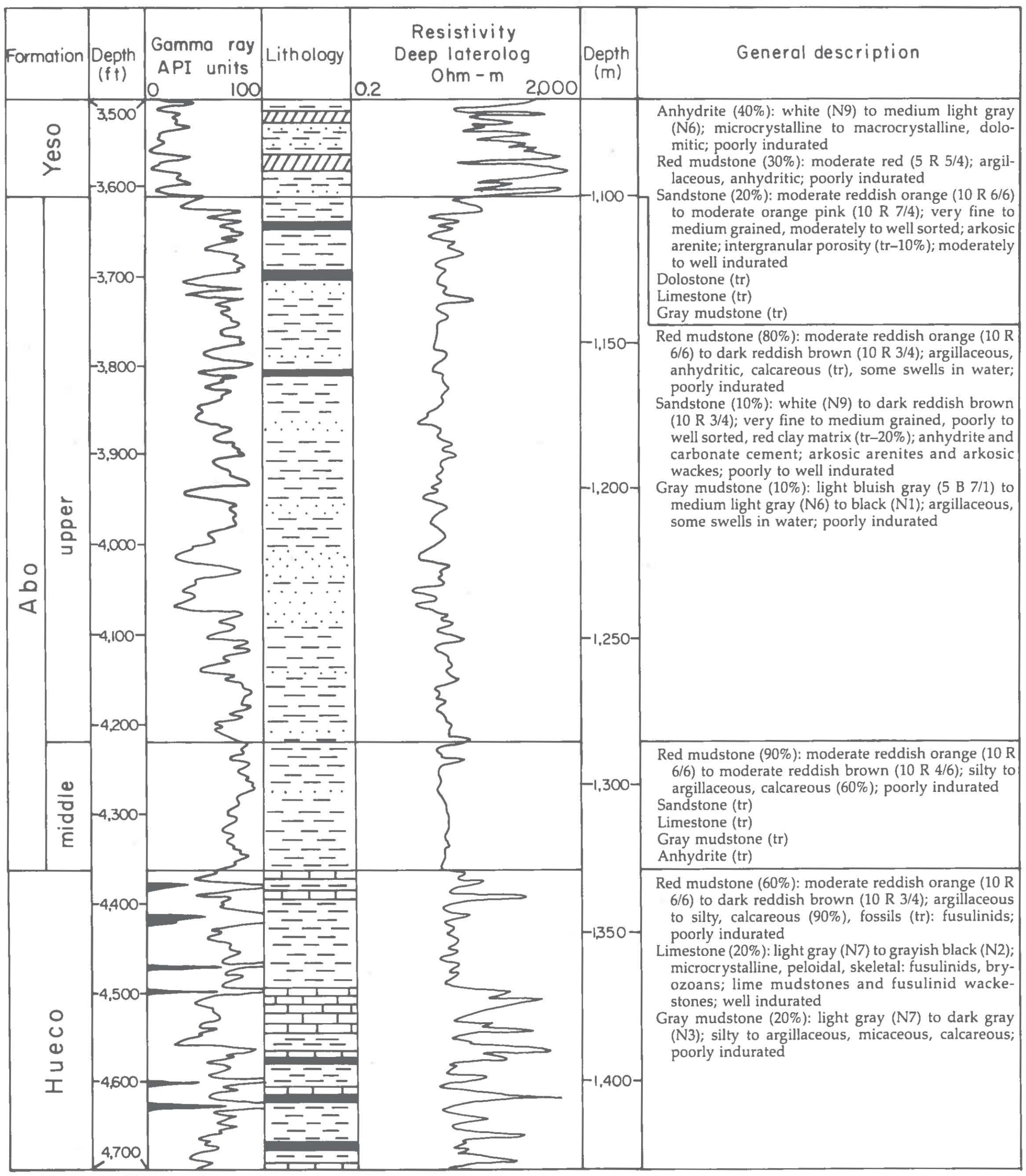

FIGURE 13—Generalized lithologic description of drill cuttings plotted against gamma-ray and resistivity borehole logs, J. D. Sandefer III No. 1 Vaughn State, sec. 21, T. 1 S., R. 26 E., De Baca County, New Mexico. See Table 1 for well-completion information and Appendix A, Table A–6 for detailed lithologic descriptions.

Lower "granite wash" unit

The lower "granite wash" unit of the Abo red beds consists of interbedded sandstone, conglomeratic sandstone, conglomerate, and red mudstone. The lower unit laterally intertongues with and is coeval with the Hueco Formation (Fig. 6); however, this lower unit is lithostratigraphically assigned to the Abo because it does not contain any significant amounts of limestone. The lower unit may be equivalent, at least in part, to the "red Hueco" of Kottlowski (1963, fig. 14). A similar facies transition is present west of the Pedernal uplift in the Sacramento Mountains where coarse Abo clastics grade laterally into the limestone-bearing Laborcita (Bursum) Formation (Otte, 1959, p. 61, pl. 13). The lower unit is not present everywhere, but only in the northern and western parts of the study area where it is proximal to Wolfcampian-age granite highs. To the west in the Mesa No. 1 Gallo State, the lower unit unconformably overlies Precambrian schist and is 870 ft (265 m) thick. To the north in the Clayton Williams No. 1 Salado Dome, the Abercrombie & Hawkins No. 1 Nappier, and the AMOCO No. 1 GM State, the lower unit conformably overlies and intertongues with the interbedded limestones and clastics of the Hueco Formation.

The conglomerates, conglomeratic sandstones, and sandstones are dark reddish brown (10R3/4) to grayish red (10R3/2) when wet. They are fine-sand- to pebble-size, moderately to poorly sorted, well-indurated arkosic arenites and arkosic wackes. Framework grains are angular quartz, potash feldspar, and granitic-rock fragments. Only a trace of clay matrix is present except in the Mesa No. 1 Gallo State. Although the cuttings from the Gallo State well are disaggregated into individual sand grains, the presence of a large amount of clay matrix is indicated by the 5–10% porosity indicated by the formation-density log and the correspondingly much greater 14–34% porosity indicated by the neutron logs. Because of the large amount of clay matrix, probably little porosity actually exists in these coarse clastics of the Gallo State well.

Nonargillaceous conglomerates occur principally to the northeast in the AMOCO No. 1 State GM where the lower unit is 298 ft (91 m) thick. Anhydrite, calcite, and dolomite are common cements. When not tightly cemented, the sandstones and conglomerates contain visual porosity ranging from a trace to 10%. Formation-density logs normally indicate 5–14% porosity and neutron-porosity logs indicate 14–20% porosity. Beds are typically 1–20 ft (0.3–6 m) thick and exhibit medium-scale cross-lamination and planar lamination. Contacts with interbedded mudstones are gradational.

Some conglomerates and conglomeratic sandstones in the lower unit are shown to be highly radioactive by gamma-ray borehole logs. The high level of radioactivity is probably caused by an abundance of unweathered potash feldspar or by a small amount of uranium mineralization in the sandstones (Scott and others, 1983).

Mudstones in the lower unit are dark reddish brown (10R3/4) when wet and are silty, sandy, and poorly indurated. Approximately 10% of the mudstones are calcareous. Beds are typically 0.1–10 ft (0.03–3.0 m) thick.

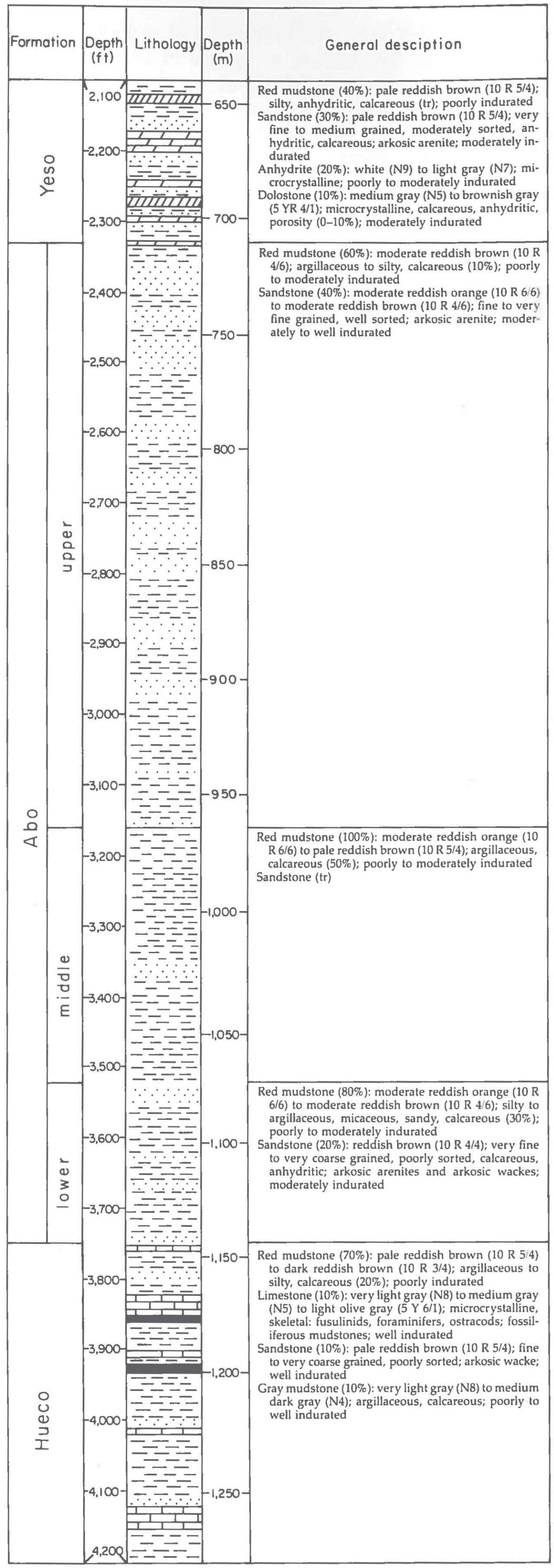

FIGURE 14—Generalized lithologic description of drill cuttings, Clayton W. Williams No. 1 Salado Dome, sec. 11, T. 4 N., R. 19 E., Guadalupe County, New Mexico. See Table 1 for well-completion information and Appendix A, Table A-7 for detailed lithologic descriptions.

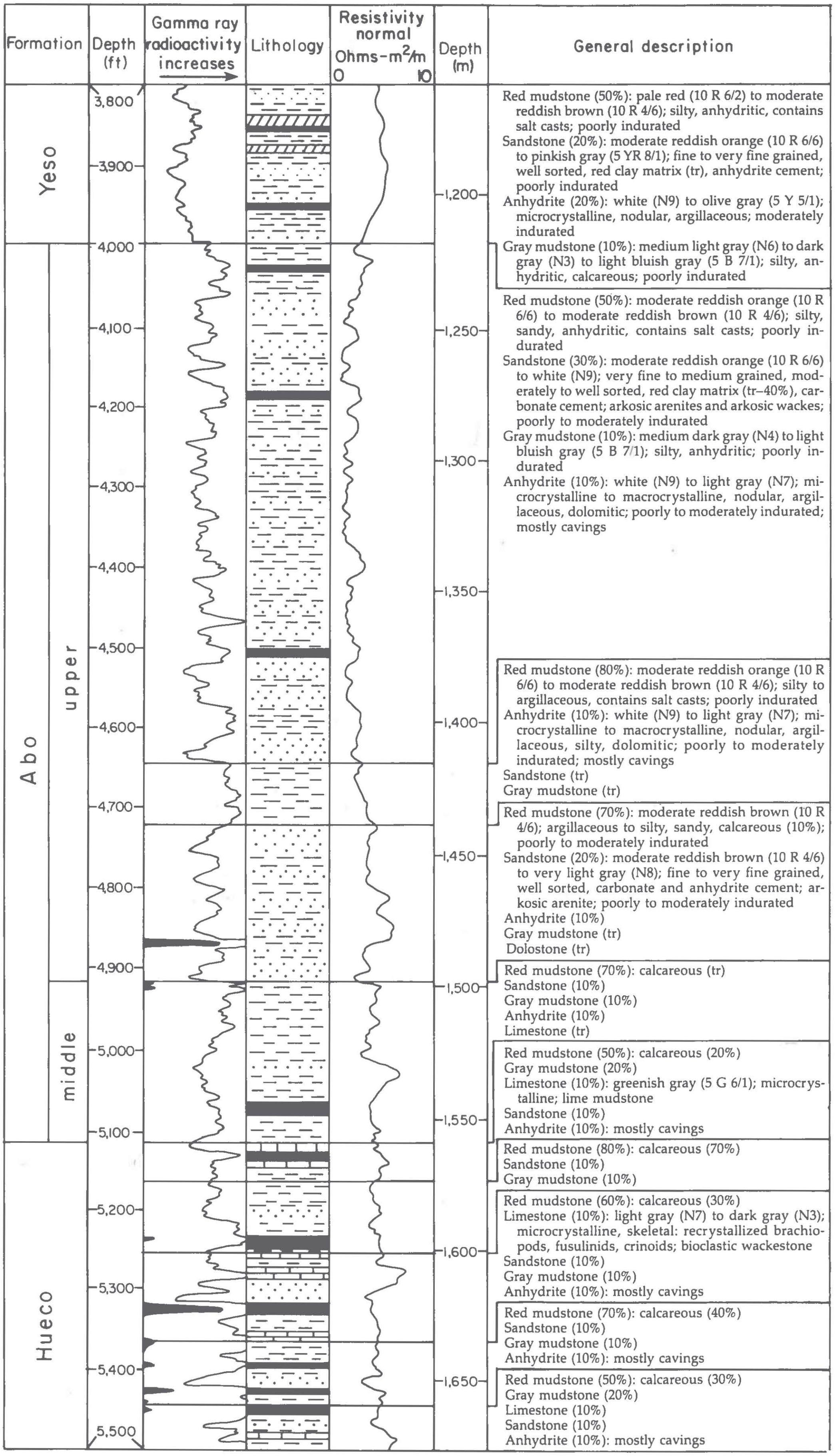

FIGURE 15—Generalized lithologic description of drill cuttings plotted against gamma-ray and resistivity borehole logs, Abercrombie & Hawkins No. 1 Nappier, sec. 22, T. 5 N., R. 25 E., De Baca County, New Mexico. See Table 1 for well-completion information and Appendix A, Table A–8 for detailed descriptions.

A few beds of nodular microcrystalline dolostone also are present in the lower unit. The dolostone beds are less than 1 ft (0.3 m) thick.

Middle unit

The middle unit of the Abo red beds consists of approximately 90% moderate-reddish-orange (10R6/6) to moderate-reddish-brown (10R4/6) mudstone and 10% dark-reddish-brown (10R3/4) sandstone. The middle unit does not vary greatly in thickness over much of Chaves and De Baca Counties, being at a minimum of 100 ft (30 m) in the Honolulu No. 1 McConkey Estate and thickening gradually to the north to 146 ft (45 m) in the AMOCO No. 1 State GM and 370 ft (113 m) in the Clayton Williams No. 1 Salado Dome. The middle unit pinches out to the west as it onlaps the Pedernal uplift (Fig. 6). Distinction between the middle and the upper units is difficult to the northeast of the State GM well.

The mudstones of the middle unit are argillaceous and approximately 10% are calcareous. Unlike mudstones of the upper unit they do not contain anhydrite. Some swell in water, indicating the presence of montmorillonite or other swelling clays. Calcareous mudstones in the AMOCO No. 1 State GM contain sparse sand-size fragments of recrystallized invertebrate fossils and calcareous algae. They are burrowed.

Interbedded sandstones in the middle unit are fine to very fine grained and well sorted. Most beds are less than 3 ft (1 m) thick, although a few beds are as thick as 10 ft (3 m). Contacts with interbedded mudstones are gradational. The sandstones are structureless, planar laminated, medium-scale cross-laminated, and bioturbated. Unlike sandstones of the upper unit, they do not contain root traces or desiccation cracks. Most beds are calcareous; some are fractured.

A trace to 10% of the cuttings from the middle unit are anhydrite. Most or all of the anhydrite appears to be caved from the Yeso because no anhydrite beds were seen in cores of the middle unit and because the

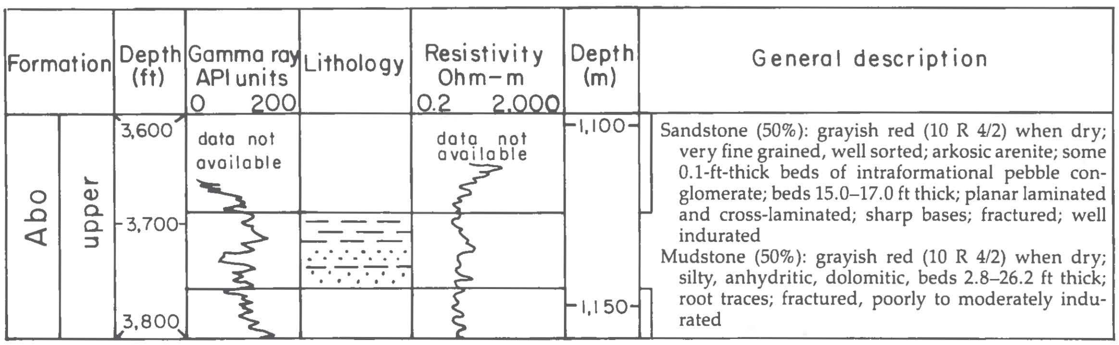

FIGURE 16—Generalized lithologic description of core plotted against gamma-ray and resistivity borehole logs, Yates Petroleum Corp. No. 1 Papalote OI State, Chaves County, New Mexico. See Table 1 for well-completion information and Appendix B, Table B–1 for detailed lithologic descriptions.

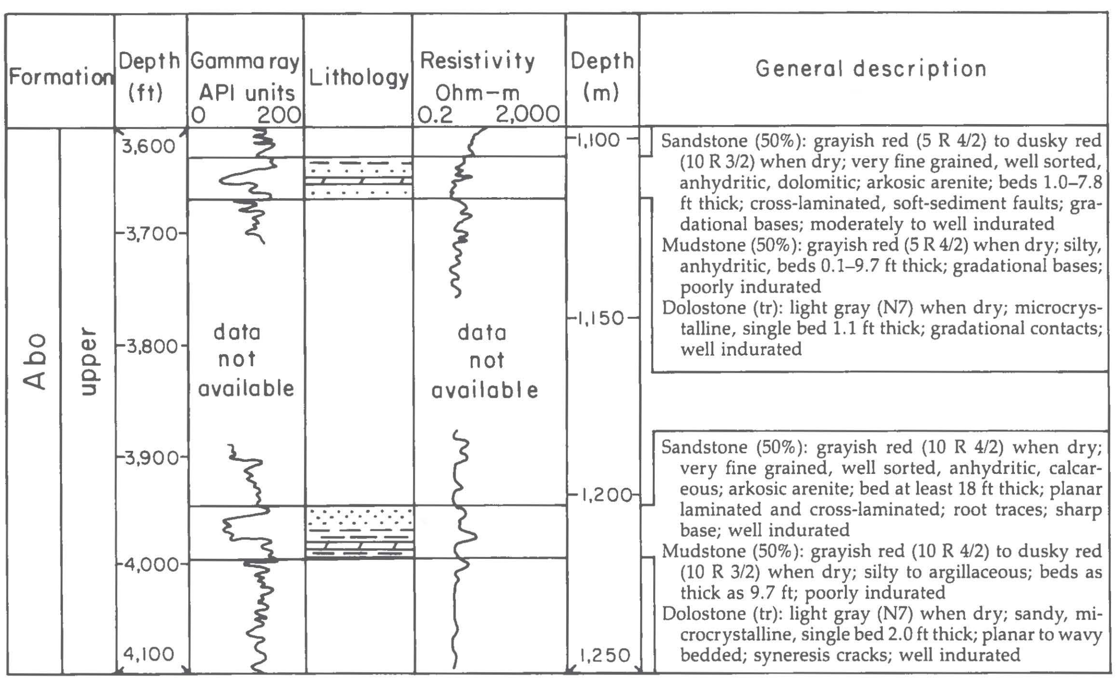

FIGURE 17—Generalized lithologic description of core plotted against gamma-ray and resistivity borehole logs, Yates Petroleum Corp. No. 2 Thorpe MI Federal, sec. 3, T. 7 S., R. 25 E., Chaves County, New Mexico. See Table 1 for well-completion information and Appendix B, Table B–2 for detailed lithologic descriptions.

anhydrite cuttings are fairly evenly distributed throughout the middle unit.

Upper unit

The upper unit of the Abo red beds is composed of interbedded red sandstones and red mudstones with a few thin dolostones south, east, and southwest of the Yates No. 1 Willow Creek (Figs. 2, 7B). The upper unit attains a maximum thickness of approximately 830 ft (253 m) in the Clayton Williams No. 1 Salado Dome in the northwest part of the study area. From there it thins to the south and east to approximately 600 ft (183 m) at the J. D. Sandefer No. 1 Vaughn State and the Yates No. 1 Willow Creek. Further south and east the upper unit is interbedded with the Abo dolostones in the Honolulu No. 1 McConkey Estate and in the Spartan Drilling Co. No. 1 Bonner & Thompson (Fig. 11) and yet further south gives way almost com-

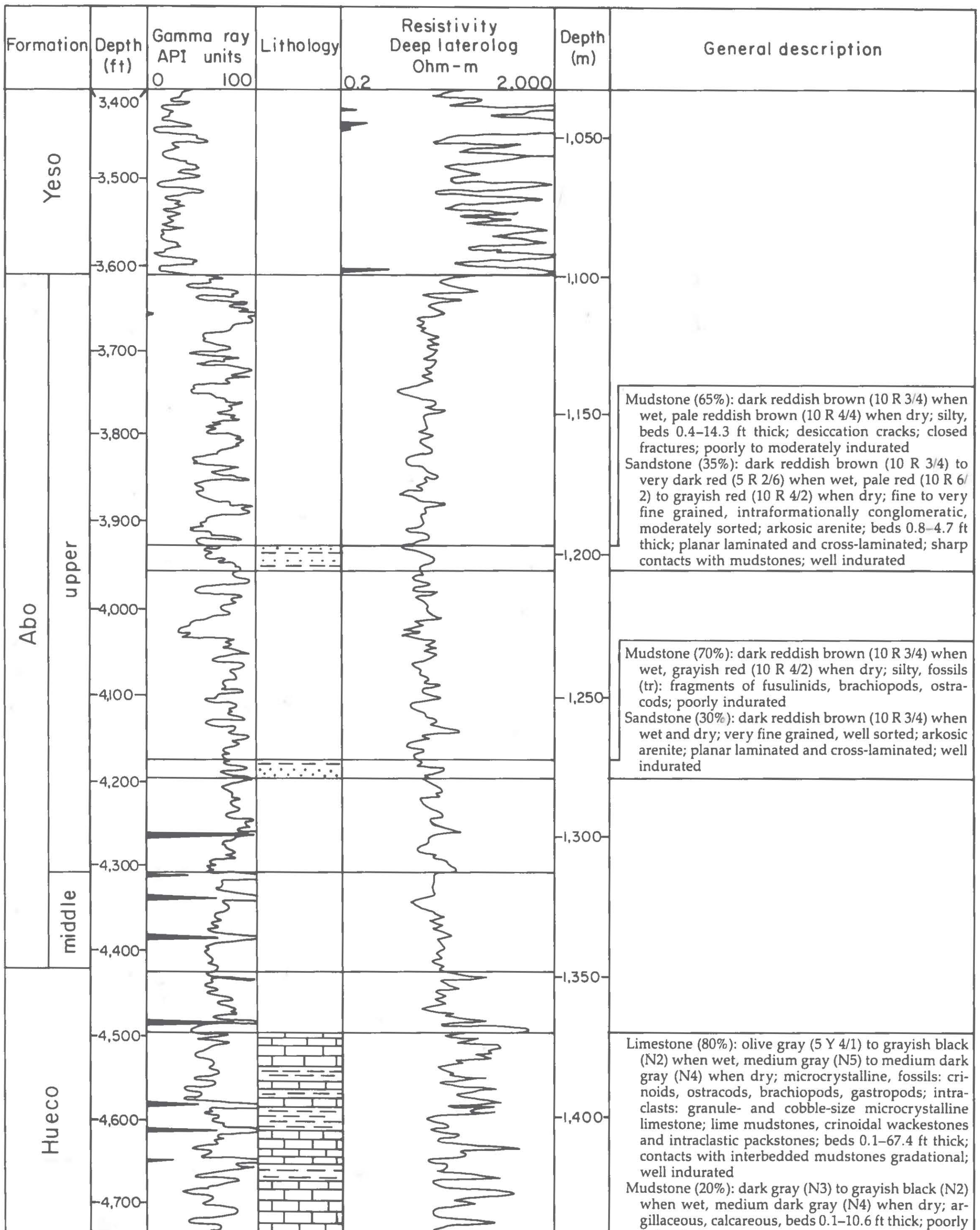

FIGURE 18—Generalized lithologic description of core plotted against gamma-ray and resistivity borehole logs, AMOCO Production Co. No. 1 GK State, sec. 32, T. 1 N., R. 26 E., De Baca County, New Mexico. See Table 1 for well-completion information and Appendix B, Table B–3 for detailed lithologic descriptions.

pletely to dolostones and mudstones in the Humble No. 1 State U where the Abo dolostone facies underlies 370 ft (113 m) of the upper unit. The upper unit rests conformably on the middle unit everywhere except to the southwest where it rests on the Hueco in the Texam No. 1 Welsh Federal; to the west in the Mesa No. 1 Gallo State, the upper unit thins to approximately 350 ft (107 m) as it onlaps the lower unit on the Pedernal uplift. Percentage of sandstone in the upper unit increases north of the Yates No. 1 Willow Creek but decreases to the west in the Mesa No. 1 Gallo State where mudstone is dominant. Percentage of sandstone decreases to a lesser extent to the south in the Honolulu No. 1 McConkey Estate and to the east in the Spartan No. 1 Bonner & Thompson where the upper unit also contains interbedded dolostone. Thus, sandstone-rich Abo forms a southward-projecting lobe centered about the Yates No. 1 Willow Creek (Fig. 7B).

Sandstones in the upper unit are generally moderate reddish orange (10R6/6) to moderate reddish brown (10R4/6) when wet and are fine to very fine grained, well-sorted, and well-indurated to friable arkosic arenites. Many are fractured. Cuttings, cores,

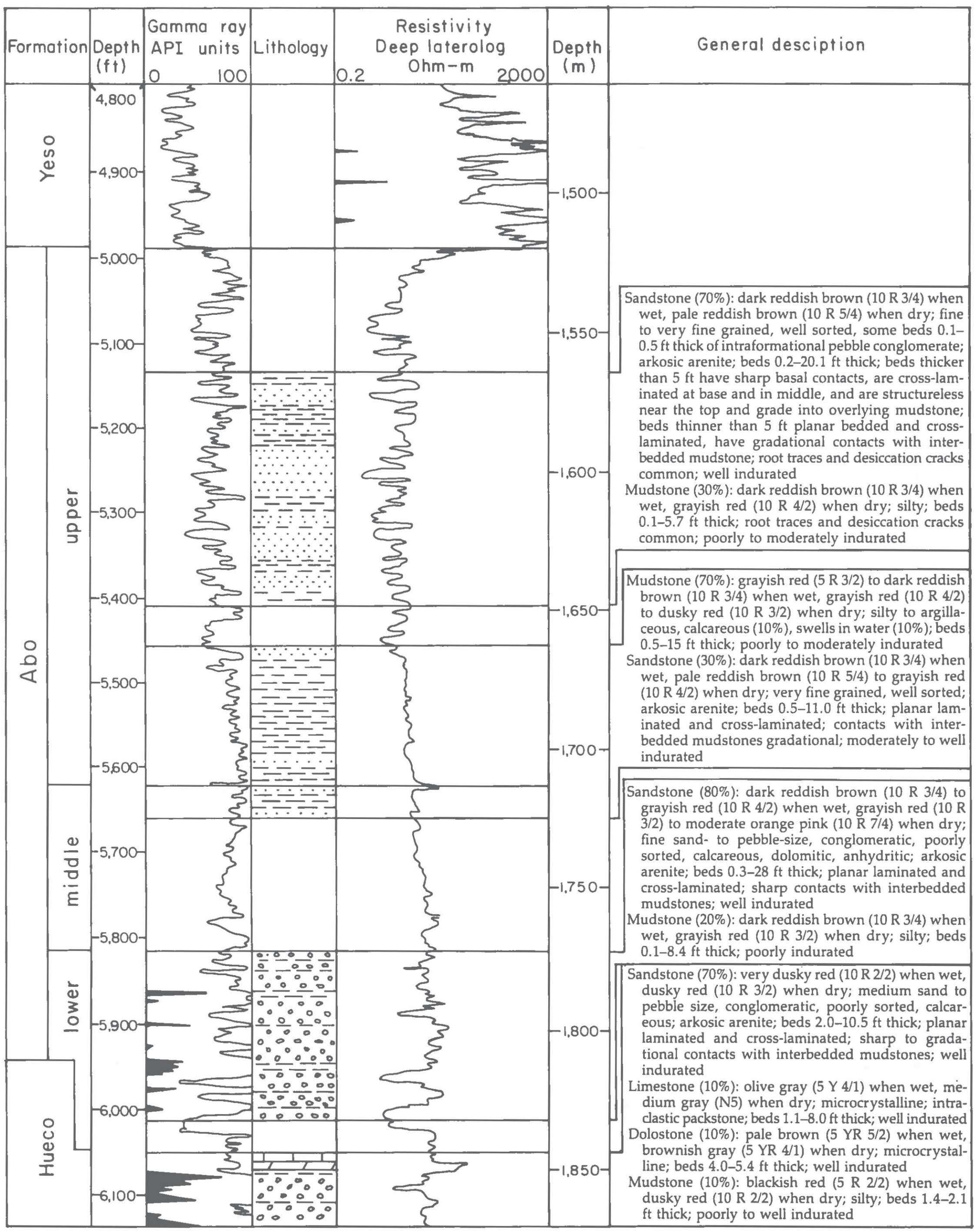

FIGURE 19—Generalized lithologic description of core plotted against gamma-ray and resistivity borehole logs, AMOCO Production Co. No. 1 GM State, sec. 16, T. 6 N., R. 29 E., Quay County, New Mexico. See Table 1 for well-completion information and Appendix B, Table B–4 for detailed lithologic descriptions.

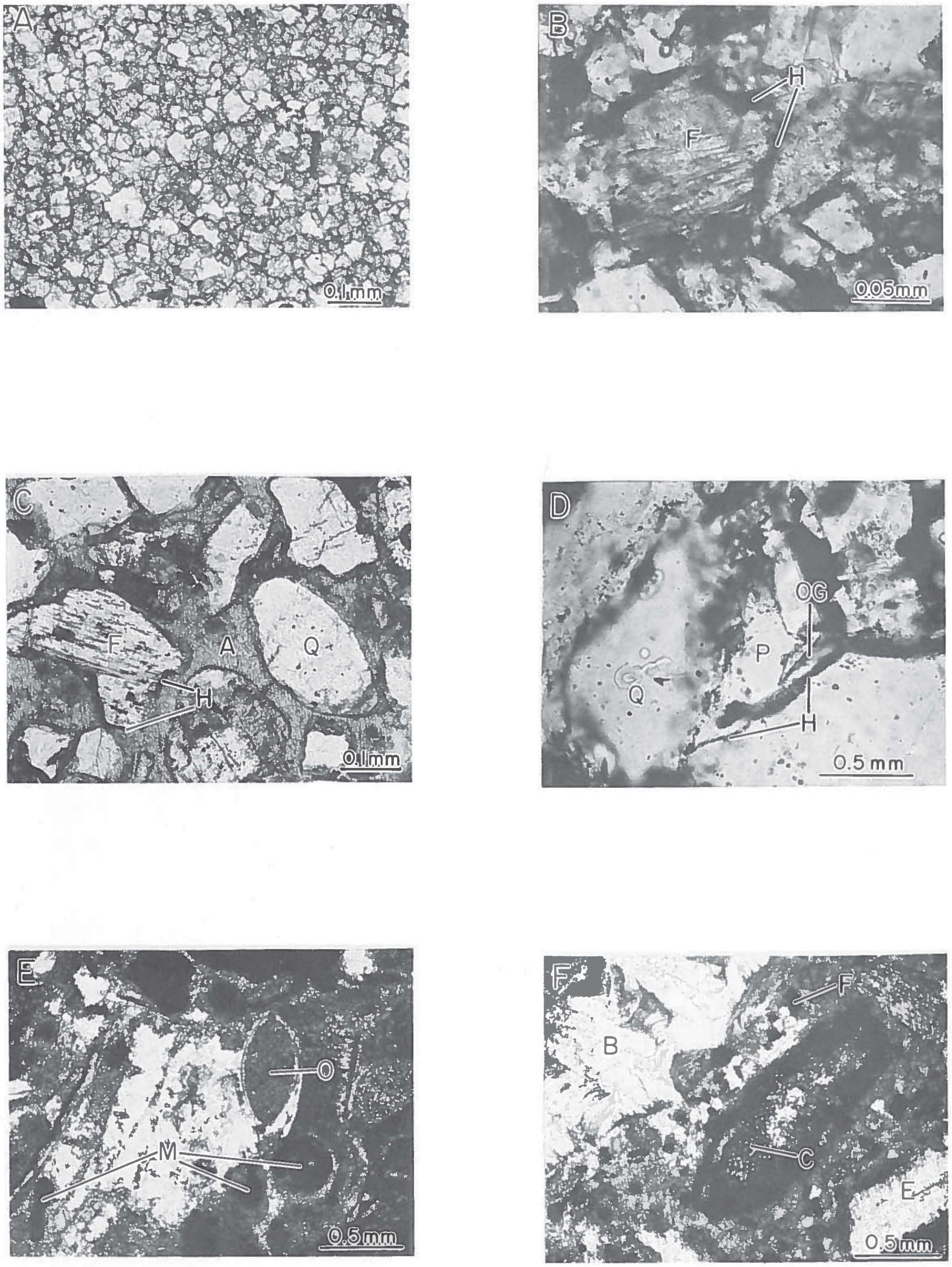

FIGURE 20—Thin-section photomicrographs.

A) Dolostone, Abo Formation, Humble Oil & Refining Co. No. 1 State U, 5,700–5,710 ft.

B) Sandstone, upper unit of Abo Formation, Yates Petroleum Corp. No. 2 Thorpe MI Federal, 3,962.4 ft. Note intergranular clay-hematite cement (**H**) and slightly altered potash feldspar (**F**).

C) Sandstone, upper unit of Abo Formation, Honolulu Oil Co. No. 1 McConkey Estate, 4,780–4,790 ft. Note poikilotopic anhydrite (**A**) cementing loosely packed subangular to subrounded quartz (**Q**) and feldspar (**F**); clay-hematite rims (**H**) separate anhydrite cement from framework grains.

D) Sandstone, upper unit of Abo Formation, Yates Petroleum Corp. No. 1 Willow Creek Unit, 4,190–4,200 ft. Note relict intergranular porosity (**P**), quartz framework grains (**Q**), clay hematite rims (**H**), and authigenic quartz over-growths (**OG**).

E) Limestone, Hueco Formation, AMOCO Production Co. No. 1 GK State, 4,497.6 ft. Ostracod (**O**) and micritized fossil fragments (**M**) in microcrystalline calcite matrix, bioclastic wackestone.

F) Limestone, Hueco Formation, AMOCO Production Co. No. 1 GK State, 4,521.6 ft. Coralline algae (**C**), brachiopod (**B**), echinoderm fragments (**E**), and micritized foraminifers (**F**) in microcrystalline calcite matrix, bioclastic wackestone.

and gamma-ray logs indicate that, although the percentage of sandstone increases northward within the upper unit, bed thickness appears to remain constant. The sandstones are generally 1–30 ft (0.3–9 m) thick and average approximately 10 ft (3 m). Sandstone bodies in the upper unit probably are lenticular, as seen in surface exposures (Broadhead and others, 1983; Speer and others, 1983). Geometry of sandstone bodies has not been determined in the subsurface because of the difficulty of tracing individual beds between wells drilled on a 160-acre spacing. Concentrations of sandstone lenses in particular stratigraphic intervals may give the illusion of lateral continuity when mapped in the subsurface; however, mapping of these intervals would still be extremely useful for exploration or development geology (*see* Scott and others, 1983).

The sandstone beds are planar laminated and cross-laminated. Beds thicker than 5 ft (1.5 m) generally exhibit a vertical sequence of sedimentary structures starting with medium-scale cross-laminae near the base which grade up into planar laminae which, in turn, grade up into small-scale cross-laminae (Fig. 21). In many of the sandstones, the planar laminae and cross-laminae randomly alternate with each other in vertical sequence. The upper 1–2 ft (0.3–0.6 m) of individual sandstone beds are structureless except for desiccation cracks and root traces. Granule- to pebble-size intraformational clasts of sandstone and mudstone form thin layers in the lower parts of beds. The sandstones generally are fine grained and grade into overlying mudstones; basal contacts are sharp. Convoluted lamination and soft-sediment faults are common. Many beds are fractured. The vertical sequence of sedimentary structures and upward-fining grain size suggest that sandstones thicker than 5 ft (1.5 m) were deposited as fluvial point bars and fluvial levees (Reineck and Singh, 1975, pp. 231–238, 244–246; LeBlanc, 1972, fig. 15; Walker and Cant, 1981), an interpretation which supports the inference of lenticular shapes for the sandstone bodies.

Sandstone beds thinner than 5 ft (1.5 m) generally contain planar laminae and/or small-scale cross-laminae, root traces, and some desiccation cracks; they have gradational upper and lower contacts with interbedded mudstones. Many of the sandstones contain horizontal to vertical fractures. The sedimentary structures and bedding contacts indicate that these thinner beds originated as crevasse-splay, natural-levee, and other overbank deposits in a fluvial system (Reineck and Singh, 1975, pp. 244–253; Walker and Cant, 1981).

Most of the sandstones in the upper unit of the Abo are fine to very fine grained, but average grain size of the sandstones does increase slightly to the north. Most of the sandstones contain from 10 to 30% coarse silt-size grains. Average grain size is approximately 0.07 mm, very fine sand, in the Honolulu No. 1 McConkey Estate and in the few rare sandstones interbedded with the dolostones of the Humble No. 1 State U. In and north of the Yates No. 1 Thorpe well, average grain size of sandstones varies between 0.10 mm, very fine sand, and 0.13 mm, fine sand; a few very fine grained sandstones of 0.07 mm average grain size are present north of the Thorpe well.

Framework grains in the sandstones are quartz and feldspar. Quartz averages 60% and ranges from 30 to 90%. Quartz is predominantly monocrystalline and angular; individual grains exhibit unit extinction indicating an unmetamorphosed igneous provenance. Feldspar averages 20% and ranges from 0 to 40%. Potash feldspar is dominant; only a few grains of twinned plagioclase were seen and then only in some of the samples. Feldspars are angular and unweathered, showing only minor alteration to clays and then only along cleavage planes. Feldspar content of the sandstones decreases generally toward the south; sandstones in the Honolulu No. 1 McConkey and in the Humble No. 1 State U contain only trace amounts of feldspar and are quartz arenites. Sandstones in wells farther north generally contain more feldspar and most of these sandstones are arkosic arenites, although a few are quartz arenites. While most Abo sandstones are only slightly radioactive on gamma-ray logs, some are highly radioactive. The high radioactivity may be caused by potassium (K_{40}) in the

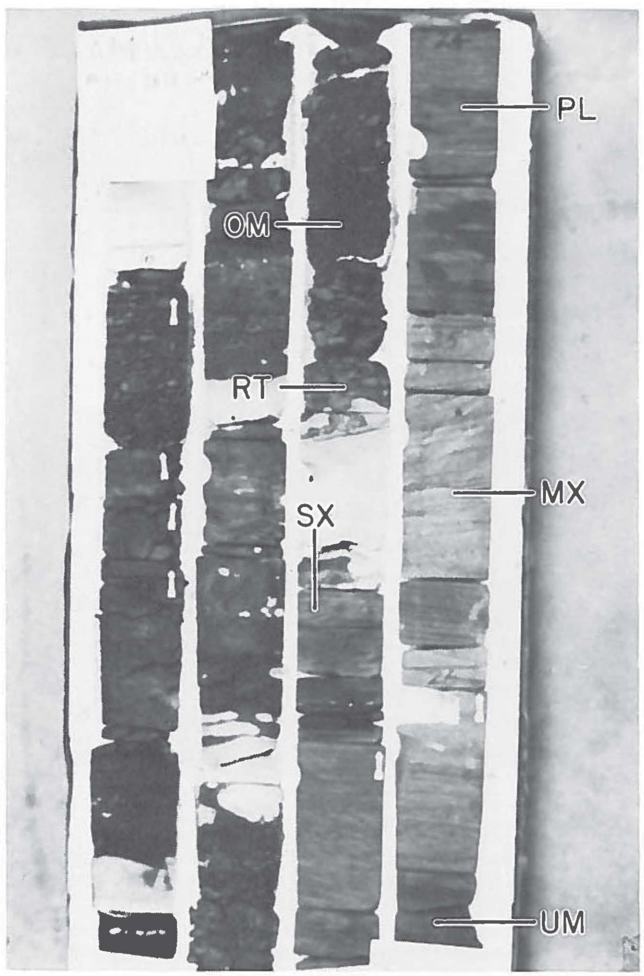

FIGURE 21—Upward-fining point-bar sequence in Abo sandstone bed, upper unit of Abo Formation. Medium-scale cross-laminae (**MX**) at base, planar laminae and a few small ripples (**PL**) in middle of bed, ripples and small-scale cross-laminae (**SX**) in upper part of bed and upward gradation into overlying mudstone (**OM**). Note root traces (**RT**) and sharp contact with underlying mudstone (**UM**); note diagenetic color mottling. AMOCO No. 1 GM State, 5,315–5,327 ft.

sandstones with large quantities of potash feldspar or it may be caused by uranium mineralization in the sandstones (Scott and others, 1983).

Clay minerals and micas are generally absent or are present only in trace amounts. Most of the clays are finely intermixed with hematite and are a cement; some are alteration products of feldspars. Rarely are clay and mica as much as 20% of the sandstone and then they are detrital. All of the mica appears to be muscovite. Clay mineral species have not been identified with X-ray diffraction.

Sandstone cements are hematite, anhydrite, calcite, dolomite, and authigenic quartz. Hematite is ubiquitous, generally present only in trace amounts and usually finely intermixed with clays. The clay-hematite cement forms thin rims around the framework grains (Fig. 20B) and imparts the red color to the sandstones. Most contacts between framework grains are separated by clay-hematite rims. The clay-hematite cement generally clogs pore throats; however, it is not responsible for complete occlusion of porosity except in sandstones with tight packing, where most grain-to-grain contacts are long rather than point. Anhydrite normally constitutes a trace to 10% of the sandstones and rarely is as much as 40%; in some cases it is absent. Anhydrite forms microcrystalline to macrocrystalline poikilotopic laths; it fills voids and in many cases has replaced the quartz and feldspar framework grains. Anhydrite cement constitutes 10% or more of the rock only where framework grains are loosely packed (Fig. 20C), indicating an early-diagenetic, precompactional emplacement for most of the anhydrite. Anhydrite either directly abuts framework grains or is separated from them by a thin hematite or clay-hematite rim, indicating an early origin for the clay-hematite rims also. The even coatings of the clay-hematite rims around the framework grains are most likely the result of mechanical infiltration of clay by influent seepage of surface water (Turner, 1980, pp. 117–120; Walker and others, 1978, pp. 19–21) and are similar to the clay cutans of Brewer (1964). The hematite-to-clay ratio seems to be much higher in the Abo than in Brewer's cutans; this suggests that some of the hematite was precipitated by oxygenated ground water (Turner, 1980, p. 280).

Carbonate cements are nearly ubiquitous in sandstones of the upper unit and are present in amounts ranging from a trace to 50%. Both calcite and dolomite occur, but dolomite is the more abundant. Dolomite is euhedral to anhedral; calcite is anhedral. Carbonate cement fills pores, replacing both framework grains and anhydrite cement. Carbonate cement occurs where sand grains have been well compacted, indicating a relatively late diagenetic origin.

Authigenic quartz overgrowths are uncommon and volumetrically insignificant. They were observed as overgrowths projecting into open pores which were not destroyed by compaction and which have not been occluded by clay-hematite, anhydrite, or carbonate cement (Fig. 20D); this indicates a late-diagenetic origin for the quartz overgrowths.

Abo sandstones are friable to well indurated. Induration generally increases with increasing amounts of carbonate and anhydrite cement. Regional trends of cementation were not observed in sandstones of the upper unit.

A trace amount of visual porosity is present in several thin sections of sandstones from the upper unit (Fig. 20D). Pore spaces are elongate to equant and are generally about .04 mm long and 0.01 mm wide. Individual pores are isolated from each other; they are classified as relict primary pores (Wescott, 1982, p. 160). Porosity determinations made from borehole logs are much higher than porosity determinations made by visual estimate of thin sections. Porosity determinations made from neutron logs range from 6 to 18%; those made from formation-density logs range from 2 to 15%. The higher measurements on logs indicate that submicroscopic pores are present, probably in the clay-hematite cement. The fact that porosity determinations made from neutron logs are generally higher than those made from formation-density logs may be explained by the clays present in the clay-hematite cement. The neutron log estimates porosity by measuring the amount of hydrogen in the rock and, by assuming that all of the hydrogen is present as pore water, can calculate the volume of pore space in the rock. However, the log cannot distinguish between the hydrogen present in pore water and hydrogen present as part of clay-mineral lattices. Because of this, clay minerals are interpreted to be pore water and are therefore interpreted as a "false porosity." Also, the micropore system will have a high irreducible water saturation (Pittman, 1979, p. 162).

Primary porosity has been almost entirely occluded by compaction and by the hematite, anhydrite, and carbonate cements. Pores are more abundant in the sandstones that have more point grain-to-grain contacts than long grain-to-grain contacts, indicating that compaction has played a significant role in the reduction of primary porosity. Study of grain-to-grain contacts in the Abo sandstones indicates that the degree of compaction of Abo sandstones does not change either with present depth of burial or with geographic location. The abundance of relict primary pores in Abo sandstones does not follow regional trends. An abundance of floating grains (those with no grain-to-grain contacts) in a sample does not indicate high porosity (see Appendix C) but does indicate an abundance of 1) detrital clay matrix, 2) early-diagenetic anhydrite cement, or 3) carbonate cement that has extensively replaced the framework grains. All visual pore space is judged to be primary and none appears to be a result of intrastratal solution.

Permeability of the sandstones is low. The New Mexico Oil Conservation Division has estimated from measurements on cores that Abo sandstones have an average in situ permeability of only 0.0067 millidarcies. Permeability has been limited by the fine grain size, compaction, and cementation.

Percentage of mudstone decreases northward within the upper unit of the Abo. Borehole logs and descriptions of cuttings indicate 70% mudstone in the southern part of the study area in the vicinity of the Honolulu No. 1 McConkey Estate and only 50% mudstone in the north at the Abercrombie and Hawkins No. 1 Nappier. Approximately 80% mudstone is present to the west in the Mesa No. 1 Gallo State. Ninety percent of the mudstone is moderate reddish orange (10R6/6) to dark reddish brown (10R3/4) when wet, and 10% is light gray (N7) to medium dark gray (N4) when wet. The red colors are caused by hematite staining. Cores indicate that gray mudstone is not present as discrete beds but as color bands and irregularly shaped blebs in red mudstone. The red and gray color bands are diagenetic phenomena that cut across primary depositional features.

Mudstones in the upper unit are argillaceous and contain an average of 60% clay and 40% or less silt to very fine sand-size detrital quartz grains. Other constituents are 0–10% detrital mica and authigenic hematite, anhydrite, carbonate, and marine fossils. All the mica appears to be muscovite. Approximately 10% of the mudstones are calcareous. Most anhydrite is disseminated, but it also occurs as birdseye lenses and as chickenwire-shaped concretions within a mudstone matrix. To the south in the Honolulu No. 1 McConkey Estate, many of the mudstones swell in water. To the north in the AMOCO No. 1 State GM, mudstones in the lower half of the upper unit swell in water, but mudstones in the upper half do not. Some mudstones in the lower half of the upper unit contain trace amounts of fusulinids, brachiopods, and ostracods. Fractures are common in the mudstones, but most are closed; the fractures that have not been closed have been cemented with either anhydrite or carbonate. Many of the mudstones in the lower half of the upper unit are bioturbated. Most of the mudstones in the upper unit are more radioactive than the interbedded sandstones; most are more radioactive than mudstones in the middle unit. To the north in the Abercrombie & Hawkins No. 1 Nappier, some of the mudstones contain salt casts.

Dolostone is rare in the upper unit. A few thin beds occur in and to the south and east of the Yates No. 1 Willow Creek, but none were observed north of that well. Thin dolostones also are present to the west in the Mesa No. 1 Gallo State and in the Texam No. 1 Welsh Federal. The dolostones are very light gray (N8) to white (N9) when wet, well indurated, microcrystalline, nonporous, and silty. They contain as much as 30% detrital silt- and sand-size quartz. Syneresis cracks and planar to wavy laminations are common. Beds are 1–2 ft (0.3–0.6 m) thick.

Ten percent to 20% of the cuttings from the upper unit are anhydrite. Most of the anhydrite is probably caved from the overlying Yeso because no anhydrite beds were seen in cores of the upper unit and because the anhydrite cuttings are fairly evenly distributed with depth. Some anhydrite is indigeneous to the Abo in the form of birdseye lenses, chickenwire concretions, fracture fillings, and perhaps a few thin and sparsely distributed beds.

Yeso Formation (Permian: Leonardian)

Where the Abo red beds are present on the Northwest shelf of the Permian Basin, they are overlain by the Yeso Formation. The contact between the Abo and the Yeso is sharp and disconformable. The following description of the lower 200–300 ft (60–90 m) of the Yeso is based on drill cuttings and geophysical logs. Cores of the Yeso were not available.

The Yeso is composed of interbedded anhydrites, dolostones, sandstones, and mudstones. Anhydrite is approximately 10–50% of Yeso cuttings and dolostone is a trace to 30%; sandstone is 20–50% and mudstone is a trace to 50%. Anhydrite and dolostone are most abundant to the south in the Humble No. 1 State U and decrease to the north, northeast, and northwest at the expense of increasing amounts of sandstone and mudstone. As mentioned previously, the basal Meseta Blanca Sandstone Member is present on top of and west of the Pedernal uplift but grades eastward into interbedded dolostones, anhydrites, sandstones, and mudstones (Fig. 6).

Anhydrites in the Yeso are white (N9) to medium light gray (N6) when wet and are microcrystalline to macrocrystalline. They are poorly indurated, and many are dolomitic or calcareous.

Dolostones are dusky yellowish brown (10YR2/2) to medium gray (N5) when wet. They are microcrystalline, anhydritic, and moderately to well indurated. Secondary vuggy and pinpoint porosity is common in amounts ranging from a trace to 10%.

Sandstones are moderate reddish orange (10R6/6) to moderate reddish brown (10R4/6) when wet. They are fine- to coarse-grained, moderately sorted, anhydritically cemented, poorly to moderately indurated arkosic arenites. The sandstones contain trace amounts of intergranular porosity.

Seventy percent to 80% of the Yeso mudstones are moderate reddish brown (10R4/6) to pale reddish brown (10R5/4) when wet; the Yeso mudstones are silty to argillaceous, anhydritic, and poorly indurated.

The Roswell Geological Society (1982a, 1982b) mapped an intertonguing contact between the Abo and Yeso Formations on the Northwest shelf. I have seen a sharp contact between the Abo and the Yeso on the Northwest shelf, and I do not believe that the two formations intertongue significantly, except possibly north of Santa Rosa, where it is difficult to distinguish lithologically between the Abo and the Yeso Formations. Sedimentologic evidence presented later in this report supports the interpretation of a disconformable Abo–Yeso contact on the Northwest shelf. The period of time represented by the Abo–Yeso disconformity is unknown, but probably short.

Sedimentology

The Hueco Formation was deposited on a flat-lying shallow-marine shelf. The presence of fusulinids, foraminifers, brachiopods, gastropods, ostracods, crinoids, and bryozoans in the limestones favors a shallow-marine origin. The presence of several kinds of fossils in a single sample suggests open-marine waters. Shallow water is indicated by the bioclastic lime wackestones and lime packstones, by the types of fossils, and by the micritization of many of the fossils by endolithic algae. The presence of abundant fossil fragments, gastropods, and limestone intraclasts suggests that much of the Hueco shelf was very shallow and affected by moderate to strong waves or tides.

Each of the three lithostratigraphic subdivisions of the Abo was deposited in a different depositional environment. The lowermost "granite wash" unit was deposited as a system of alluvial fans which extended from a subaerial piedmont setting into the shallow, carbonate-accumulating Hueco sea. Coarse clastic sediments of the lower unit were eroded from Wolfcampian uplifts of Precambrian basement which ringed the Northwest shelf of the Permian Basin. The middle unit was deposited as shallow-marine muds and sands and was derived from a delta to the north. The upper unit was deposited as the fluvial delta and associated alluvial plain that prograded southward over the middle unit.

The coarse clastics of the lower unit of the Abo laterally intertongue with and grade into the Hueco limestones and mudstones. The abundant medium-scale cross-lamination in the conglomerates and conglomeratic sandstones suggests braided-stream deposition (Walker and Cant, 1981, pp. 27–29). The proximity of the coarse clastics to Wolfcampian-age highs of Precambrian basement and the short distance in which they grade laterally into the Hueco suggest fairly high depositional relief between the crest of the Pedernal uplift and the bottom of the shelf seas. Stratigraphic relations also indicate this relief. The high depositional relief, proximity to uplifts of basement rock, and braided rivers are typical of alluvial-fan deposition (Rust, 1981, pp. 14–17). The lower unit forms a fairly even piedmontlike apron. The muddy clastics in the Mesa No. 1 Gallo State may be mudflow deposits. The conglomerates in the AMOCO No. 1 State GM probably were derived from a buried positive element in southwest Curry County, mapped by Foster and others (1972, fig. 10). The correlation of the granite wash with the Hueco limestones indicates that active faulting and uplift of the Pedernal positive element occurred during Hueco time. Speer (1983) and Speer and Scott (1983) concluded that lower parts of the Abo Formation in the Sacramento Mountains, west of the Pedernal uplift, were deposited as alluvial fans.

The middle mudstone-rich unit of the Abo overlies the lower unit where the lower unit is present and rests conformably on the Hueco limestones where the lower unit is absent. The sharp upward change from coarse clastics of the lower unit to fine clastics of the middle unit reflects a sudden and drastic variation in the depositional milieu. The middle unit is interpreted to be a marine deposit because of 1) the presence of marine fossils in the mudstones (albeit in small amounts), 2) calcareous content of the mudstones, 3) the swelling clays in the mudstones (Parham, 1966), and 4) the lack of root traces and desiccation cracks so common in the dominantly nonmarine upper unit. The few sandstones in the middle unit may have been deposited as thin sheet sands on a dominantly mudstone shelf. Medium-scale cross-lamination in some of the sands suggests that they were deposited in water shallow enough to be influenced by waves or tidal currents. Possibly parts of the middle unit were deposited as mudflats and sand shoals on a marine shelf.

The upper unit is interpreted to be a predominantly nonmarine fluvial-deltaic deposit (Fig. 22), an interpretation recently supported by Scott (1982) and Scott and others (1983). Abundant root traces and desiccation cracks and an absence of marine fossils in the upper parts indicate a nonmarine origin. The sandstones generally appear to be of two types, both lenticular in shape. Beds thicker than 5 ft (1.5 m) have erosional bases, grade upward into overlying mudstones, and exhibit a vertical sequence of sedimentary

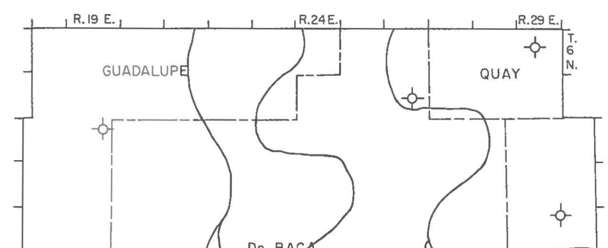

FIGURE 22—Major depositional environments at end of Abo time, Northwest shelf of Permian Basin, and area of Abo red-bed gas production.

structures characteristic of fluvial point bars and fluvial levees (Fig. 21; Reineck and Singh, 1975, pp. 231–238, 244–246; LeBlanc, 1972, fig. 15; Walker and Cant, 1981). Toward the south, sandstones in the Yates No. 1 Thorpe and No. 1 Papalote do not exhibit the regularity of the vertical sequence of sedimentary structures characteristic of the northern wells, a feature that probably reflects deposition in the more distal distributary channels of the delta and perhaps suggests a predominance of levee and overbank deposits over point-bar deposits. Sandstone beds thinner than 5 ft (1.5 m) also are nonmarine deposits, but their gradational upper and lower contacts and the prevalence of internal planar lamination and small-scale cross-lamination suggest a nonchannel origin as levee, crevasse-splay, and other overbank deposits (Reineck and Singh, 1975, pp. 244–253; Walker and Cant, 1981). The abundance of desiccation cracks, hematite cement, interbedded dolostones, and the precompactional diagenetic origin of the anhydrite cement indicate an arid climate as does the presence of abundant unweathered potash feldspar; alternatively, the presence of desiccation cracks, unweathered potash feldspar, and hematite cement may be explained by a temperate climate with alternating humid and semiarid regimes, which is the interpretation used by Millot (1970, pp. 159–161) to explain the origin of the red color of most large red-bed deposits. The facies transition from nonmarine clastic deposits in the north to marine dolostones in the south, the northerly increase in sandstone percentage, and the slight northerly increase in sandstone grain size all indicate that the fluvial upper unit of the Abo prograded southward over the marine middle unit. Scott and others (1983) mapped southward-flowing Abo rivers in Chaves County. The fine grain size of the upper unit and the presence of meandering-stream deposits indicate low depositional relief.

Some of the mudstones in the upper unit are marine deposits. They occur mostly in the lower half of the upper unit. These mudstones are interpreted to be marine deposits because they contain trace amounts of marine fossils and also because fewer sandstones are found in the lower half of the upper unit than in the upper half of the upper unit. The marine mudstones and the sandstones interbedded with them are similar lithologically to mudstones and sandstones of the middle unit. These marine mudstones contain swelling clays; swelling clays do not appear to be present in significant amounts in nonmarine mudstones of the upper unit. The environmental distribution of swelling clays in the Abo is consistent with the observed variation of clay mineralogy as a function of depositional facies in many other stratigraphic units (Parham, 1966). The marine mudstones in the lower half of the upper unit define a transitional facies between the marine middle unit and the predominantly nonmarine upper unit.

A deltaic origin for the upper unit also is suggested by the lobate outline of nonmarine facies in the upper unit; a central nonmarine facies with almost no dolostone in the Yates No. 1 Willow Creek forms a lobe that is outlined by transitional facies with interbedded dolostones and mudstones in the Spartan Drilling Co. No. 1 Bonner & Thompson, the Honolulu No. 1 McConkey Estate, and the Mesa No. 1 Gallo State. The dolostones located at the fringes of the deltaic lobe may be interdistributary bay or delta-plain lake deposits.

The Abo dolostone facies to the south was deposited in a marine environment (LeMay, 1961). The dolostones examined in this study are finely crystalline back-reef deposits. Further south in northern Eddy County, the dolostones are finely to coarsely crystalline shelf-margin deposits of the Abo reef (Fig. 5). The reef dolostones are the reservoirs for the Empire–Abo field, the most productive oil pool in New Mexico (Arnold and others, 1981, p. 28). The dark-brown to black argillaceous limestones, dolostones, and fine-grained sandstones of the basinal Bone Spring Formation are present south of the Abo reef.The Bone Spring produces oil and some gas.

The Yeso disconformably overlies the Abo over the entire study area. To the west in Torrance County, the Yeso unconformably onlaps Precambrian basement in the few places where Precambrian of the Pedernal uplift was never completely buried by the Abo (Kelley, 1972, p. 9). The interbedded sandstones, dolostones, and anhydrites of the Yeso have been interpreted as shallow-marine deposits (Hunter and Ingersoll, 1981, pp. 51–52). The sudden transition from Abo nonmarine red beds to Yeso marine deposits records a rapid transgression of the shallow-shelf sea during Leonardian time.

Structure

The two major structural features that dominate the Northwest shelf of the Permian Basin are the Pedernal uplift (Fig. 1) and the Pecos slope (Fig. 23). Numerous smaller structures, including small folds and northeast-trending buckles (Fig. 24), are superimposed on the Pecos slope.

The Pecos slope is Laramide in age (Kelley, 1971, p. 60) and dominates the surface structure of the study area; rocks ranging in age from Precambrian to Triassic dip gently eastward. The Abo dips gently eastward on the Pecos slope at an average inclination of 3/4° (Fig. 23). Very few anomalies interrupt this regional dip except for a few small east–southeast-trending synclines and a large positive area in western Curry County. The Curry County positive area probably reflects drape over a Pennsylvanian-age fault block (mapped by Foster and others, 1972, fig. 10). Depth to the top of the Abo ranges from approximately 1,800 ft (550 m) at the western part of the study area to approximately 4,500 ft (1,370 m) at the southeast edge.

The minor structures present on the Pecos slope have been described excellently by Kelley (1971, pp.

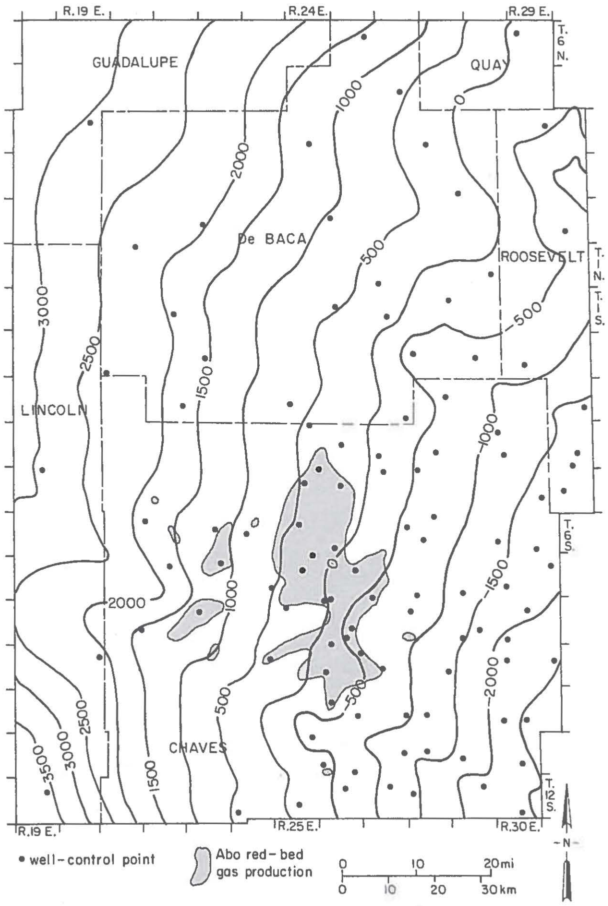

FIGURE 23—Structure on Abo Formation and relation to Abo red-bed gas production. The broad regional dip to the southeast forms the Pecos slope. Datum = sea level; contour interval = 500 ft.

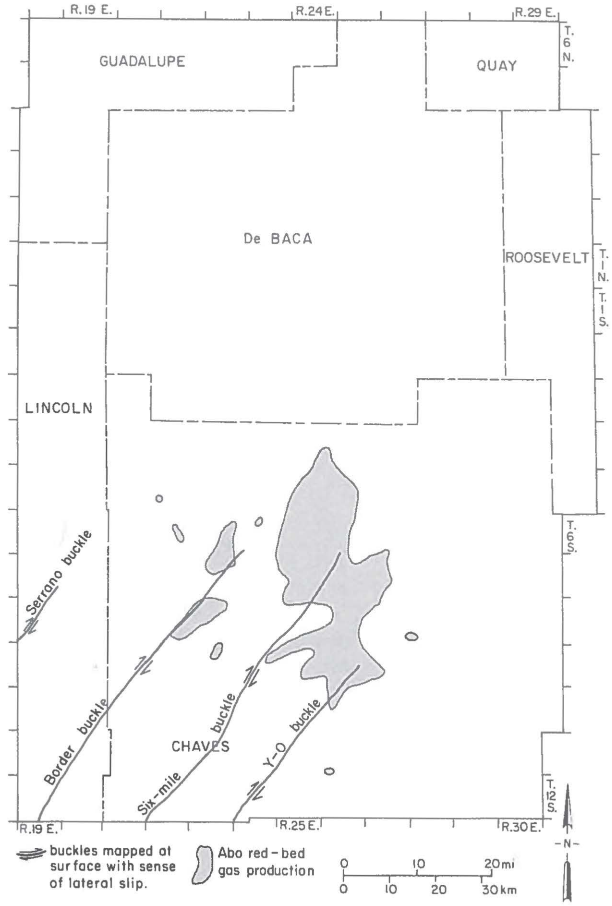

FIGURE 24—Major surface structures mapped by Kelley (1971, fig. 12) and relation to Abo red-bed gas production.

37–55). The minor structures are relatively small folds and buckles; they are exposed on the surface in post-Abo Permian rocks. The buckles are the most distinctive structures (Fig. 24). They are northeast-trending linear features which can be traced for distances of 40–80 mi (60–130 km). The buckles are parallel to each other and are spaced at distances of 8–20 mi (13–32 km) from each other. They are expressed on the surface as folds in some places and as faults in other places. Where expressed as faults, the upthrown block changes sides along strike. Both sides of the buckles are turned generally upward in a zone that measures a few tens of feet to 4,000 ft (1,200 m) wide. Commonly, a buckle occupies the center of a larger uplift or anticline which may be as wide as 4 mi (6.4 km). The buckles plunge northeast and have had strike-slip movement, mapped as right-lateral movement by Kelley (1971, fig. 12). Kelley believes that the buckles originated as large shear zones in the Precambrian and continue upward into overlying rocks.

Other important structural features on the Pecos slope are Tertiary-age volcanic and intrusive bodies. Most of the igneous bodies occur in Lincoln County to the west of the study area, but a few east-trending dikes have been mapped on the surface in eastern Chaves County. No Tertiary-age igneous rocks were seen in the subsurface during this study.

Gas production

The sandstones of the upper Abo unit are the producing reservoirs in the Abo red beds. Because of their low permeability, the sandstones must be artificially stimulated before economic levels of production can be obtained. The stimulation is a two-step process; the sandstones are first acidized, and then they are artificially fractured. The fracture processes involve either a sand-water mixture, carbon dioxide, or nitrogen. Calculated open flow jumps from a few tens of MCFGPD (thousand ft^3 gas per day) before stimulation to a few MMCFGPD (million ft^3 gas per day) after stimulation. Data obtained from 92 completed Abo wells (Fig. 25) indicate an average initial calculated open flow of 2,172 MCFGPD, ranging from 18 MCFGPD to 15,500 MCFGPD for individual wells. The 90% confidence interval around the mean value

TABLE 3—COMPOSITIONAL ANALYSES OF ABO RED BEDS GAS, PECOS SLOPE ABO FIELD. Values are mole fractions; **BTU** = British Thermal Unit; **psi** = pounds per inch^2; **°F** = degrees Fahrenheit.

Operator, well no., lease, location (section–township–range, county)	Nitrogen	Carbon dioxide	Methane	Ethane	Propane	iso-Butane	n-Butane	iso-Pentane	n-Pentane	Hexanes	Heptanes+	Measured specific gravity	Heating value BTU/ft^3 @ 14.73 psi, 60°F
Yates Petroleum Corp. No. 1 Hilltop NQ State 7–7S–25E, Chaves	.0749	.0007	.8465	.0434	.0183	.0031	.0065	.0020	.0021	.0015	.0010	.656	1025
Yates Petroleum Corp. No. 1 Kuykendall OP Com. 11–6S–25E, Chaves	.0472	.0004	.8741	.0444	.0178	.0036	.0055	.0018	.0019	.0019	.0014	.645	1054
Yates Petroleum Corp. No. 1 Leeman OC Federal 18–7S–26E, Chaves	.0649	.0009	.8602	.0444	.0168	.0027	.0057	.0016	.0018	.0009	.0000	.644	1022
Yates Petroleum Corp. No.1 McClellan MB Federal 31–5S–25E, Chaves	.0617	.0001	.8493	.0528	.0198	.0033	.0070	.0021	.0021	.0013	.0004	.650	1046
Yates Petroleum Corp. No. 1 McConkey HX 10–9S–26E, Chaves	.0482	.0000	.8648	.0505	.0207	.0033	.0064	.0020	.0019	.0006	.0015	.644	1060
Yates Petroleum Corp. No. 1 Redman OY State 35–4S–24E, Chaves	.0631	.0007	.8590	.0448	.0176	.0030	.0063	.0020	.0022	.0013	.0000	.648	1031
Yates Petroleum Corp. No. 1 Selman Draw NS State 9–7S–24E, Chaves	.1107	.0003	.8283	.0383	.0139	.0022	.0041	.0010	.0009	.0003	.0000	.643	956
Average values	.0672	.0004	.8546	.0455	.0178	.0030	.0059	.0018	.0018	.0011	.0006	.647	1028

of 2,172 MCFGPD is 382 MCFGPD; therefore, the average initial calculated open flow for discovered and undiscovered Abo gas has a 90% probability of lying between 1,790 and 2,554 MCFGPD per well.

Compositional analyses of Abo gas from seven Pecos Slope Abo wells are shown in Table 3. Methane (CH_4) is the most abundant volatile constituent of the gas with an average mole fraction of 0.8546. Ethane (C_2H_6) is next with an average mole fraction of 0.0455. All gases heavier than ethane have an average combined mole fraction of only 0.0320. Nitrogen and carbon dioxide are the only two nonvolatile components present in Abo gas, and they have a combined average mole fraction of 0.0676; almost all of the nonvolatile fraction is nitrogen. The average heating value of Abo gas is 1,028 BTU/ft^3 (British Thermal Units/ft^3 of gas). The average measured specific gravity is 0.647.

A primary factor which may affect the composition of produced gas is the introduction of foreign material into the Abo reservoirs during completion operations. The well data listed in Table 4 are an example of the decline in mole-fraction carbon dioxide with time for a well that had been artificially fractured with CO_2. Initial measurements of the CO_2 fraction were high and reflect inundation of the reservoir with CO_2 during the "frac" job. The artificially introduced CO_2 is then produced along with the natural gas until all of it has been flushed out of the reservoir. Thus, the CO_2 values listed in Table 3 are upper limits of the true values.

Industry geologists commonly locate gas-charged Abo sandstones by detecting the "gas effect" differential between porosities measured on formation-

TABLE 4—MOLE FRACTION CO_2 AS A FUNCTION OF TIME, ABO GAS PRODUCED FROM PECOS SLOPE. Note decreasing mole fraction of CO_2 in gas with time. Initial high CO_2 fraction results from reservoir contamination during well completion. Data from Yates Petroleum Corp. No. 1 McClellan MB, sec. 31, T. 5 S., R. 25 E., Chaves County, New Mexico.

Mole fraction CO_2 in Abo gas	Date measured
0.0083	7/7/80
0.0006	1/14/81
0.0005	5/26/81
0.0001	4/6/82

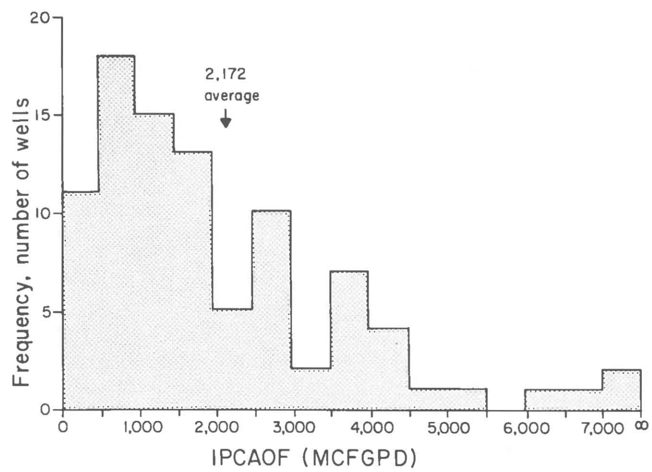

FIGURE 25—Histogram of initial calculated open flow (IPCAOF) for 92 Abo gas wells, Chaves County, New Mexico. Average IPCAOF = 2,172 MCFGPD (thousand ft^3 gas per day).

density logs and neutron logs. The neutron log measures the amount of hydrogen present in the rock; the formation-density log measures the density of electrons in the rock. When gas is present in a rock, the neutron log indicates a very low apparent porosity because of the low density of natural gas and a correspondingly low density of hydrogen atoms in the gas. Formation-density logs measure a very high apparent porosity in gas-filled rocks because of the low density of gas. Therefore, where gas is abundant in a formation, the formation-density log indicates a higher porosity than the neutron log; the opposite or equal porosity readings are observed in formations that contain no gas or only small quantities of gas (Schlumberger, 1972, p. 72; Dresser Atlas, 1975, pp. 7-13–7-14).

Geologic controls of gas production

Gas in the Pecos Slope Abo field is produced from sandstones in the upper unit of Abo red beds. Gas traps are found where reservoir sandstones are overlain by a thick mudstone seal (Roswell Geological Society, 1982a, 1982b). Mechanisms of gas storage and entrapment are controlled by the nature of the reservoir rock and the mudstone seal and by the petrophysical and petrographic differences between producing and nonproducing Abo sandstones. The Roswell Geological Society (1982a, 1982b) recently published geophysical-log cross sections of the Pecos Slope Abo field.

A producing Abo sandstone is shown in Fig. 20B. The striking feature about this reservoir rock is its lack of visual porosity. Although one might expect a fluvial sandstone to have a fairly high depositional porosity ranging from 17 to 52% (Pryor, 1973, p. 162), no porosity was seen in thin section; the neutron log indicated only 8% porosity and the formation-density log indicated 15% porosity. The presence of gas in the sandstone causes the formation-density log to indicate a higher apparent porosity than the neutron log as previously discussed. Clay minerals finely intermixed with the hematite cement will cause the neutron porosity of 8% to be too high. Most porosity reduction resulted from mechanical compaction during burial and from cementation by the clay-hematite matrix. Anhydrite and carbonate cements also occlude primary porosity but to a much lesser extent.

Some micropores too small to be seen with the petrographic microscope probably are present in the hematite-clay matrix, but such a micropore system probably could not act as the primary gas reservoir nor contribute significantly to production (Wescott, 1982, p. 173). Micropores possibly could serve as a secondary storage space for the gas and contribute to long-term production. The high surface area to pore volume ratio of the micropore system causes the sandstone to have a high irreducible water saturation (Pittman, 1979, p. 162) and should be kept in mind when analyzing water-saturation data calculated from borehole logs.

In contrast to the producing sandstones, at least some of the nonproducing sandstones that were analyzed have a trace of visual porosity in thin section (Fig. 20D). The visual porosity is relict, intergranular, primary porosity (Wescott, 1982, p. 160), which was not eliminated by either compaction or cementation. Relict primary porosity exists only as isolated pores in a low-permeability sandstone. The relict porosity would hardly seem likely to contribute significantly to production because of the low storage volume it would contribute and because of the impermeable rock matrix (Wescott, 1982, p. 168). Relict primary pores probably will be found with the study of additional thin-section samples of producing sandstones.

Both the producing and the nonproducing sandstones are nonporous and impermeable. The average in situ permeability of the Abo is 0.0067 millidarcies. Petrographically, producing and nonproducing sandstones appear similar.

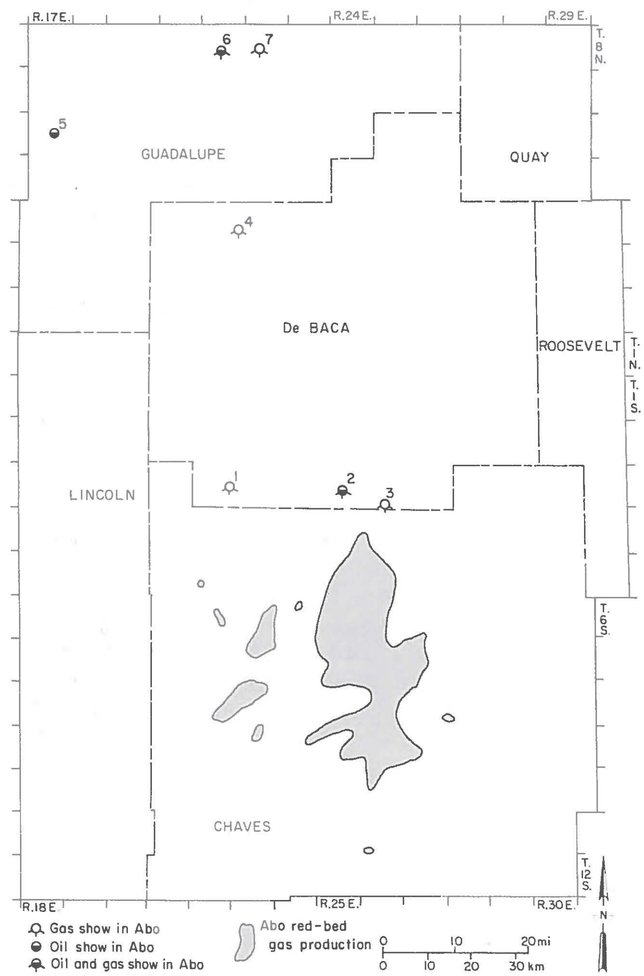

FIGURE 26—Abo red-bed gas production and wildcat wells with significant gas shows in the Abo. See Table 5 for well data.

TABLE 5—Wells encountering hydrocarbons in Abo outside of main producing area. **TD** = total depth; **MCFGPD** = thousand ft^3 gas per day; **BWPD** = bbl water per day. See Fig. 26.

No. on Fig. 27	Location (section–township–range, county)	Operator, well no., lease	Completion date (mo/yr)	TD (ft)	Rock unit at TD	Reported formation tops, depth (ft)	Remarks
1	23–3S–21E, De Baca	Mesa Petroleum Co. No. 1 Devils Federal	8/81	3,800	Abo (Permian)	Abo–2,800	Noncommercial gas show in Abo through perforations from 3,134–3,155 ft and 3,292–3,312 ft
2	20–3S–24E, De Baca	Mesa Petroleum Co. No. 1 Arana Federal	10/81	5,304	granite wash	Glorieta–1,332 Yeso–1,624 Tubb–2,882 Abo–3,432 Hueco–4,218	Swabbed 19 bbl oil from Abo through perforations from 3,484–3,498 ft
3	33–3S–25E, De Baca	Rault Petroleum Corp. No. 1 Mark Williams Isler	well not completed at time report was written	4,250			Abo gas discovery flowed 155 MCFGPD
4	30–4N–22E, De Baca	Hunt Oil Co. No. 1 Cooper Ranch Federal	7/82	4,505	Hueco (Permian)	San Andres–470 Glorieta–1,075 Abo–2,950 Hueco–4,000	Cored lower "granite wash" interval from 3,430–3,489 ft, received sandstone with slight fluorescence
5	22–6N–17E, Guadalupe	Cibola Energy, Inc. No. 1 Mesa Leon Unit	12/81	4,920	granite (Precambrian)	Glorieta–1,254 Yeso–1,558 Cimarron–1,850 Abo–1,962 Precambrian–4,762	Oil show in "granite wash" through perforations from 4,512–4,536 ft and 4,692–4,711 ft
6	21–8N–21E, Guadalupe	Alta Energy Corp. No. 1 Walker	8/82	4,000	Pennsylvanian	San Andres–714 Yeso–1,458 Abo–2,288 Hueco–3,448 Pennsylvanian–3,895	Gas show in Abo through perforations from 2,514–2,609 ft, 3,226–3,230 ft, 3,250–3,255 ft, 3,289–3,291 ft; oil show through perforations from 2,840–2,846 ft
7	20–8N–22E, Guadalupe	O. H. Berry No. 1-X Tucumcari FNB	3/82	3,320	Hueco (Permian)	San Andres–537 Glorieta–1,023 Abo–2,470	Flowed 88 MCFGPD and 120 BWPD from Abo through perforations from 2,796–2,802 ft, 2,812–2,824 ft, 2,916–2,926 ft, 2,968–3,020 ft

The Abo gas probably comes from fractures because many of the sandstone cores are fractured. Many of the mudstones contain fractures, but fractures in the mudstones either are closed or cemented tight with anhydrite or carbonate. The mudstones function as seals to the fractured sandstones. Thus, the best traps are located in places which have abundant, thick mudstone seals as well as thick and abundant sandstone reservoirs. All the Abo production found so far has been in the distal end of the fluvial-deltaic system where sandstone-to-mudstone ratios are relatively low but where thick fluvial sandstones are still present. The few wells drilled to the north in De Baca and Guadalupe Counties may not have found commercial quantities of gas because the sandier, more proximal parts of the fluvial-deltaic system are located in De Baca and Guadalupe Counties, where good mudstone seals are not as abundant. A similar trapping mechanism was used to explain the distribution of oil in the Sespe red beds (Eocene) of California (Bailey, 1947); Bailey proposed that oil is trapped in the Sespe red beds only where there is enough mudstone to seal the sandstone reservoirs. The western limit of gas production in the Abo probably is controlled by a facies change in the upper unit to dominantly mudstone. The southern and eastern limits of production are controlled by a facies change to impermeable and nonporous dolostone and mudstone.

Although the northern, more proximal Abo in De Baca and Guadalupe Counties is sandier than the more distal Abo in Chaves County where the gas production occurs, the Abo will not necessarily be barren of gas north of Chaves County. Several wells to the north and west of the producing area have encountered promising, but noncommercial, gas shows and oil shows (Fig. 26; Table 5). Abundant mudstone is still present in the north and, because mudstones in meandering fluvial systems tend to form wide sheets (Selley, 1978, p. 25; Potter and others, 1980, p. 61; LeBlanc, 1972, fig. 15), good traps are likely to occur north of present production. Because of closer proximity to the sediment source, the northern mudstone blankets may not be as extensive as those in Chaves County, and Abo gas fields may be smaller in De Baca and Guadalupe Counties. Because fluvial-deltaic deposits extend almost 100 mi (160 km) north of present production, the area underlain by potential Abo sandstone reservoirs is at least five times greater than the area which is currently productive. Other Abo sandstone reservoirs could possibly be present to the south, east, and west of present production. Although the Abo consists mostly of impermeable dolostone and mudstone to the south and east, abandoned deltaic lobes could be present. The facies change to mudstones limits Abo production to the west, but abandoned deltaic lobes also possibly lie to the west of the one in Chaves County.

Abo production does not appear to be controlled by either subsurface or surface structures (Figs. 23, 24), a conclusion also reached by Scott and others

(1983). Production does not appear to be limited to fractures possibly formed by the northeast-trending buckles mapped on the surface. The entire Abo may have been fractured during the regional tilting that formed the Pecos slope during Laramide deformation. Observations on cores indicate that the upper unit of the Abo is fractured in De Baca and Guadalupe Counties.

Do the middle and lower units of the Abo contain potential reservoirs? The middle unit probably does not contain major reservoirs because the sandstone percentage is too small and the sandstone beds are thin, generally less than 3 ft (1 m) thick. The lower unit of the Abo contains potential reservoirs in the porous and permeable conglomerates and conglomeratic sandstones. The overlying mudstones of the middle unit would make an effective seal for this reservoir. Lateral updip barriers to fluid migration are needed in addition to the overlying mudstone seal. The low percentage of mudstone within the lower unit precludes the presence of any major stratigraphic barrier. Either structural closures or hydrodynamic trapping conditions probably are needed to form petroleum accumulations in the lower unit of the Abo. The Mobeetie field of the Texas panhandle produces oil from structural traps in Upper Pennsylvanian coarse-grained arkosic arenites that are similar lithologically and depositionally to the conglomerates and sandstones of the lower unit of the Abo (Dutton, 1982, pp. 404–405); the Mobeetie field is located in the Anadarko Basin, north of the Wichita granite uplift.

The argillaceous sandstones and conglomerates of the lower unit in the Mesa No. 1 Gallo State may not contain sufficient matrix porosity to produce commercial quantities of petroleum unless they are naturally fractured. Cleaner, better sorted sandstone and conglomerate lenses within the lower unit in and around the Gallo State well might be potential exploration targets, however.

Gas source

What are the source rocks of the Abo gas? The source of any petroleum accumulation is a basic consideration in the analysis of the occurrence. In this case, identification of the gas source could be important to future exploration because the distribution of the source rocks may have partially controlled the present distribution of gas within the Abo.

The first possibility to be examined is that the Abo red beds are their own gas source. Might gas generated in the Abo mudstones have migrated into the sandstones? Many fluvial and deltaic deposits commonly contain source beds of gas because of their high content of terrestrial organic matter (Barker, 1979, pp. 126, 129–133), but fluvial and deltaic red beds do not act as source rocks because they have a low organic-matter content (Hunt, 1979, p. 236; Barker, 1979, p. 108). The red color of the mudstones and sandstones results from an oxidizing stage during early diagenesis (Turner, 1980, pp. 246–250). The presence of abundant root traces and some plant remains indicates that abundant organic material may have been deposited initially in the Abo. The organic material certainly must have been oxidized along with the enclosing rock; therefore, any petroleum-generating capacity of the rock would have been destroyed. If the organic material suffered rapid, aerobic decay, it could not have generated substantial amounts of gas either by thermal maturation or through biogenic processes. Also, the presence of a large amount of sulfate in the system (as early-diagenetic anhydrite) precludes the production of biogenic gas (Rice and Claypool, 1981, p. 9).

If the gas is not indigenous to the Abo, then it had to migrate into the Abo from an external source. Two obvious possible gas sources are the dark-gray marine mudstones and limestones of the underlying Hueco Formation and the downdip shelf-margin dolostones of the Abo reef, which produce large volumes of oil and gas. Marine rocks of the Pennsylvanian System, which underlies the Hueco, are a third possible source. A fourth possible source is the Mississippian System which is truncated with angular unconformity by Pennsylvanian rocks in central Chaves County (George L. Scott, Jr., personal communication, 1983). Organic-carbon isotope measurements (Stahl, 1977; Reitsema and others, 1981; James, 1983) made on the Abo gas and on potential sources should indicate the most likely gas source.

Recommendations

Two projects could be undertaken to answer unsolved questions and to aid in the future exploration for gas in the Abo red beds. First, geochemical source-rock analyses of the Abo gas and its possible source rocks would delineate favorable source facies. Second, detailed surface and subsurface studies of fracture trends within areas of favorable source and reservoir facies would delineate potentially productive fairways within the Abo.

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Selected conversion factors*

TO CONVERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, μm
Area		
in^2	6.452	cm^2
ft^2	9.29×10^{-2}	m^2
yds^2	8.361×10^{-1}	m^2
mi^2	2.590	km^2
acres	4.047×10^{3}	m^2
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^3	1.639×10^{1}	cm^3
ft^3	2.832×10^{-2}	m^3
yds^3	7.646×10^{-1}	m^3
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	l
U.S. gallons, gal	3.785	l
U.S. gal	3.785×10^{-3}	m^3
acre-ft	1.234×10^{3}	m^3
barrels (oil), bbl	1.589×10^{-1}	m^3
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^{1}	grams, gr
troy ounces, oz	3.1103×10^{1}	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{-1}	3.43×10^{1}	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}

TO CONVERT	MULTIPLY BY	TO OBTAIN
Pressure, stress		
lb in^{-2} (= lb/in^2), psi	7.03×10^{-2}	kg cm^{-2} (= kg/cm^2)
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^{3}	newtons (N)/m^2, N m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^{2}	mm of Hg (at 0° C)
inches of Hg (at 0° C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^{6}	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^3)	2.768×10^{1}	gr cm^{-3} (= gr/cm^3)
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	l sec^{-1}
gpm	6.308×10^{-5}	m^3 sec^{-1}
ft^3 sec^{-1}	2.832×10^{-2}	m^3 sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^2
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	m^2 sec^{-1}
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	l sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^{5}	gammas
Energy, heat		
British thermal units, BTU	2.52×10^{-1}	calories, cal
BTU	1.0758×10^{2}	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahrenheit)
°F − 32	5/9	°C (Celsius)

**Divide by* the factor number to reverse conversions.
Exponents: for example 4.047×10^{3} (see acres) = 4,047; 9.29×10^{-2} (see ft^2) = 0.0929.

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Drafter: James C. Brannan

Type faces: Text in 10 pt. Palatino, leaded one point
References and Index in 7 pt. Palatino, leaded one point
Display heads in 24 pt. Palatino medium

Presswork: Miehle Single Color Offset
Harris Single Color Offset

Binding: Saddlestitched with softbound cover

Paper Cover on 12 pt. Kivar
Text on 70-lb. white matte

Ink: Cover—PMS 320
Text—Black

Quantity: 900

Contents of pocket

(microfiche)

APPENDICES