SUBSURFACE ANALYSIS OF THE (PERMIAN) ABO FORMATION IN THE LUCERO REGION, WEST-CENTRAL NEW MEXICO

by

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ABSTRACT

Outcroppings of the Abo Formation in the Lucero region are generally limited to the Zuni Mountains, Joyita Hills, areas east of Socorro and in the Sierra Lucero-Lucero Mesa area. Analysis of drill cuttings and geophysical logs of petroleum exploration wells provide a stratigraphic framework between surface exposures. Subsurface data correlate with complete Abo sections near Lucero Mesa and east of Socorro.

In the Lucero region, the Abo Formation overlies Precambrian rocks, Pennsylvanian limestones, rocks assigned to the Bursum Formation and is overlain by the Meseta Blanca Member of the Yeso Formation. Thickness of the Abo Formation varies from between 400 and 450 feet over the Zuni uplift to 820 feet near Mesa Lucero.

The relative amounts and vertical distribution of sandstones, siltstones and mudstones in the Abo Formation vary significantly within the study area. In the western portion of the study area, sandstones and siltstones dominate the Abo Formation; sandstone plus siltstone to mudstone ratios are as high as 3.7 to 1. Sandstones, siltstones and mudstones are uniformly distributed through the stratigraphic section. Mudstones become more prevalent to the east with sandstone plus siltstone to mudstone ratios as low as 1 to 3.9. The eastern Abo stratigraphic section consists of a lower, mudstone-rich section overlain by a sandstone and siltstone-rich section.

The use of log curve shape analysis to determine depositional environments is an unreliable method when applied to the Abo Formation. Errors can be attributed to: high clay content in coarse-grained sandstones; variable composition of sandstones, clays and cements; and variations in the degree of cementation.

Depositional environments of the Abo Formation in the Lucero region reflect the influence of the Zuni, Penasco and Uncompahgre uplifts. The Abo of the eastern Lucero region was deposited on a broad, flat coastal plain which was succeeded by the distal portion of an alluvial fan or a gently sloping coastal plain. The Abo of the western Lucero region was deposited by local alluvial fans that "retreated" to the northwest. Overlying deposits represent deposition by either the distal portion of an alluvial fan or a gently sloping coastal plain.

In the Lucero region, the most promising potential resource of the Abo Formation is petroleum. The most likely petroleum reservoirs are the upper sandstones in the eastern and central portions of the study area.

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Table of Contents

List of Figures

List of Tables

CHAPTER 1

INTRODUCTION

Purpose and Scope

The purpose of this thesis is to: (1) determine thickness trends and stratigraphy of the Abo Formation between surface exposures in west-central New Mexico, (2) to establish the regional depositional environment between surface exposures of the Abo Formation, (3) to attempt to use and assess the use of characteristic log signatures to interpret subenvironments of deposition within the Abo Formation, and (4) to evaluate the resource potential of the Abo Formation.

The scope of this study is strictly regional in nature with control points commonly tens of miles apart. The focus of this study has been placed on the Abo Formation and the only other units studied are those that are, at least somewhere in the study area, stratigraphically above or below the Abo Formation.

Background

The Abo Formation is an extensive unit in New Mexico which has been correlated to part of the Supai Formation of Arizona, the lower Cutler Group of Colorado, Utah, and northern New Mexico (Baars, 1962), and the Sangre de Cristo Formation of northern New Mexico (Foster et al., 1972). Surface workers interpret the Abo Formation to be of continental origin and have traced it southward into marine facies of the Hueco Formation. The Abo's terrestrial origin is indicated by mud cracks; land vertebrate bones and tracks; land plant imprints and remains; and rain drop imprints. It's clastic character, lenticular bedding, current ripple marks and paleocurrent patterns further suggest an alluvial origin for the Abo Formation.

The Abo Formation is both a red bed copper and natural gas producer. Copper was sporadically mined from Abo exposures, in the Zuni, Scholle and High Rolls districts of central New Mexico, from the early 1900's until the early 1960's. Natural gas was first discovered in 1977 in red bed sandstones, of the Pecos Slope Abo field of eastern New Mexico (Broadhead, 1984). In 1980 the Federal Energy Regulatory Commission designated the Abo as a "tight gas" sandstone allowing producers to sell the gas at higher regulated prices. This action set off a drilling boom for the Abo target in eastern New Mexico (Broadhead, 1984).

Recently, interest in petroleum exploration has increased in west-central New Mexico and adjacent Arizona. Lease applications on state and federal lands have been filed by several petroleum companies with primary targets believed to include Abo sandstones (Brennan, 1986).

In the Pecos Slope Abo field, natural gas is produced from sandstones in the upper part of the Abo Formation that are similar to channel sandstones at Scholle and in the Cerros de Amado area (Broadhead, 1983a). Identification of similar lithologies and/or facies within the Abo Formation of west-central New Mexico may enhance natural gas exploration there.

In exposures east of Socorro, Cappa (1975) interpreted the Abo Formation to be dominantly flood-plain deposits of a meandering fluvial environment, with a thin basal section of braided stream deposits. Near the type section, Lemley (1984), using Schumm's (1963) classification, found paleochannels to be mainly straight, regular or irregular, with fewer tortuous channels. In the Zuni Mountains, where the Abo unconformably overlies Precambrian crystalline rocks, MacMillan (personal communication, 1986) has found the lower 50 feet or less of the Abo Formation to be alluvial fan deposits which are overlain by straight (braided) channel sandstones interbedded with flood-plain mudstones.

Very little work has been done on the Abo Formation in the subsurface between these surface exposures. Foster (1964) and Wengard (1959) both did general subsurface studies within the study area, but neither focused on Abo depositional environments in any detail. Martin (1971) worked in almost the exact same study area, but concentrated on Pennsylvanian biostratigraphy.

Methodology

The study area includes parts of Socorro, Catron, Cibola, McKinley, Bernalillo and Valencia counties of west-central New Mexico (Figure 1-1). Wengard (1959) and Martin (1971) referred to this general area as the Lucero region. The boundaries of the study area are arbitrarily selected based on the availability of subsurface well data. There are very few wells to the west, south and east of the study area boundaries. To the north, there is an overabundance of wells, however most were drilled to targets shallower than the Abo Formation.

Figure 1-2 shows the surface outcrops of the Abo Formation within the Lucero region. Control points for this thesis include 20 subsurface wells along with two complete surface stratigraphic sections (Table 1-1; Figure 1-2). Drill cuttings for four of the wells were logged by the author. Roy Foster (while at the New Mexico Bureau of Mines and Mineral Resources) logged 10 of the wells used in this study. Two of these ten wells (B2 and B3 of Figure 1-2 and Table 1-1) were published by Foster (1964). Logs of the remaining eight wells are on file at the New Mexico Bureau of Mines and Mineral Resources petroleum records library in Socorro, New Mexico. They are in the same interpretive log format as those that are published.

When logging these wells, Foster did not integrate his interpretive lithologies with geophysical logs. To insure consistency, one of Foster's published wells (Huckleberry Federal No. 1; B2 of Figure 1-2) was also logged by the

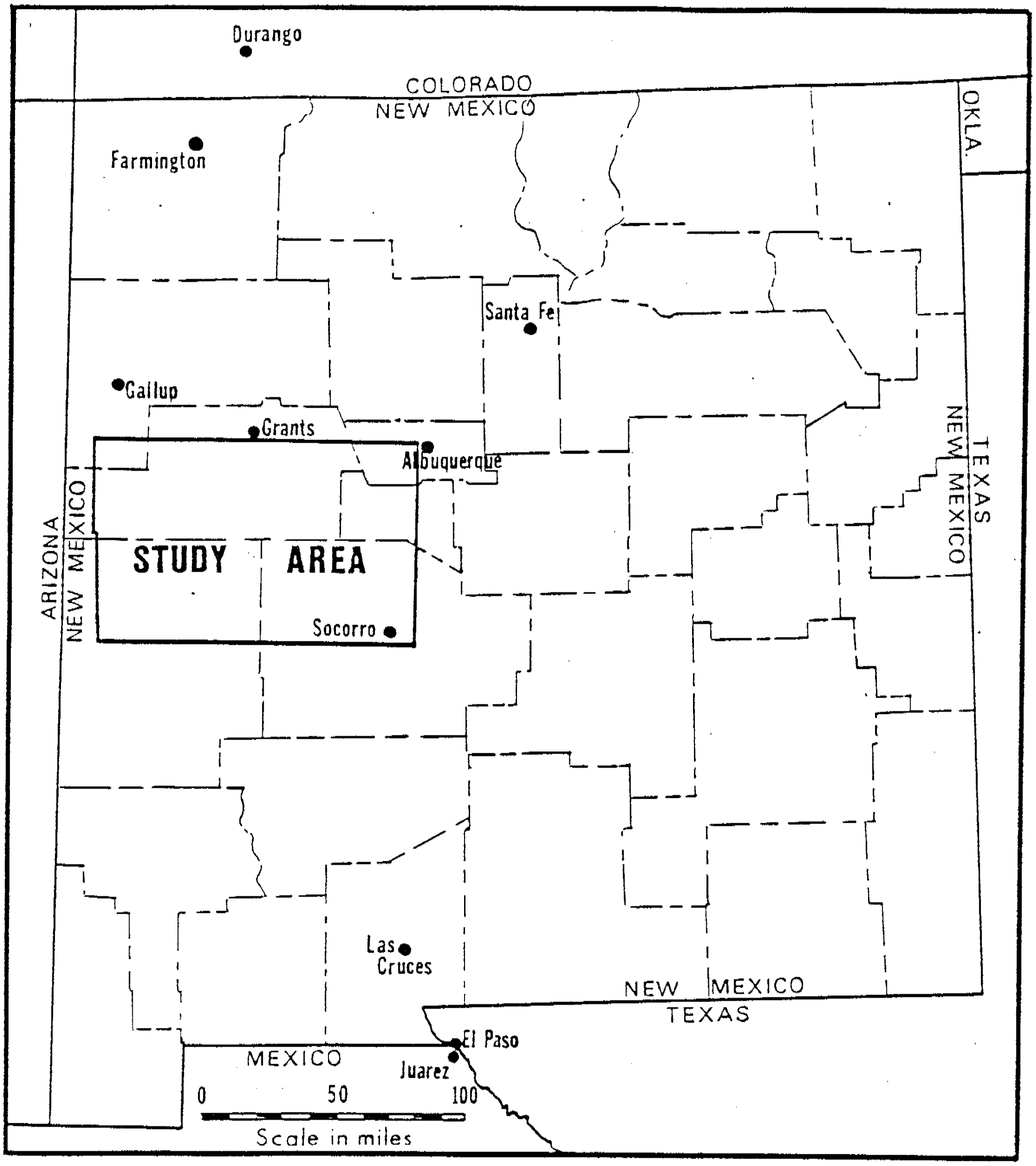


Figure 1-1. Location of the study area (Lucero region) within New Mexico.

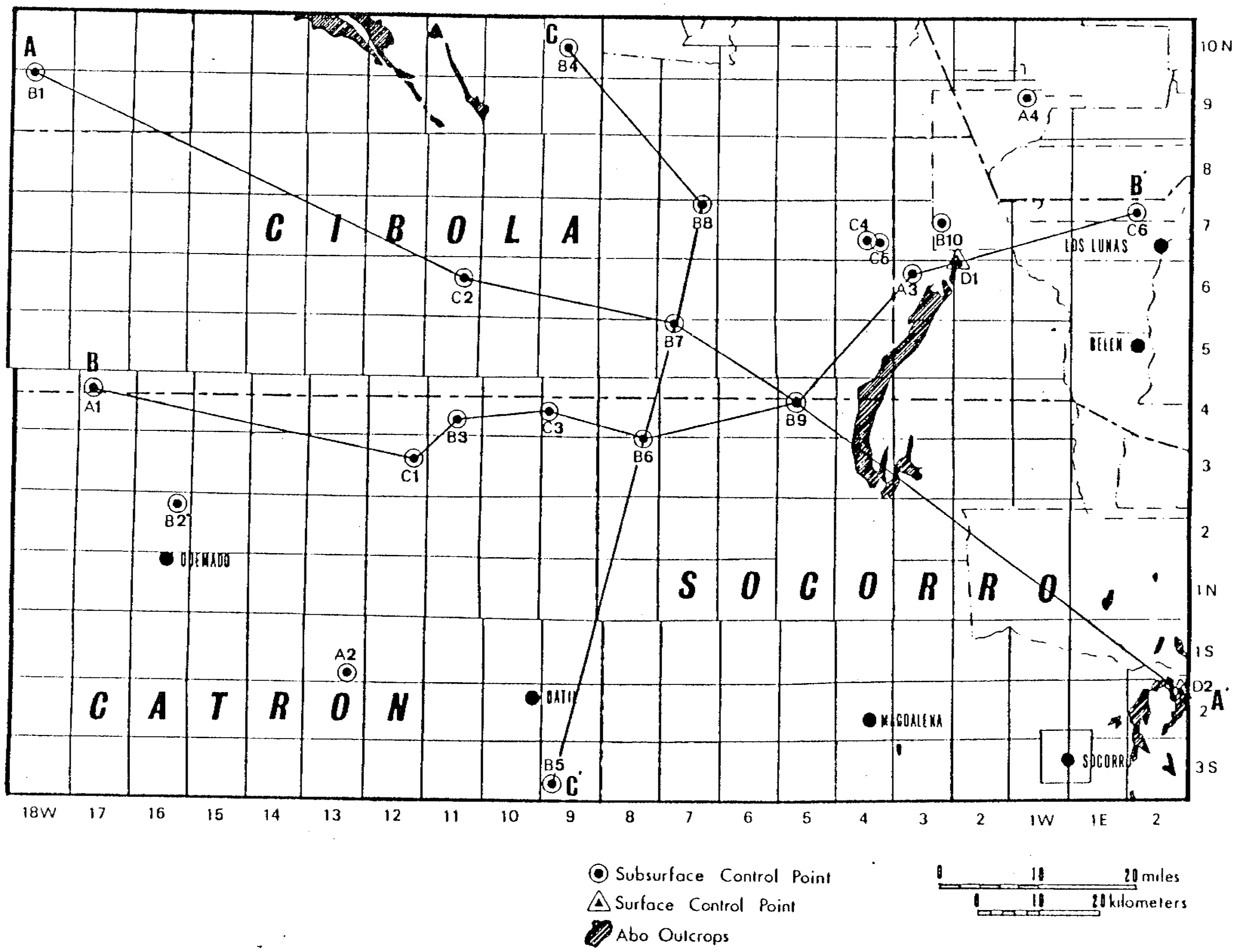


Figure 1-2. Surface exposures of the Abo Formation, control points used in this study, and lines of cross sections A-A' (Fig. 7-2), B-B' (Fig. 7-3) and C-C' (Fig. 7-4). See Table 1-1 for an explanation of control point prefixes and numbers.

Table 1-1. Control points used in this study; see Figure 1-2 for locations. Points prefixed 'A' are subsurface wells with drill cuttings logged by the author. Points prefixed 'B' are subsurface wells with drill cuttings logged by Roy Foster. A few of these wells were also logged by various stratigraphic service companies. The cuttings for points prefixed 'B' were spot checked and the stratigraphy was reinterpreted by the author using wire-line logs. Points prefixed 'C' are subsurface wells without drill cuttings. Points prefixed 'D' are surface stratigraphic sections. (B2 was logged by both Foster and the author; B6 has no wire-line logs or drill cuttings and is directly based on Foster's interpretation of the driller's log).

Control Point	Plate Number	Operator, Lease, Well No., Location (section, township, range, county)	Completion Date (mo/yr)	TD (ft)
A1	1	Tiger Oil Co. Unit H State No. 1 8-4N-17W, Catron	(9/59)	5392
A2	2	Tenneco Oil Co. Federal No.1 35-1S-13W, Catron	(7/67)	7900
A3	3	Reese & Jones Tecolote No. 1 8-6N-3W, Valencia	(5/74)	3564
A4	4	Shell Oil Co. Shell Laguna Wilson Trust No.1 8-9N-1W, Bernalillo	(12/72)	11107
B1	5	Cities Service Oil Co. Zuni A-1 27-9N-18W, McKinley	(11/63)	2590
B2	6	Claude Huckleberry Huckleberry Federal No. 1 11-2N-16W, Catron	(12/56)	5592
B3	7	Spanel & Heinze Santa Fe-Pacific No. 1-9617 27-4N-11W, Catron	(9/59)	5392
B4	8	Larrazola & Cornell Co. Gottlieb No. 1 21-10N-9W, Cibola	(5/54)	4600

Table 1-1 (cont.)

Control Point	Plate Number	Operator, Lease, Well No., Location (section, township, range, county)	Completion Date (mo/yr)	TD (ft)
B5	9	Sun Oil Co. Plains of San Augustine Unit No. 1 29-3S-9W, Catron	(6/66)	12284
B6	10	Mitchel & Sons Red Lake No. 1 2-3N-8W, Socorro	(?/25)	4012
B7	11	Spanel & Heinze Santa Fe-Pacific No. 1-9612 5-5N-7W, Catron	(7/59)	4992
B8	12	Sun Oil Co. Pueblo of Acoma No. 1 2-7N-7W, Cibola	(3/60)	4794
B9	13	Spanel & Heinze Santa Fe-Pacific No. 1-9608 17-4N-5W, Socorro	(8/59)	4774
B10	14	Richard King, Jr. Wilson Heirs No. 1 14-7N-3W, Valencia	(10/58)	3994
C1	15	Samedan Oil Co. Laguna Federal No. 1 14-3N-12W, Catron	(11/84)	5915
C2	16	Southland Royalty Federal Lucero No. 1-14 14-6N-11W, Cibola	(5/60)	4638
C3	17	Cambridge & Nail Santa Fe-Pacific No. 1 19-4N-9W, Catron	(7/81)	5100
C4	18	Byron Gore New Mexico-Arizona Land Co. No. 1 27-7N-4W, Cibola	(9/56)	3658
C5	19	Byron Gore Federal No. 1-B 26-7N-4W, Cibola	(9/58)	3674

Table 1-1 (cont.)

Control Point	Plate Number	Operator, Lease, Well No., Location (section, township, range, county)	Completion Date (mo/yr)	TD (ft)
C6	20	Shell Oil Co. Shell Isleta No.1 7-7N-2E, Valencia	(4/74)	16346
D1	21	Surface Stratigraphic Section location: NW1/4, 6-6N-2W to NE1/4, 1-6N-3W to SE1/4, 36-7N-3W		
D2	22	Surface Stratigraphic Section location: NE1/4, SW1/4, NE1/4 to E1/2, SW1/4, SE1/4, NE1/4, 12-25-2E		

author and reinterpreted using geophysical logs. In addition, the remaining nine wells were also reinterpreted to incorporate geophysical logs by spot checking the drill cuttings.

Six holes used in this study had no cuttings available, so information on these wells is limited to geophysical logs. These wells were mainly used to complete thickness trends of formations that were correlatable to them.

Subsurface stratigraphic sections are correlated to surface stratigraphic sections so that this study may be easily correlated to surface work in central New Mexico. A stratigraphic section measured in Carrizo Arroyo, southeast of Mesa Lucero (D1 of Figure 1-2), and a section measured by Colpitts (1986),in the Canoncito de la Uva area (D2 of Figure 1- 2), are used in this study. A stratigraphic section of the Abo Formation in the Zuni Mountains was desired for this study, however poor exposures made this impossible.

A surface gamma-ray survey was also measured over Colpitts's section (D2 of Figure 1-2 and Table 1-1) using a hand-held scintillometer. This was done to test the gamma-ray log response over known lithologies of the Abo Formation.

Paleocurrents are also measured in an upper sandstone bed, of the Abo Formation in Carrizo Arroyo, to be integrated with paleocurrents measured by Adams (1980), Cappa (1975), Lemley (1984) and MacMillan (1987).

Previous Work

The "Abo Sandstone" name was first used by Lee and Girty (1909) in reference to red beds exposed in Abo Canyon at the southern end of the Manzano Mountains. Darton (1928) described the distribution of the Abo red beds in New Mexico, and recognized the transition from a continental facies, in northern and central New Mexico, to a shallow marine facies further south.

In 1943, Needham and Bates formally described the Abo Formation near Scholle, a few miles east of Abo Canyon, where Lee and Girty (1909) first coined the name. They measured a thickness of 914 feet for the Abo Formation at the type section, and determined a continental origin based on it's red color and clastic character; casts of halite crystals; mud cracks; ripple marks; bones and tracks of land vertebrates; and land plant remains.

Bates et al. (1947) redefined the upper contact of the Abo Formation based on a closer affinity of sandstones and shales, previously considered uppermost Abo Formation, to the marine origin and character of the Yeso Formation. In doing so, they reduced the thickness of the Abo Formation by 104 feet giving it a total thickness of 810 feet at the type section. The deleted 104 feet have since been termed the Meseta Blanca Member of the Yeso Formation.

Unfortunately the change in the Abo type section was commonly overlooked in the literature and the original 914 feet, described by Needham and Bates (1943), was frequently used. In an attempt to remedy this, the type section modification was restated by an anonymous writer (New Mexico Geol. Soc. Guidebook) in 1963, and again by Hatchell et al. in 1982.

The exact age of the Abo Formation is a complex subject throughout New Mexico. The Abo has been dated by two basic methods: (1) stratigraphic relationships with fusulinid bearing sections of the Bursum (and equivalents) and Hueco Formations, and (2) by land plant and vertebrate fossils within the Abo Formation.

Problems have been encountered in using both of these methods. In using stratigraphic relationships, lateral correlation has been the major problem (King, 1945; Kottlowski, 1963). Questions also arise from the identification of fusulinids and the definitions of the ages they represent (Kottlowski, 1963). Using this method the Abo Formation has been dated as Wolfcampian by

Baars (1961, 1962), Otte (1959) and Pray (1961); Wolfcampian and Leonardian by Pray (1952); and Leonardian by King (1945).

In dating the Abo Formation directly with fossils, problems arise in defining fossil assemblages or floras and the ages they represent (Hunt, 1983; Kottlowski, 1963; Read and Mamay, 1964). Problems also originate from poorly located sample sites and confusion over formational boundaries (Hunt, 1983; Kottlowski, 1963). A third problem, noted by Hunt (1983),is that most fossils occur in the upper portion of the Abo Formation, with fewer age dates possible in the lower portions of the section. Using this method the Abo Formation has been dated as Wolfcampian and in part Leonardian by Hunt (1983), Read (in Bachman and Hayes, 1958; in King, 1942; in Wilpolt et al., 1946; in Wilpolt et al., 1951) and Read and Mamay (1964).

Amidst all this confusion most workers in central New Mexico consider or assume the Abo Formation to be either Wolfcampian in age (Bauch, 1982; Maulsby, 1981; LaPoint, 1976; and others) or both Wolfcampian and Leonardian in age (Broadhead, 1984; Cappa, 1975; Hatchell et al., 1982; Lemley, 1984; and others).

The depositional environment of the Abo Formation has been interpreted by numerous workers. Throughout northern and central New Mexico, the Abo Formation is thought to represent, at least in part, a broad, low gradient, coastal plain environment (Baars, 1962; Broadhead, 1984; Cappa, 1975; Crabaugh and McPherson, 1984; Kelley and Silver, 1952; McKee, 1967; Otte, 1959; Pray, 1961; Tonking, 1957; and others). Locally, near uplifts, the Abo commonly has a basal conglomerate unit representing a braided stream-alluvial fan environment (Bachman, 1964; Broadhead, 1984; Cappa, 1975; Kottlowski and Stewart, 1970; Speer, 1983; and others).

CHAPTER 2

PHYSIOGRAPHY AND GENERAL GEOLOGY

Physiography

The study area covers parts of the Navajo and Datil sections of the Colorado Plateau Province and the Mexican Highland section of the Basin and Range Province. Using Fenneman's (1930, 1931) work, Foster (1964) and Martin (1971) located the boundaries for these three sections differently. Their major difference was the location of the line separating the Datil section and the Mexican Highland section. Figure 2-1 shows the physical features in and around the Lucero region and the physiographic divisions based on the U.S. Department of Agriculture physical divisions of New Mexico Map (Williams and McAllister, 1979).

Surface Geology

Figure 2-2 shows the surface geology and Laramide or younger tectonic subdivisions of the study area. The tectonic elements are based on work done by Kelley (1955), Kelley and Silver (1952) and Martin (1971). Although Kelley did this work some time ago, the tectonic subdivisions are still widely used in subsurface work, particularly in oil and gas exploration.

The Mogollon slope is the largest tectonic division within the Lucero region. It is an essentially flat structure that covers the western and south-central portions of the study area. Outcrops in the northwestern portion of the Mogollon slope, within the Lucero region, consist of Mesozoic sedimentary rocks and Cenozoic volcanic mountains and lava beds. Further south and southeast the Mogollon slope exposures consist of Cenozoic alluvial valleys and volcanic mountains.

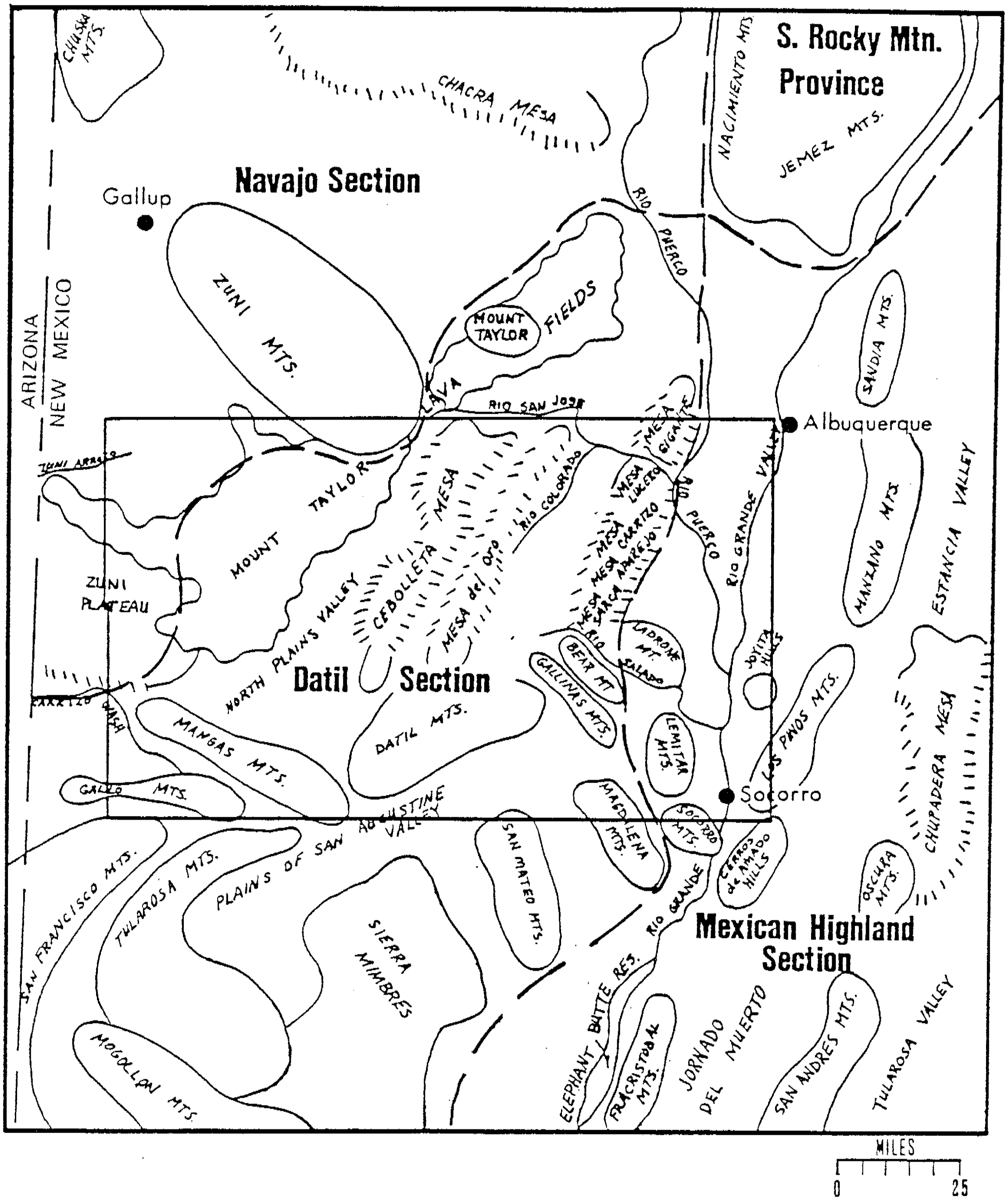
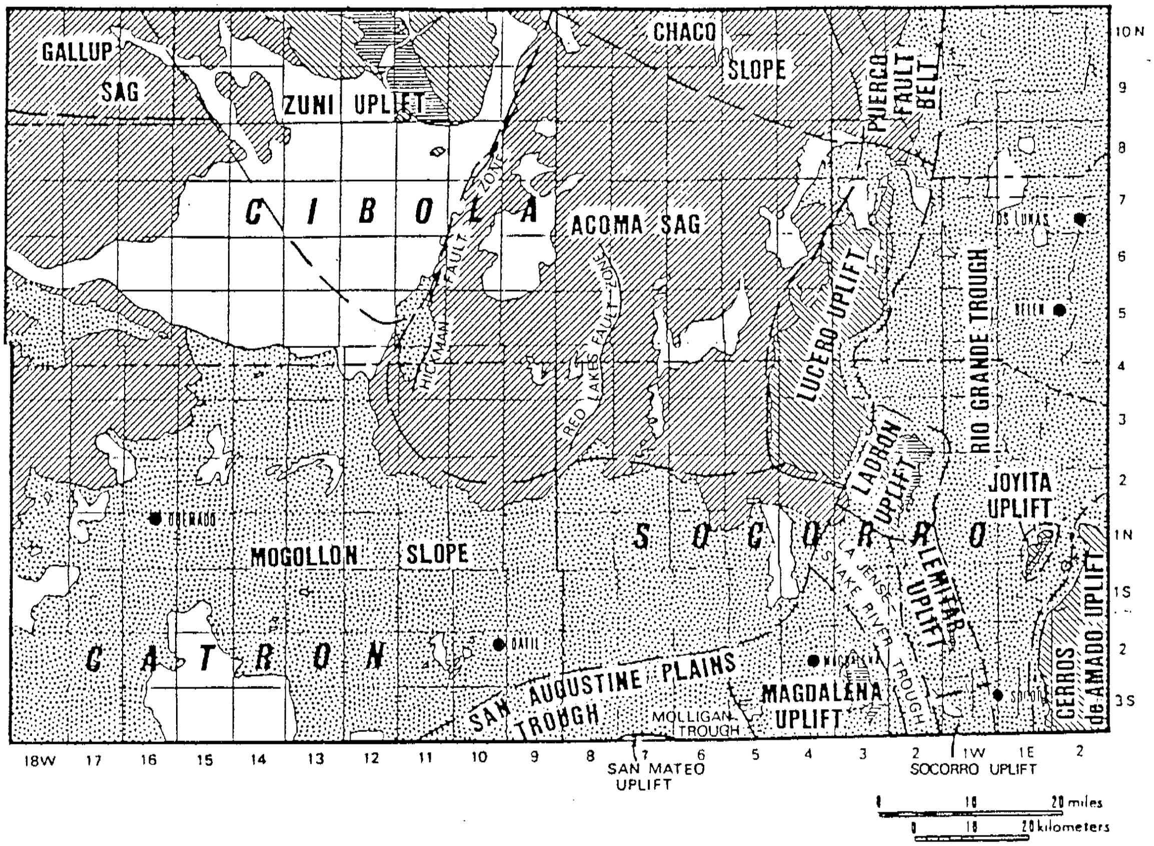


Figure 2-1. Physiographic features and physical divisions in and around the Lucero region (Modified from Martin, 1971). Physical divisions are based on the U.S.D.A. physical divisions of New Mexico map as shown by Williams and McAllister (1979).



SYMBOL	GENERAL DESCRIPTION (After Martin, 1971)
□	Tertiary and Quaternary volcanic rocks.
░	Tertiary and Quaternary sedimentary rocks. Conglomerate, breccia and sandstone with some mudstone and siltstone.
▨	Mesozioc sedimentary rocks. Includes red mudstone, sandstone and conglomerate of the Triassic System, sandstone and some gypsum of the Jurassic System and sandstone and mudstone of the Cretaceous System.
▧	Paleozoic sedimentary rocks. Includes rocks of Permian, Pennsylvanian and Mississippian ages. Permian: Primarily nonmarine sandstone, siltstone and mudstone (Abo Formation); siltstone, sandstone, some mudstone, minor limestone and considerable gypsum (Yeso Formation); and a basal sandstone overlain by limestone, some sandstone, and gypsum (San Andres Formation). Pennsylvanian and Mississippian: Limestone with minor basal terrigenous clastic rocks of Mississippian age overlain by Pennsylvanian strata that are mainly terrigenous clastics (Atokan), limestone (Desmoinesian) and limestone and mudstone (Missourian and Virgilian).
▤	Precambrian igneous and metamorphic rocks.

Figure 2-2. Generalized geologic map of the study area, with tectonic subdivisions. Geologic map is highly generalized from Dane and Bachman (1965). Tectonic subdivisions modified from Kelley (1955), Kelley and Silver (1952), Martin (1971) and Wengard (1959).

The Gallup sag is north of the Mogollon slope and occupies the northwest corner of the study area. Kelley (1955) interprets most of the "sags" of the Colorado Plateau as embayments of adjacent basins. Thus, the Gallup sag is interpreted as an embayment of the San Juan basin to the north-northeast. It is a broad synclinal depression separating the Zuni uplift from the Defiance uplift of eastern Arizona. Within the area of interest, outcrops on the Gallup sag are comprised of Mesozoic sedimentary and Cenozoic volcanic rocks.

The Zuni uplift is to the east of the Gallup sag and east- northeast of the Mogollon slope. It is a northwest trending uplift which is asymmetrical to the southwest. Although the surface expression of the Zuni uplift is limited to the Zuni mountains area, the uplift extends much further south and southeast in the subsurface. Precambrian crystalline rocks are exposed along the crest of the Zuni Mountains while Permian and Mesozoic sedimentary rocks successively surround the Precambrian exposures.

The Rio Grande trough is situated along the eastern edge of the study area. It is bounded on the west by the Puerco fault belt and the Lucero, Ladron, Lemitar, and Socorro uplifts. To the east-southeast, within the area of interest, the Rio Grande trough is bounded by the Cerros de Amado and Joyita uplifts. Kelley (1955) describes the trough as a complex series of down dropped north-northeast trending grabens which "follow" the course of the Rio Grande river. Only Cenozoic sedimentary and volcanic rocks are exposed within the trough.

The Puerco fault belt is between the Nacimiento uplift to the north and the Lucero uplift to the south. Kelley (1955) cites it as one of the few areas where the Colorado Plateau and the Rio Grande trough are not separated by an uplift. The fault belt consists of numerous closely spaced high angle faults. Kelley (1955) states that the easternmost fault or two are down towards the

Rio Grande trough and have at least several thousand feet of throw. The remaining faults within the Puerco fault belt all have throws less than a few hundred feet, with down throws dominantly towards the Colorado Plateau. Outcrops within the Puerco fault belt consist of Mesozoic or Cenozoic sedimentary rocks.

The Chaco slope lies along the northern edge of the study area between the Zuni uplift and the Puerco fault belt. Like the Mogollon slope it is a relatively undeformed area which forms the southern margin of the San Juan basin. Within the study area, Chaco slope exposures are dominantly Mesozoic sedimentary rocks with minor occurrences of Cenozoic volcanic rocks.

South of the Chaco slope is the Acoma sag, also known as the Acoma basin (Broadhead, 1983b), Lucero sag (Martin, 1971) and the Lucero basin (Martin, 1971; Wengard, 1959). The Acoma sag is a broad synclinal depression that separates the Zuni and Lucero uplifts. Wengard's (1959) Hickman fault zone is along the Zuni uplift-Acoma sag boundary, and the Red Lakes fault zone is located in the center of the Acoma sag. Outcrops consist mainly of Mesozoic sedimentary rocks with minor occurrences of Cenozoic sedimentary and volcanic rocks.

The Lucero uplift lies to the east of the Acoma sag and south of the Puerco fault belt. Kelley (1955) describes it as an asymmetrical, north-northwest trending uplift with a gentle western flank and a steep, thrust faulted eastern flank. Thrusting is to the east with both high and low angle thrust faults present. Kelley interprets these thrusts as Laramide in age, but notes that they are "masked" considerably by late Tertiary faults which greatly lowered the Rio Grande trough. Paleozoic sedimentary rocks are exposed along most of the Lucero uplift with fewer Mesozoic sedimentary rocks, and Cenozoic sedimentary and volcanic rocks.

The Ladron, Lemitar and Socorro uplifts all lie to the south- southeast of the Lucero uplift. Martin (1971) describes the uplifts as complexly faulted Basin and Range type fault blocks that are tilted to the west. The Ladron and Lemitar uplifts both have exposed Precambrian cores with flanks of Paleozoic and Cenozoic sedimentary rocks. Outcrops on the Socorro uplift consist primarily of Cenozoic volcanic and sedimentary rocks.

To the east, the Cerros de Amado uplift forms the eastern boundary of the Rio Grande trough in the area referred to as the Socorro constriction. It is a southern extension of the Manzano and Los Pinos uplifts. The Cerros de Amado uplift is a complexly faulted and folded fault block that is tilted to the east. Exposures are dominantly Paleozoic sedimentary rocks and minor Mesozoic and Cenozoic sedimentary rocks. A few small Precambrian outcrops also occur along the eastern side of the uplift.

The Joyita uplift is situated to the west-northwest of the Cerros de Amado uplift. It is separated from the northern Cerros de Amado and southern Los Pinos uplifts by a structurally low region that contains Cenozoic alluvial deposits thinly covering Mesozoic sedimentary rocks (Kottlowski and Stewart, 1970). Kottlowski and Stewart describe the uplift as a complex Cenozoic horst on the east side of the Rio Grande graben. Precambrian rocks are exposed along the crest of the north-northeast trending hills, with Permian rocks sloping off the Precambrian rocks to the west.

Between the Mogollon slope and the Ladron, Lemitar, and Socorro uplifts is an area of Basin and Range uplifts and troughs (Martin, 1971). The uplifts are the Magdalena and the San Mateo, only a part of which is in the study area, and the troughs include the San Augustine Plains, Molligan and La Jense-Snake River troughs. The Magdalena uplift has a Precambrian core with Paleozoic and Cenozoic sedimentary rocks exposed on it. Outcrops on the San

Mateo uplift consist of Cenozoic volcanic and sedimentary rocks. Exposures in the troughs are Cenozoic sedimentary rocks with a few volcanic exposures of the same age.

Stratigraphy

In the study area the Abo Formation overlies Precambrian, Mississippian and Pennsylvanian rocks, as well as rocks assigned to the Bursum Formation. Figure 2-3 shows the units immediately underlying the Abo Formation in the Lucero region. The Meseta Blanca Member of the Yeso Formation overlies the Abo Formation throughout the study area.

Precambrian Rocks

The Abo Formation unconformably overlies rocks considered Precambrian in age (Fitzsimmons, 1967; Foster, 1957, 1964; Martin, 1971; Smith, 1957) over the Zuni Uplift, in the western portion of the study area, and locally in the Joyita Hills to the east (Figure 2-3). The Precambrian lithology is variable and its distribution is poorly understood in west-central New Mexico. The dominant lithologies in the core of the Zuni Mountains are granite and granite gneiss with minor amounts of metarhyolite, schist and greenstone (Fitzsimmons, 1967; Foster, 1957, 1964; Smith, 1957). The Precambrian in the Ladron, Lemitar and Socorro Mountains consists of granite, metagabbro, metadiabase, and metasediments (Condie, 1975; Condie and Budding, 1979; Foster, 1957). In the Magdalena mountains the Precambrian lithologies are granite and metasediments, while the core of the Joyita Hills is granite and biotite gneiss (Condie and Budding, 1979). In drill holes, the Precambrian lithologies encountered are dominantly granites and granite gneisses with fewer incidences of quartzites and schists.

The Precambrian is easily picked in the subsurface with drill cuttings

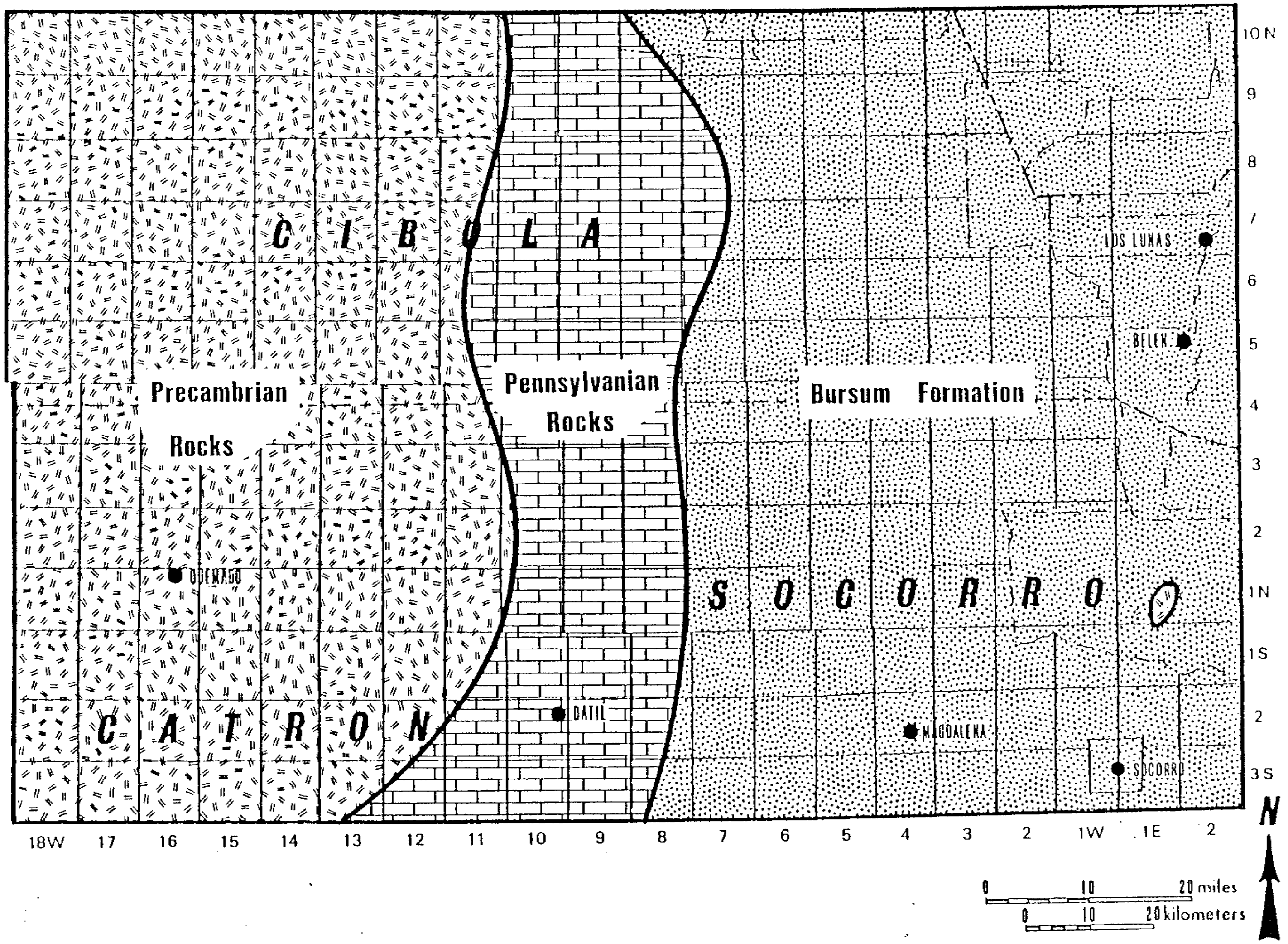


Figure 2-3. Map of units directly underlying the Abo Formation.

and/or geophysical logs. Log responses include high to very high gamma ray counts, high to very high resistivities, and low interval transit times on the sonic log.

Mississippian Rocks

A thin succession of Mississippian rocks assigned to the Caloso and Kelley Formations exists in the southeastern portion of the study area (Armstrong, 1955; Martin, 1971). The Mississippian rocks are not in direct contact with the Abo Formation in the Lucero region, and thus are not pertinent to this study.

Pennsylvanian Rocks

The terms Pennsylvanian rocks and Pennsylvanian strata are loosely used here to indicate rocks of the Sandia and Madera Formations of the Magdalena Group. The Pennsylvanian strata are overlain directly by the Abo Formation in the central portion of the study area, and overlain by the Bursum Formation in the eastern portion of the study area.

The Bursum Formation and it's equivalents in central New Mexico are a complex subject. Kottlowski and Stewart (1970), using a limited number of control points, only recognized the Bursum Formation in the southeastern corner of the study area. Based on this, Martin (1971) also did not recognize the Bursum Formation in the Lucero region and extensively mapped the Abo Formation directly over the Pennsylvanian strata as Kottlowski and Stewart had. Despite this, the author does recognize the Bursum Formation within the study area for reasons that will be discussed below under the heading "Bursum Formation" in this chapter.

In the Lucero region the Pennsylvanian strata range from Atokan to Virgilian in age (Martin, 1971). Martin divided the Pennsylvanian stratigraphic section into a lower, dominantly clastic unit and an overlying carbonate rich unit.

The lower unit comprises the Sandia Formation and consists of dull brown and gray sandstones, siltstones, mudstones, conglomerates and limestones. The upper unit comprises the Madera Formation and consists primarily of gray limestones with minor dull brown and gray sandstones, siltstones and mudstones (Martin, 1971).

In the eastern part of the study area, Pennsylvanian strata reach a maximum thickness of almost 3000 feet along the axis of the Lucero basin (Acoma sag)(Figure 2-4), from which they thin both to the east and west. Martin (1971) interpreted limestones in the Lucero basin to be shallow water shelf deposits. He concluded that the thick accumulations of Pennsylvanian rocks were due to differential subsidence and not filling in of a deep basin. Thicker accumulations of transitional Bursum Formation lithologies on the eastern margin of the Lucero basin suggest that the thinning is due to primary deposition and that erosion was not an important factor. To the west the pinch out of Pennsylvanian rocks is probably due to a low angle, angular unconformity (McKee, 1967; Martin, 1971; Wengard, 1959). This is based primarily on the abrupt change from clean marine limestones with very little clay or silt content to the basal Abo red beds. Martin (1971) also notes other clues such as pre-Abo subaerial exposure at several of his outcrop localities, late-Virgilian erosion indicated by calcarenite-calcirudite limestone deposits in the Sun No. 1 Plains of San Augustine unit, and post- Pennsylvanian erosion as indicated by the presence of limestone rock fragments of typical Pennsylvanian lithology in basal Abo conglomerates.

The contact between the Abo and the Pennsylvanian is placed above the highest limestone and below the lowest red bed. The limestone is easily picked with cuttings and readily detectable by high resistivities on electric logs. The contact between the Pennsylvanian strata and the Bursum Formation is inter-

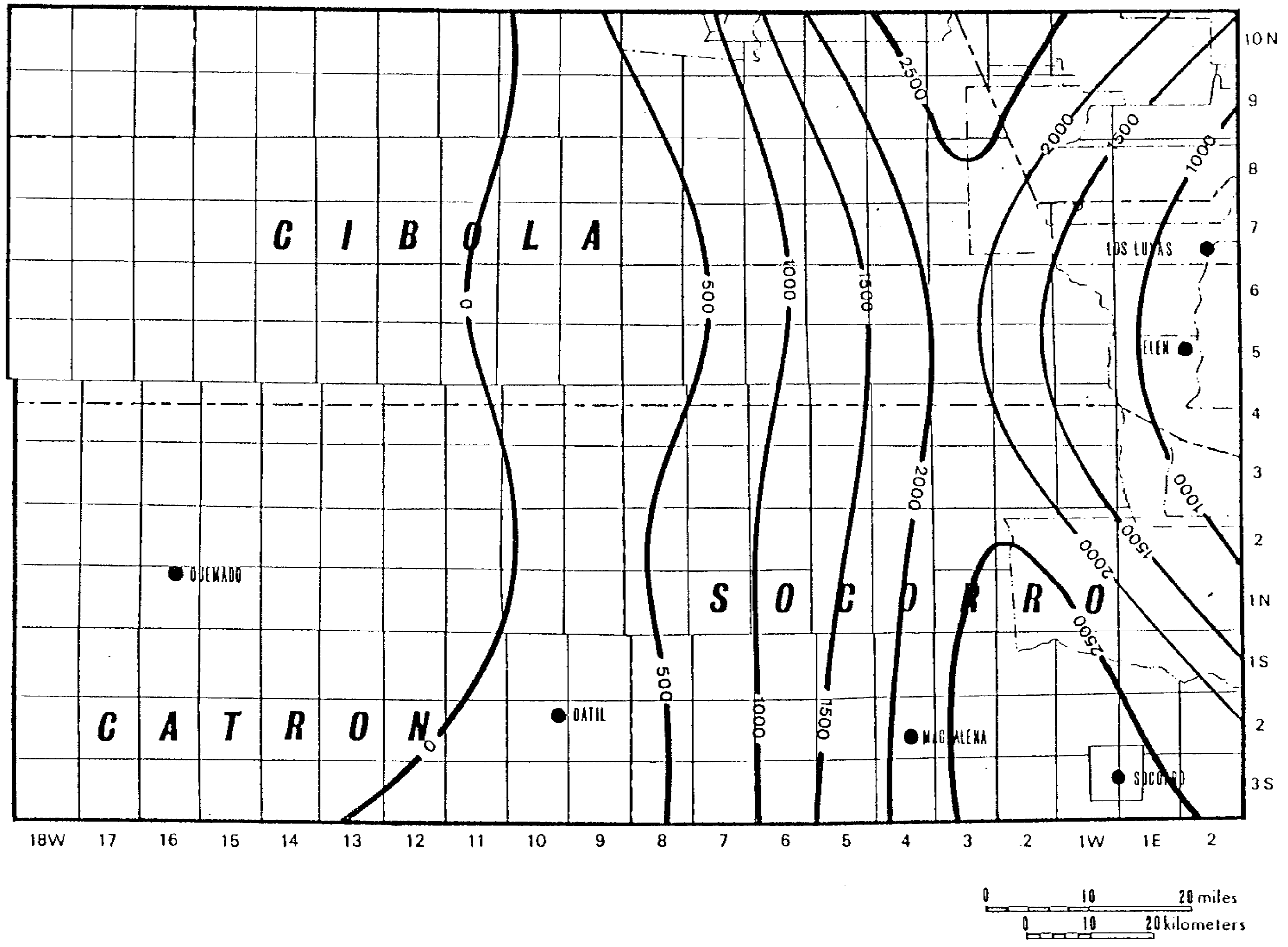


Figure 2-4. Isopach map of Pennsylvanian rocks. Modified from Martin (1971) to subtract the Bursum Formation. Contour interval = 500 feet.

preted to be conformable based on transitional nature of the Bursum Formation and the general lack of evidence to suggest regional erosion. It is placed below the lowest red mudstone bed of the Bursum Formation. Mudstones below this contact are either gray or a dull brown. In the subsurface this contact can only be picked with the aid of drill cuttings. The reasoning behind this method of picking the contact is discussed below.

Bursum Formation

As mentioned above, the Bursum Formation and its assumed equivalents in central New Mexico are a very complex topic. The Bursum Formation is believed to be correlative, at least in part, to Kelley and Wood's (1946) Red Tanks Member of the Madera Formation, Otte's (1959) Laborcita Formation, and Thompson's (1942) Bruton Formation.

Within the study area the Bursum name has been used for exposures near Abo Canyon, outcrops east of Socorro, and in the Joyita Hills area (Bates et al., 1947; Cappa, 1975; Kottlowski and Stewart, 1970; Wilpolt et al., 1946; Wilpolt et al., 1951; and others). Meanwhile, the Red Tanks terminology has been used in the Lucero Mesa region and in the Ladron Mountains (Kelley and Wood, 1947; Kues and Kietzke, 1976; Martin, 1971; Wengard, 1959).

Both the Red Tanks Member of the Madera Formation and the Bursum Formation are generally interpreted as alternating marine and continental rocks recording the transition from the dominantly marine environment of the underlying Pennsylvanian strata to the continental environment of the overlying Abo Formation. The significant difference between the two terminologies appears to be the inferred ages of the units. The Red Tanks Member of the Madera Formation infers a Pennsylvanian age, while the Bursum Formation has traditionally been viewed as Permian in age.

Fusulinid dating of the Red Tanks Member of the Madera Formation and the Bursum Formation has been done in the study area. Wendell Stewart, formerly of Texaco, Inc., interpreted a Virgilian age for the uppermost limestone of the Red Tanks in the Ladron Mountains (Martin, 1971). Kues and Kietzke (1976) interpreted the lower two-thirds of the Red Tanks in Carrizo Arroyo as Pennsylvanian in age and suspected the upper third to be Permian in age, but east of Socorro, Altares (unpublished data) found Wolfcampian age fusulinids in the lower Bursum Formation; because these are individual efforts, which lack consistency, the author feels a definite correlation is impossible.

Foster (1957, 1964) referred to the transitional unit, between the Pennsylvanian strata and the Abo Formation, as the Bursum Formation throughout west-central New Mexico. For simplicity the same approach is used in this study. The author regards the Bursum Formation as a lithostratigraphic unit independent of age. Thus, a "Bursum facies" interpretation is preferentially used over a "Bursum zone or age" as suggested by Kottlowski and Stewart (1970).

In the Lucero region, the Bursum Formation consists of purplish red, red and green mudstones separated by quartzose and arkosic sandstones, arkosic and limestone pebble conglomerates, and gray limestones.

The thickness of the Bursum Formation is approximately 200 to 250 feet in the eastern portion of the study area, but thins westward and pinches out near the center of the region (Figure 2-5). There is an anomalous thickness of about 450 feet of Bursum (Red Tanks) reported in Carrizo Arroyo by Kues and Kietzke (1976). It is simply noted here, but is not included in the isopach map because it has not been field checked to insure consistency with the Bursum Formation definition used here. For simplicity, the western pinch out of the Bursum formation is assumed to be depositional. Figure 2-6 schematically

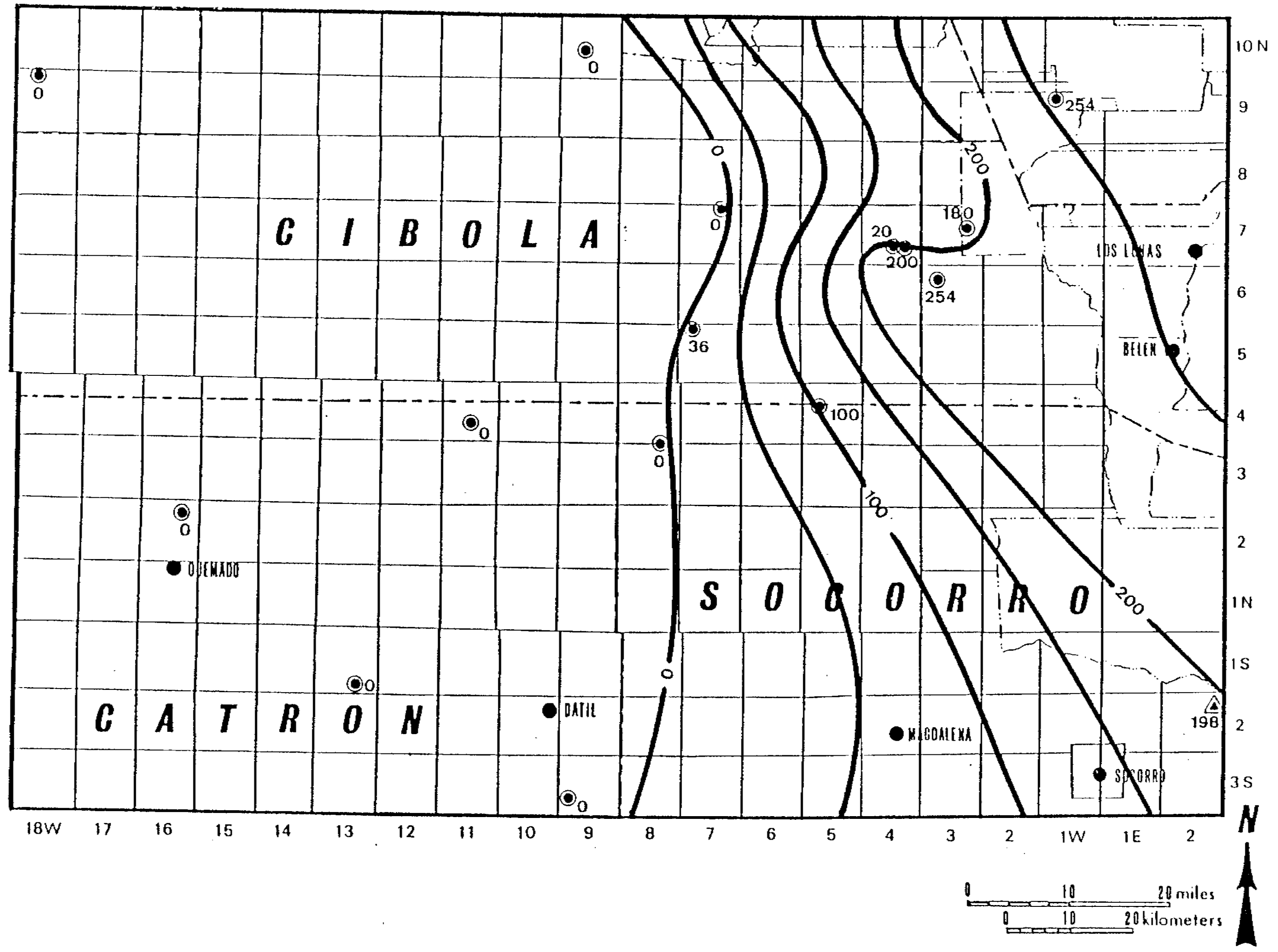


Figure 2-5. Isopach map of the Bursum Formation. Contour interval = 50 feet.

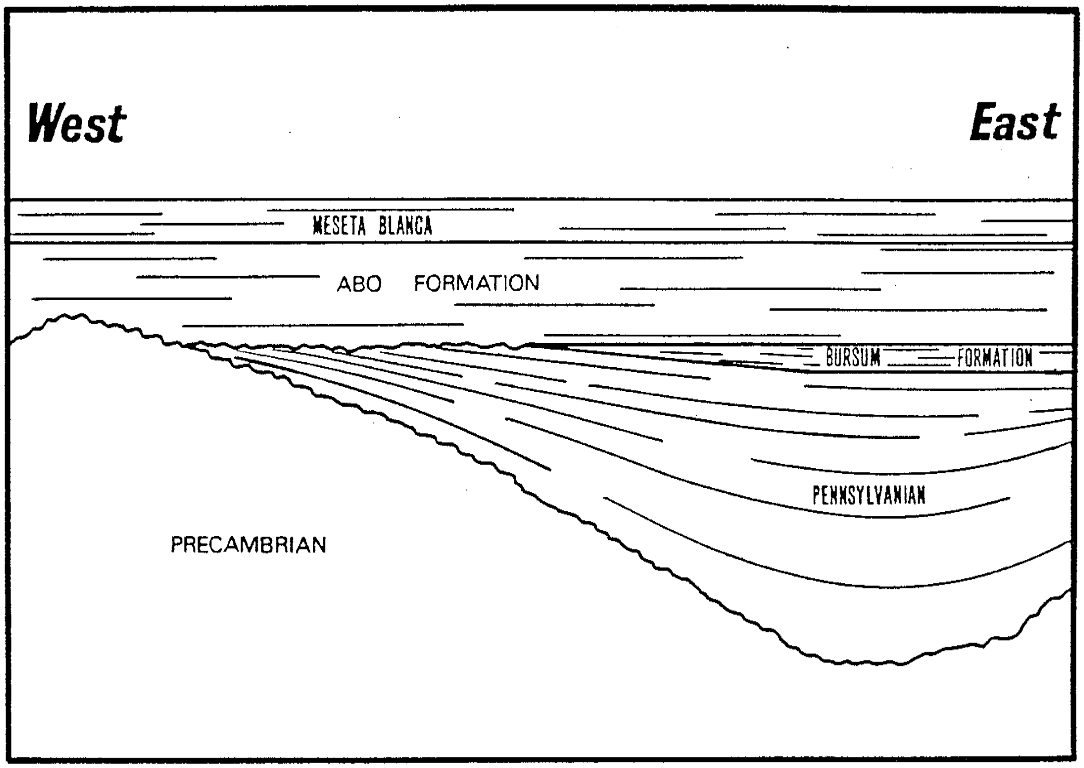


Figure 2-6. Schematic diagram showing the interpreted contact relationships between the Abo Formation and surrounding units.

shows the interpreted contact relationships between the Abo Formation and the underlying units. The Bursum will be treated as conformable with both the Abo Formation and Pennsylvanian rocks, however, the western pinch out of the Bursum Formation could also be interpreted to be either totally or partially due to the same unconformity that separates the Abo Formation and Pennsylvanian rocks (Figure 2-7). The Abo-Pennsylvanian unconformity may also extend under the Bursum pinch out.

As mentioned above, the Bursum Formation lies conformably on the Madera Formation. In the eastern portion of the study area the top of the Madera Formation is marked by thick, cliff forming limestones (Wilpolt et al., 1946; Wilpolt et al., 1951; various unpublished New Mexico Tech theses). To the west and in the subsurface the contact is not as distinct. Although it is not ideal, the only practical distinguishing feature between the Madera and Bursum Formations is the color of the mudstones. Red mudstones are known to occur in Pennsylvanian strata, but the first occurrence of dull brown or gray mudstones while moving down section generally occurs near the Bursum Formation-Madera Formation contact in outcrops east of Socorro and in the Ladron Mountains. Thus, while realizing it's limitations this criterion was used to pick the contact in the subsurface.

The contact between the Bursum Formation and the overlying Abo Formation is considered conformable by most workers (Bates et al., 1947; Kelley and Wood, 1946; Kottlowski and Stewart, 1970; Kues and Kietzke, 1976; Wengard, 1959; Wilpolt et al., 1946; Wilpolt et al., 1951; others). The author interprets the contact as dominantly conformable with disconformities occurring only locally in the Lucero region.

The contact is placed at the top of the highest limestone. As with the Pennsylvanian-Abo contact, the uppermost limestone is easily picked with geo-

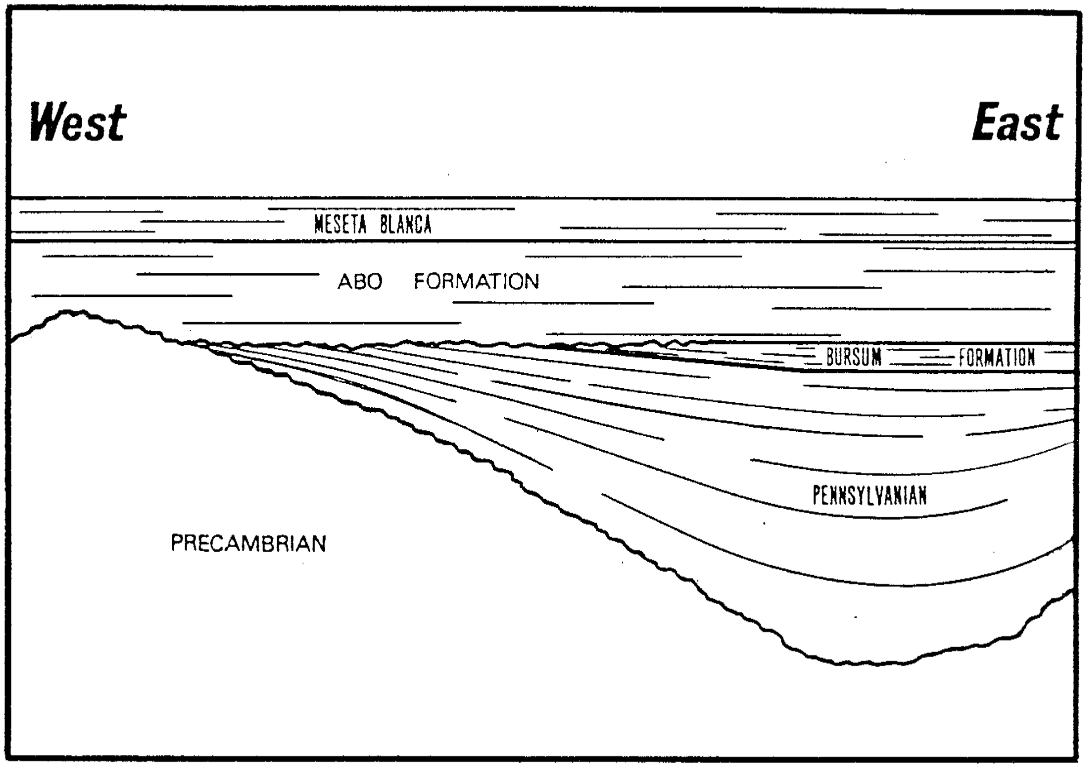


Figure 2-7. An alternative interpretation of the Bursum pinch out.

physical logs and/or drill cuttings.

Abo Formation

In the Lucero region the Abo Formation consists dominantly of red, reddish-brown and green mudstones interbedded with siltstones, very fine-grained arkosic and quartzose sandstones, and limestone pebble conglomerates. The lower part of the Abo Formation in the Zuni Mountains consists of medium to very coarse-grained sandstones along with arkosic conglomerates containing pebble to cobble sized quartz, feldspar and granite clasts. This coarse-grained "granite wash" facies is much thinner in the Zuni Mountains than similar facies reported in the Sacramento Mountains and along the Uncompahgre uplift. Coarse grained sandstones also occur in the base of the Abo Formation around the Joyita Hills, however, they are not as coarse as the equivalent beds in the Zuni Mountains. In outcrops the sandstones and siltstones usually display lenticular bedding. Primary sedimentary structures are common and include current ripple marks, cross stratification, mud cracks, rain-drop impacts, tool marks and channel forms. Other features include plant impressions, vertebrate tracks and burrow casts.

As mentioned earlier, the age of the Abo Formation is a somewhat controversial subject. For the purpose of this thesis the Abo Formation is considered to be both Wolfcampian and Leonardian in age throughout the Lucero region.

Within the study area the Abo Formation ranges from an anomalously thin 356 feet section in the Sun Oil Co. No. 1 Plains of San Augustine Unit (Sec. 29, T3S, R9W) to a maximum of 820 feet thick in the Wilson Heirs #1 well (Sec. 14, T7N, R3W)(Figure 2-8). The thickness of the Abo Formation in the San Augustine Plains Unit has been ignored when constructing the isopach map because that particular section has been intruded by almost 1500 feet of

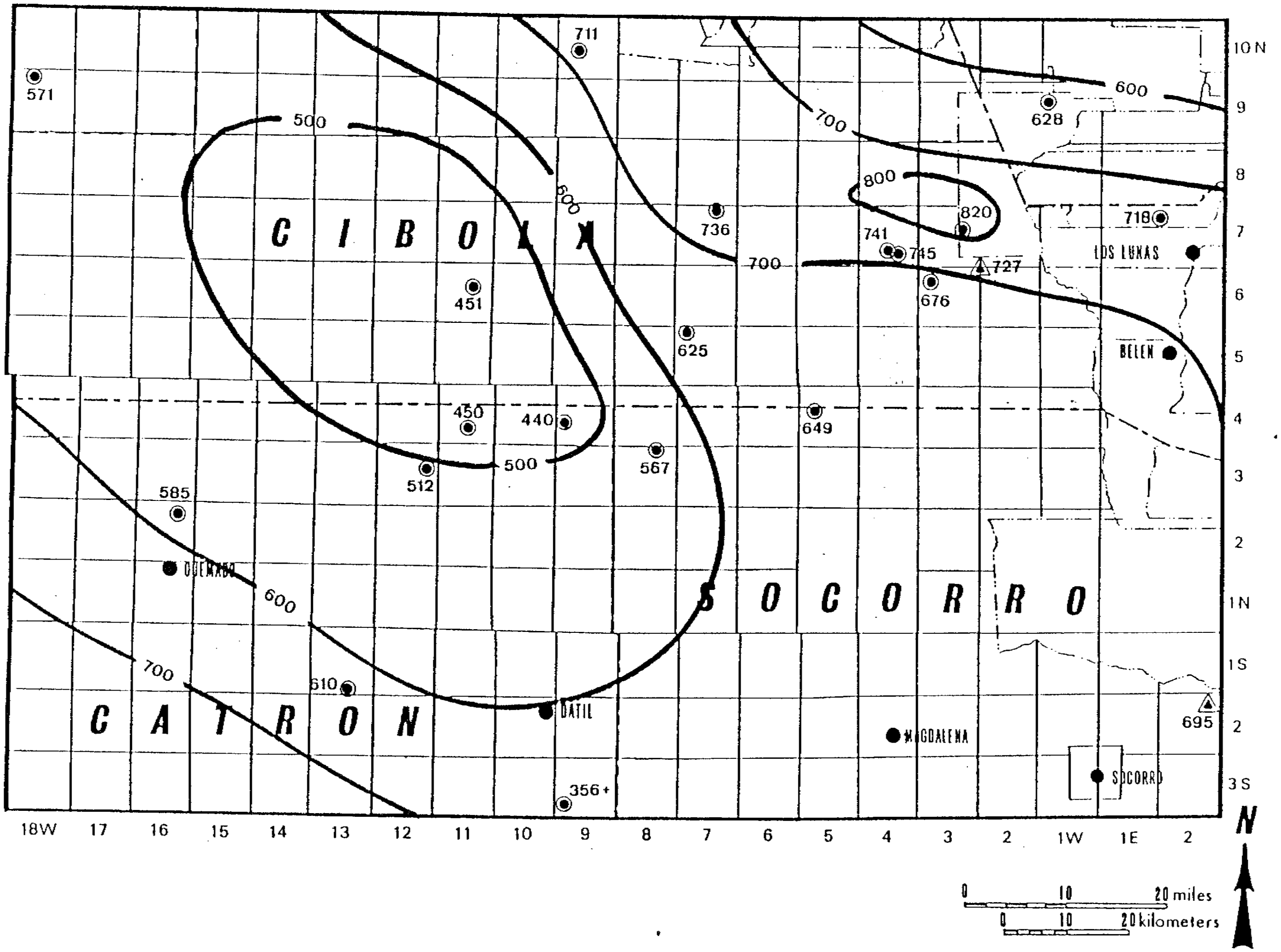


Figure 2-8. Isopach map of the Abo Formation. The Plains of San Augustine Abo section (Sec. 29, T3S, R9W) has been intruded and probably is not complete. Contour interval = 100 feet.

hypabyssal igneous rock. The Abo Formation is notably thinner over the Zuni uplift in the western and northwestern portion of the study area. There the Abo is about 400 to 450 feet thick.

The contact between the Abo Formation and the Meseta Blanca Member of the Yeso Formation has been described differently by various workers throughout New Mexico. However, most agree that the contact is gradational and some have suggested that it may be an intertonguing contact (Hatchell, et al., 1982; Myers, 1977).

Cappa (1975) defines the transition by a color change from the dark reddish browns of the Abo Formation to a reddish orange in the Meseta Blanca Member of the Yeso Formation. Cappa also uses the lowest occurrence of halite casts and thin beds of dolostone to define the Meseta Blanca. Hatchell et al. (1982) place the contact below the lowest tangentally crossbedded sandstone as Northrop and Wood (1946) had, but added the presence of salt hopper and gypsum casts as an indicator of the transition. Broadhead et al. (1983) distinguished the Meseta Blanca by a distinct orange color, higher percentage of sandstone, slightly coarser grained sandstones, and a greater lateral continuity of beds.

On surface outcrops the criteria of Broadhead et al. (1983) has been used with salt casts used only as a secondary indicator of the contact. In subsurface analysis the lateral continuity and salt casts are not detectable using well logs and cuttings. Color was also found to be unreliable in some wells. Therefore, in the subsurface the Abo-Meseta Blanca transition was detected by a higher percentage of sandstones and slightly coarser grained sandstones in the Meseta Blanca, along with a color change in some wells.

Wireline logs show the transition reasonably well. The gamma-ray readings are lower and more constant in the Meseta Blanca reflecting a higher percentage of coarser, cleaner sands. The sonic log has a characteristic arcuate shape in the Meseta Blanca with higher interval transit times in the middle portion of the section. This distinguishing shape also shows up, although not as distinctly, on deep resistivity logs and other density logs.

These two indicators (gamma-ray and sonic logs) don't always indicate a contact at the same depth. The gamma-ray log will usually suggest a contact higher in the section than the sonic log with an interval of overlap up to 90 feet thick. The overlap of the inferred contacts of the two logs may be due to the transitional nature of the contact.

The gamma-ray log is believed to be more reliable and is usually easier to pick. For these reasons the upper contact of the Abo Formation was picked primarily using the gamma-ray log and drill cuttings while noting that the contact is a gradational one.

Meseta Blanca

The Abo Formation is overlain by the Meseta Blanca Member of the Yeso Formation throughout the study area. Baars (1962) correlated the Meseta Blanca with the De Chelly sandstone and showed it to be an extensive unit throughout east-central Arizona, central New Mexico and the Colorado Plateau. Baars (1962) suggested that the Meseta Blanca and the upper Supai Formation of east-central Arizona be referred to as the De Chelly sandstone. This terminology has not been commonly accepted and thus the Meseta Blanca terminology of central New Mexico is used here.

The Meseta Blanca is considered Leonardian in age based primarily on stratigraphic relationships (Baars, 1962; Bates et al., 1947; Kottlowski, 1963; Northrop and Wood, 1946; and others). It is characterized by uniformly bedded, orange-brown to red-brown variegated sandstones, siltstones and mudstones. The sandstones are generally quartzose and range in size from very fine to medium-grained sands.

The Meseta Blanca ranges from 160 feet to 370 feet thick in the Lucero region (Figure 2-9). The thinnest sections occur over the Zuni uplift and then thicken to the northeast and southwest.

The top of the Meseta Blanca is placed at the base of the lowest "non-clastic" sedimentary rocks above a thick section of sandstones in the basal Yeso Formation. The "non-clastic" sedimentary rock usually consists of limestone or dolostone and is easily picked with cuttings and geophysical logs.

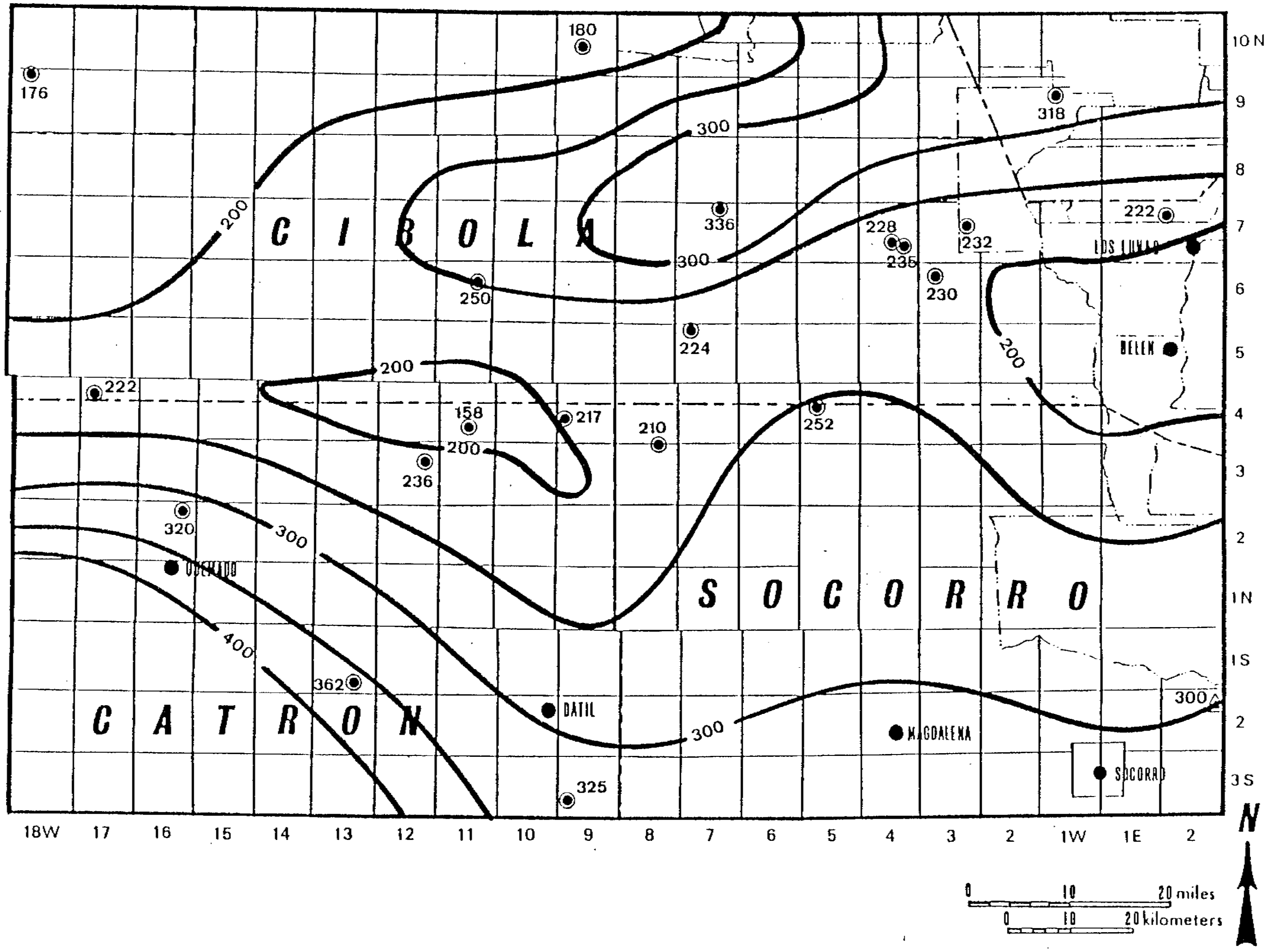


Figure 2-9. Isopach map of the Meseta Blanca Member of the Yeso Formation. Contour interval = 50 feet.

CHAPTER 3

SUBSURFACE ANALYSIS

Introduction

Subsurface stratigraphic information can be obtained from seismic data, cores, and various geophysical and sample logs produced of wells. Seismic data and cores were not available. Therefore, well logs are the only source of subsurface information used in this study.

The term well log is generally used in reference to geophysical or wire-line logs, but well logs, in a broad sense, may refer to a variety of logs produced during and after a hole is drilled. These include drilling-rate, mud, sample and geophysical or wire-line logs. Sample logs and geophysical logs are the primary logs used in this study.

Sample logs are lithologic logs produced from examination of rock samples (cuttings) which have come out of the drill hole. Geophysical logs are produced by moving various measuring instruments up the borehole and recording changes in various properties related to lithologies.

Drill Cutting Analysis

Drill cuttings are small pieces of rock produced by the drill bit in the drilling process. Most oil and gas drillers in central New Mexico use rotary drills. These drills use bits to cut or break the rock into small fragments which are then flushed to the surface by drilling mud that circulates down the drill stem and back up the borehole. The cuttings are then separated from the mud by a screen mesh and washed. Then they are studied. Textures of the rock being drilled can be significantly altered by the bit and drilling mud during the drilling process (Graves, 1986), therefore caution must be exercised when studying cuttings.

Because of time and expense, most petroleum wells are only cored on a limited basis, if at all. Thus, drill cuttings are usually the only source of lithologic samples. Logging drill cuttings has been a common practice of geologists for more than 100 years. Over the years different methods of logging drill cuttings have been used. Maher (1959) describes three basic types of logs produced by geologists analyzing drill cuttings in the laboratory. These are the percentage, interpretive and composite interpretive logs.

A percentage log is one in which the percentage of each lithology in a sample is shown in the corresponding interval of the well. Percentage logs can be subdivided into qualified percentage logs and unqualified or straight percentage logs. Qualified percentage logs only show and describe the percentage of lithologies thought to represent the interval drilled. Interpretation is done to disregard lithologies which are believed to have come from sidewall cavings, differential lag, or operational errors. Straight percentage logs show no interpretations and simply report and describe the percentage of all lithologies present.

Interpretive logs are lithologic interpretations based on first appearances of specific lithologies or fossils, relative amounts of rock types, and the known stratigraphic sequence in the area. The interpreted lithologies are plotted across the column similar to the way surface stratigraphic columns are drawn.

Composite interpretive logs are produced using the same criteria used with interpretive logs, but geophysical well logs are also used to enhance detail of the stratigraphic column. Geophysical logs aid in quantifying bed thicknesses and depths and help establish bed-for-bed successions in alternating lithologies.

Composite interpretive logs were produced for 13 wells in the study area (Plates 2 through 14). In wells prefixed A, the author recorded drill-cutting data in a straight-percentage format (Appendix C), and later interpreted it with the aid of geophysical well logs to produce the composite interpretive logs. The percentage of a given lithology was visually estimated using a drill-cutting percentage chart from Swanson's (1981) Sample Examination Manual. In wells prefixed B, interpretive logs made by Roy Foster were used; those logs are on file at the New Mexico Bureau of Mines and Mineral Resources petroleum records library. The author randomly inspected the drill cuttings from those logs to verify or modify the interpretations, and then refined or reinterpreted the logs using geophysical well logs.

In this study, drill cuttings were examined using a low power binocular microscope ranging in power from 7X to 20X. The cutting sizes varied from 1 millimeter up to 1 centimeter with an average size of approximately 2 to 3 millimeters.

The only bit-generated texture recognized is bit sand as defined by Graves (1986). Bit sand is a sand produced by the drill bit when its grinds rock into sand-sized grains. The bit sand ranges from fine-grained to coarse-grained sand-size cuttings and only occurs in the lower part of the Abo Formation in the western portion of the study area. The main constituent of the bit sand is quartz, which occurs in a variety of morphologies including subhedral to euhedral crystals, angular clasts, and well-rounded, frosted grains. The bit sand also contains other constituents such as pyrite, Fe-Mg oxides and a few rounded calcite grains; however some of these mineralogies may be from sidewall cavings in overlying formations. No feldspar grains were noted in the bit sand.

The bit sand is believed to represent coarse-grained, poorly indurated lithologies similar to some of the basal lithologies of the Abo Formation in the Zuni Mountains. These lithologies may also contain constituents, such as micas and altered feldspars, which did not survive the mechanical abrasion, and subsequent mud flushing and sample washing.

Geophysical Well Log Analysis

Geophysical well logs are run routinely in petroleum wells and occasionally in mineral exploration holes and water wells. The most common wire-line logs in the study area are spontaneous potential (SP), gamma-ray, sonic and resistivity logs. The theory and principles of geophysical logs is explained in numerous books on the subject (Asquith, 1982; Helander, 1983; Hilchie, 1982; Rider, 1986; Schumberger Limited, 1972; and others).

The geophysical logs used in this study were produced from as far back as 1954 and as recent as 1984. Although more advanced wire- line logs were run in the newer holes, the quality of the logs aren't necessarily as good as the older logs. One example of this is the Transocean Oil Co. No. 1 Henderson-Santa Fe Railroad well drilled in 1977 and located in township 1 north and range 6 west. This would have been a useful control point for this study, but the wire-line logs are essentially uninterpretable due to either operator error or undesirable drill hole conditions. Samples were not available for this well, consequently the well is of no use to this study.

In this thesis, gamma-ray, SP, sonic and resistivity logs are the most common geophysical logs used for stratigraphic analysis because they are available for most of the wells in the area. In most cases the gamma-ray log was used in preference to the SP log because it is usually less affected by borehole fluids and more sensitive to lithologic changes. SP logs were used in cases where gamma-ray logs are not available. Sonic logs are particularly helpful in picking the upper and lower contacts of the Abo Formation. However, cycle skipping frequently made interpretation of the intraformational stratigraphy impossible with sonic logs. Resistivity logs are used extensively in this thesis.

Compensated neutron and formation density logs are available for a few wells in the study area and were also utilized in the stratigraphic analysis of the Abo Formation.

Geophysical Log Analysis of the Abo Formation

When conducting subsurface stratigraphic studies using wire-line logs it is useful to first verify log response with known lithologies. This is particularly desirable in formations that contain unusual or complex lithologies. In the Abo Formation the main concern is the gamma-ray log response to arkosic sandstones, which frequently give "shaley" readings due to radioactive potassium in K-feldspars.

Ideally the testing of log responses is done in a well that has both geophysical logs and core. Unfortunately, there are no such wells in the study area, therefore a surface gamma-ray log (Plate 22) was constructed for the Abo stratigraphic section measured by Colpitts (1986).

Methods of measuring gamma-rays on an outcrop are described by Chamberlain (1984) and Ettensohn et al. (1979). The two methods are identical except Chamberlain held his scintillometer over the outcrop, whereas Ettensohn et al. placed the scintillometer directly on the outcrop. Since low readings were encountered in this study, the method employed by Ettensohn et al. is used here.

Because outcrop surfaces can be very irregular they may cause problems with the construction of a surface gamma-ray log. Concave surfaces can give anomalously high readings since more volume of rock is adjacent to the detector. Conversely, convex surfaces may give lower readings than normal. Wet surfaces will also give lower readings, because the pore spaces are filled with water thereby making the rock "denser" to gamma-rays traveling through it.

Furthermore, the gamma-ray detector will be affected by the adjacent lithologies to a greater extent on vertical sections as opposed to slopes. Finally, slopes are generally weathered, and weathering generally reduces the natural radioactivity of a stratum.

In an attempt to minimize these affects the scintillometer was placed on dry, flat surfaces along a relatively uniform slope. The scintillometer used in this study was borrowed from the New Mexico Bureau of Mines and Mineral Resources. This instrument was calibrated about four years ago, therefore the accuracy of the units may be off, however, the relative readings and general profile should be correct.

Plate 22 shows the surface gamma-ray log plotted together with a simplified version of Colpitts' (1986) stratigraphic section. The vertical scale is the same scale used on most of the well logs in this thesis.

Curiously, the arkosic sandstones do not produce high gamma-ray counts. The fact that they read lower than surrounding mudstones could simply be that the mudstones are even more radioactive than the arkoses, however, the arkoses produce readings as low as non- arkosic sandstones and siltstones of the Abo Formation. This was checked at several locations east of Socorro and the same results were found.

Cappa (1975) did whole-rock x-ray analyses on Abo arkoses of the Cerros de Amado area and unexpectedly found no K-feldspar peaks and fairly good albite peaks. To follow up on this he analyzed a single grain which appeared to be microcline and found it to be of albite composition. Cappa suggests alteration of K-feldspars to albite by sodium-rich waters produced by the dissolution of overlying evaporites. This phenomena doesn't appear to be a local occurrence as high percentages of arkosic drill cuttings commonly coincide with low gamma-ray peaks.

The surface profile also showed the gamma-ray log response to mudstones to be highly variable in the Abo Formation. Typical sandstone or siltstone peaks appear in areas where there are no sandstone or siltstone lithologies. Drill cuttings and wire-line logs indicate that this also occurs in the subsurface.

The anomalous mudstone responses in the Abo Formation could be due to several factors including changes in the degree and/or type of cementation, variations in the relative abundance of potassium bearing clay minerals, variations in the hole diameter and chemical variations in the drilling fluid. Since it also occurs on the surface, drilling mud and hole factors probably aren't a major cause of the irregular responses in the gamma-ray log.

The peculiar gamma-ray log response to mudstones makes picking a shale baseline difficult, however, the surface log suggests that the shale baseline changes through the Abo Formation. The shale baseline appears to go toward lower gamma-ray readings near the base of the Abo section. This changing shale baseline pattern is also seen in subsurface gamma-ray logs within the study area (Plates 3,12,13). The pattern occurs most often when the Abo overlies limestone lithologies which suggests that lower gamma- ray responses are caused by calcite cements.

Volume of shale calculations, as described by Asquith (1982), Helander (1983), Rider (1986) and others, were initially planned for this study, however, the complex mudstone log responses make any results from this method questionable.

Porosity-log crossplots to determine lithology were done on wells that have the appropriate geophysical logs available. The results of the crossplots usually indicated limestone or dolostone lithologies, which is contradictory to lithologies indicated by the corresponding drill cuttings. It is suspected that the various porosity logs were strongly affected by cements in the mudstones, siltstones, and sandstones of the Abo Formation. As a consequence, the lithologies indicated by crossplots are rarely used in this study.

CHAPTER 4

SURFACE ANALYSIS

Surface Stratigraphic Sections

Abo Formation outcrops are very limited in the Lucero region comprising only two to five percent of all the surface lithologies present (Figure 1-2). The Abo frequently weathers to form gentle, rolling hills with poorly exposed outcrops. In the Zuni Mountains, poor exposures make it impossible to measure a complete stratigraphic section, however, exposures east of Socorro and in the Mesa Lucero area are locally of sufficient quality to measure stratigraphic sections of the Abo Formation.

Stratigraphic sections used in this study were measured using a Jacob's staff as described by Compton (1962) and Kottlowski (1965). Classifications used to describe the rocks are shown in Appendix A.

A stratigraphic section measured by Colpitts (1986) is used as a control point in the area east of Socorro (D2 of Figure 1-2). Plate 22 shows a simplified version of the stratigraphy along with a gamma-ray profile drawn to the same scale as the subsurface well logs used in this study. This stratigraphic section was rechecked by Colpitts and the author as the surface gamma-ray profile used in this report was produced.

The base of the Abo Formation as defined in this report differs from that assigned by Colpitts (1986). In his report, Colpitts interpreted the sandstones above the highest Bursum limestone as marine in origin and therefore included them in the Bursum Formation. Because of the limitations of subsurface analysis, the Bursum-Abo contact used in this thesis is placed at the top of the uppermost limestone (presumably marine, but not always definite), and is used for both surface and subsurface sections.

Another stratigraphic section was measured in Carrizo Arroyo, southeast of Mesa Lucero (D1 of Figure 1-2). Plate 21 shows the stratigraphy drawn to the same scale as the subsurface logs used in this study. Appendix D lists the detailed stratigraphy measured in Carrizo Arroyo. Paleocurrents were also measured at this location so that they may be integrated with paleocurrent data from the Zuni Mountains (MacMillan, 1987) and east of Socorro (Cappa, 1975).

Paleocurrent Analysis

Paleocurrent directions were measured from cross-strata sets using methods employed by Cappa (1975) and Lemley (1984). McKee and Weir's (1953) definition of a set is used in this study. They define a set as "a group of essentially conformable strata or cross-strata, separated from other sedimentary units by surfaces of erosion, non-deposition, or abrupt change in character." Scales of sets were classified by the maximum thickness of the cross-strata, with small scale being less than ten centimeters, medium scale being between ten centimeters and one meter, and large scale being greater than one meter.

Thirty paleocurrent measurements were taken from one irregularly bedded sandstone unit near the middle of the Abo section in Carrizo Arroyo (Plate 21). Measurements were from medium and large scale cross-strata which are interpreted as stacked channel fill or bar deposits. Cross-strata morphologies were generally gradational between trough shaped and tabular forms.

Paleocurrents were either directly measured from exposed foreset beds or calculated from apparent dips of foreset beds measured along two or more surfaces. Paleocurrent data collected from Carrizo Arroyo are listed in Appendix B. Measurements were then corrected for regional dip using a stereonet.

The paleocurrent data was plotted in the form of a rose diagram (Figure

4-1) by a computer program written by Daut (1978) and later modified by Lemley (1984). The program also calculates the vector mean and vector strength of the paleocurrent data. The vector mean is the trend of the vector resulting vector addition of all paleocurrent vectors assigned a unit magnitude. Vector strength is a measure of the variability of the data and ranges from zero to one, where one represents absolutely no variation. For a detailed description of statistical methods applied to paleocurrent data of the Abo Formation the reader is referred to Lemley (1984).

The results of paleocurrent analysis of a single sandstone bed of the Abo Formation in Carrizo Arroyo indicate a southward flow direction (Figure 4-1). The vector mean is 179 (S1E) and the vector strength is .56, which is slightly lower than vector strengths of channel sands calculated by Lemley (1984).

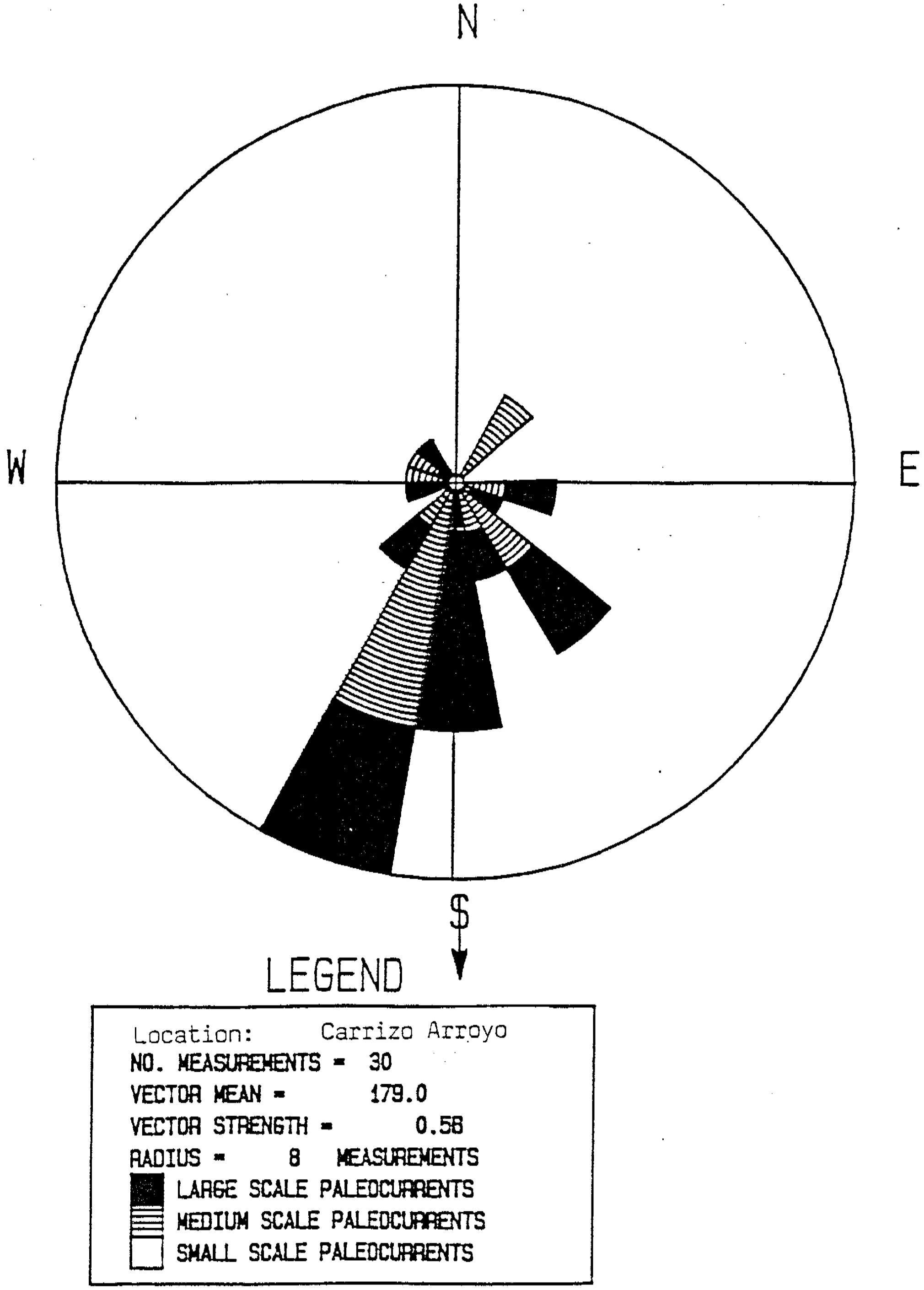


Figure 4-1. Rose diagram of paleocurrent data measured in Carrizo Arroyo, southeast of Mesa Lucero. See Plate 21 for the stratigraphic location of the bed measured.

CHAPTER 5

STRATIGRAPHY

Introduction

As discussed in the previous two chapters, the detailed stratigraphy of the Abo Formation is based primarily on wells with both wire-line logs and lithologic samples and, to a lesser extent, measured stratigraphic sections. The Mitchel and Sons No. 1 Red Lake well (Plate 10) is little used for detailed stratigraphy because wire-line logs and samples are not available for review. The Sun Oil Co. No.1 Plains of San Augustine well also is little used because a portion of the Abo Formation is believed to be missing. The incomplete stratigraphic section is suggested by the anomalously thin Abo section that is bisected by hypabyssal igneous rocks.

Abo Formation Lithologies

In this study, clastic sedimentary rocks are divided into sandstones (including conglomeratic sandstones), siltstones and mudstones. Definitions used in this study are in accordance with those of the American Geological Institute's Glossary of Geology. Mudstones are defined here as they were by Broadhead (1984) to denote a rock in which more than 75% of the detrital grains are of clay and silt size. A silty mudstone contains more silt than clay and an argillaceous mudstone has more clay than silt. Sandstones are detrital rocks composed of at least 25% sand-size grains and less than 5% gravel. A conglomeratic sandstone is a sandstone containing 5-30% gravel. As defined by Pettijohn (1975), a siltstone is an intermediate lithology between a sandstone and a mudstone in which at least two-thirds of the grains are silt-size. This definition will be used for the purpose of this study.

Carbonate sedimentary rocks in the area consist of limestones and dolostones. Limestones are composed of the mineral calcite while dolostones are composed of the mineral dolomite. Many lithologies are reported as being anhydritic. As Broadhead (1984) points out, mineralogies interpreted as being anhydritic may be gypsum and/or hemihydrate as the three minerals are difficult to distinguish with a low power stereoscopic microscope.

Classification systems used in this study are shown in Appendix A. Sandstones are categorized using a classification modified from Dott (1964) while limestones are subdivided using Dunham's (1962) classification. Dunham's mudstone term is referred to as a lime mudstone to distinguish it from a detrital mudstone.

The stratigraphy of the Abo Formation in the Lucero region is shown for numerous wells and the two surface stratigraphic sections in Plates 1-14, 21 and 22. Locations of the wells and stratigraphic sections are shown in Figure 1-2.

Mudstones of the Abo Formation are highly variable in composition and can be calcareous, dolomitic, anhydritic or micaceous (approximately greater than 5% mica). It is very common for the mudstones to compositionally reflect the surrounding lithologies. For example, mudstones stratigraphically near limestones are typically calcareous. In some areas, calcareous mudstones also contain calcareous nodules. The mudstones are generally red to reddish brown in color and locally have pale green reduction spots.

The majority of Abo sandstones are very fine to fine grained and moderately sorted. Individual grains are usually subangular to subrounded. Coarser grained sandstones and conglomeratic sandstones occur locally and are typically poorly sorted with angular grains. Compositions of the sandstones vary from quartz arenites and wackes to arkosic arenites and wackes. The major constituents are quartz and feldspars, which are commonly altered.

Minor constituents include biotite, muscovite and mafic grains. Sandstone cements consist primarily of calcite and dolomite, but also include hematite, anhydrite and silica. Sandstones of the Abo Formation are commonly reddish brown to reddish orange in color.

Siltstones are common in the Abo Formation and appear to be finer grained equivalents of the Abo sandstones. They appear to have the same composition as the sandstones and possess similar cements and colors.

A few thin, discontinuous beds of limestone and dolostone occur locally in the Abo Formation of west-central New Mexico, but are rare. One such bed of limestone is exposed a few miles south of Bluewater Lake, in the Zuni Mountains north of the study area. Within the study area, Abo dolostone beds are present in the Cities Service Oil Co. No. 1A Zuni(Plate 5) and in the Tenneco Oil Co. No. 1 Federal (Plate 2) wells. Limestones are also interpreted to occur in the Mitchel and Sons No. 1 Red Lake well (Plate 10), however, stratigraphic control is poor in this particular well. All the limestones and dolostones of the Abo Formation are microcrystalline and appear to be unfossiliferous.

Subdivisions of the Abo Formation

The Abo Formation of west-central New Mexico has been subdivided in several studies involving the formation on a local scale. In or near the study area, the Abo Formation has been divided either into two units (Cappa, 1975; LaPoint, 1976; Myers, 1977; Tonking, 1957) or three units (Hatchell, et al., 1982).

Cappa (1975) divided the Abo Formation of the Cerros de Amado area into a lower unit of arkosic sandstones and conglomerates with minor mudstones, and an upper unit of interbedded sandstones, siltstones and mudstones. In a study of the Puertocito Quadrangle, Tonking (1957) divided the formation into a lower unit of interbedded siltstones, mudstones, arkoses and limestone pebble conglomerates overlain by an upper unit of feldspathic sandstones and siltstones. Myers (1977) used similar subdivisions when mapping the Scholle Quadrangle, where the type section is located. In a study of sandstone copper deposits, LaPoint (1976) divided the Abo Formation at the Blue Star Mine, near Scholle, into a lower copper-bearing unit and an upper "copperless" unit.

Hatchell et al. (1982), working at the Abo type section, divided the formation into three units; a lower arkosic unit, a middle mudstone unit and an upper sandstone and siltstone unit. Broadhead (1983a, 1984) and Speer (1983) also used three unit separations further east, over and east of the Pedernal uplift.

On a regional scale, the Abo Formation can easily be divided into two units in the eastern half of the study area. There the Abo Formation consists of a lower dominantly mudstone section overlain by section consisting primarily of sandstones and siltstones (Plates 3,4,8,11-14,21,22).

A threefold division of the Abo Formation in the eastern half of the Lucero region is a little more difficult. A problem arises in the definition of the lower unit. Typically the lower unit of a three unit system is dominated by coarser grained arkosic sandstones and conglomerates. Near the eastern edge of the study area, Cappa (1975) reported a lower arkosic unit which is characteristic of the "classic" lower Abo unit or member. The Abo Formation in Colpitts's (1986, Plate 22 of this report) study area also has some coarse grained arkosic sandstones and conglomerates low in the section, but there is also a considerable amount of very fine grained sandstone and siltstone present. Further west, in the Richard King Jr. No. 1 Wilson Heirs well (Plate 14) and in the stratigraphic section measured near Mesa Lucero (Plate 21) the lower Abo consists of mudstones, siltstones and very fine to fine grained, arkosic and nonarkosic sandstones.

The question arises as to whether the lower lithologies of the Abo Formation shown in Plates 14, 21 and 22 are to be considered correlatable to the "lower Abo unit" of Cappa or not. If so, then there is considerable change in the nature of the lower Abo unit. If this is not the lower Abo unit then it must represent a change in the character of the lower portion of the middle Abo unit of a three unit system.

In the western portion of the study area the nature of the Abo Formation is quite different. There, sandstones and siltstones are uniformly present throughout the formation (Plates 1,2,5-7). The mudstone unit which would represent either the middle unit of the three unit system or the lower unit of a two unit system is notably missing.

In applying the three unit system, the upper unit would be interpreted as directly overlying the lower unit. In the Tenneco Oil Co. No. 1 Federal (Plate 2), Huckleberry No. 1 Federal (Plate 6) and Spanel and Heinze No.9617 SF-P (Plate 7) wells, the contact between upper and lower units can be placed above the highest conglomeratic sandstone. Picking the contact in the Tiger Oil Co. No. 1 Unit H State well (Plate 1) is much more difficult. Conglomeratic sandstones are scattered throughout the formation, however, nonarkosic and arkosic, very fine to fine grained sandstones also occur throughout the formation. In the Cities Service Oil Co. No. 1A Zuni well (Plate 5) sandstones throughout the section are very fine to fine grained with no coarse grained or conglomeratic sandstones present at all. The stratigraphic section in this well would classically be interpreted as only representing the upper Abo unit.

The main purpose for subdividing the Abo Formation would be to separate sections of the formation which are interpreted as representing different depositional environments, however, this may be very difficult to do near the Zuni Uplift. For example, the lower Abo unit, of the three unit system, is usually interpreted as a deposit from a high energy alluvial fan or braided stream system with sediments coming from nearby Precambrian crystalline rocks (Broadhead, 1983a, 1984; Hatchell et al., 1982; Speer, 1983). Typically these sediments are coarse grained sandstones and conglomerates, however, if the crystalline rocks are of a lithology which weathers to form fine grained sediments, then a section of the Abo Formation may be misinterpreted as the upper Abo unit when it actually represents the depositional environment of the lower Abo unit.

The Precambrian lithologies vary considerably over the Zuni Uplift (Plates 2,5,6,7,9) and would be expected to affect the composition and texture of the lower Abo lithologies. This may be the cause of the basal fine grained lithologies present in the Zuni A-1 well (Plate 5).

Because of the problems discussed above, it is very difficult to accurately subdivide the Abo Formation on a regional scale in west-central New Mexico and therefore is not attempted in this study. Instead, general trends of the Abo Formation, which in some cases may be viewed as units, are noted for various portions of the study area without placing distinct boundaries on units and without attempting to correlate boundaries across the Lucero region.

General Trends

As mentioned above the Abo stratigraphy of the eastern portion of the study area differs from that of the western portion. Most notably the Abo Formation is thicker to the east and south, and thins to the west-northwest (Figure 2-7). In the western portion of the study area, sandstones and siltstones are much more prevalent than they are further east (Plates 1,2,5,6,7). There are no thick mudstone sections present in the western region as is common to the east. Conglomeratic sandstones, to the west, are generally concentrated in the basal section of the formation (Plates 2,6,7), but may extend far up the section (Plate 1) or not occur at all (Plate 5).

In the eastern portion of the study area, the Abo Formation is characterized by a lower mudstone-rich section overlain by a sandstone and siltstone-rich section (Plates 3,4,8,11-14,21,22). Locally the basal Abo Formation contains sandstones and siltstones (Plates 14,21,22), but usually thick mudstone sections directly overlie Bursum or Pennsylvanian limestones (Plates 3,4,8,11-13). In outcrops, conglomerates are most common in channel lag deposits which comprise only a minor portion of all the sandstones and siltstones present. There is no apparent trend or pattern to the occurrence of arkosic sandstones either vertically or laterally in the Abo Formation within the study area.

Figure 5-1 shows the sandstone plus siltstone to mudstone ratios for the Abo Formation in the Lucero region. In the west-northwest portion of the study area, sandstones and siltstones dominate the Abo stratigraphic section by almost four to one over mudstones. Mudstones become more prevalent to the southeast with sandstone plus siltstone to mudstone ratios as low as one to four.

The trend observed in Figure 5-1 is largely a reflection of the presence of the mudstone-rich, lower portion of the Abo Formation in the eastern Lucero region. However, it should be noted that the uppermost Abo in the Cities Service Oil Co. No. 1A Zuni well (Plate 5) also contains less mudstone then the upper portions of the Abo seen in any of the eastern wells. Thus, the trend of increasing sandstone and siltstones to the northwest is not totally skewed by thick mudstone sections in the lower Abo Formation of the eastern Lucero region.

There also appears to be a trend along the eastern third of the study area from higher sandstone and siltstone content in the north to higher mudstone

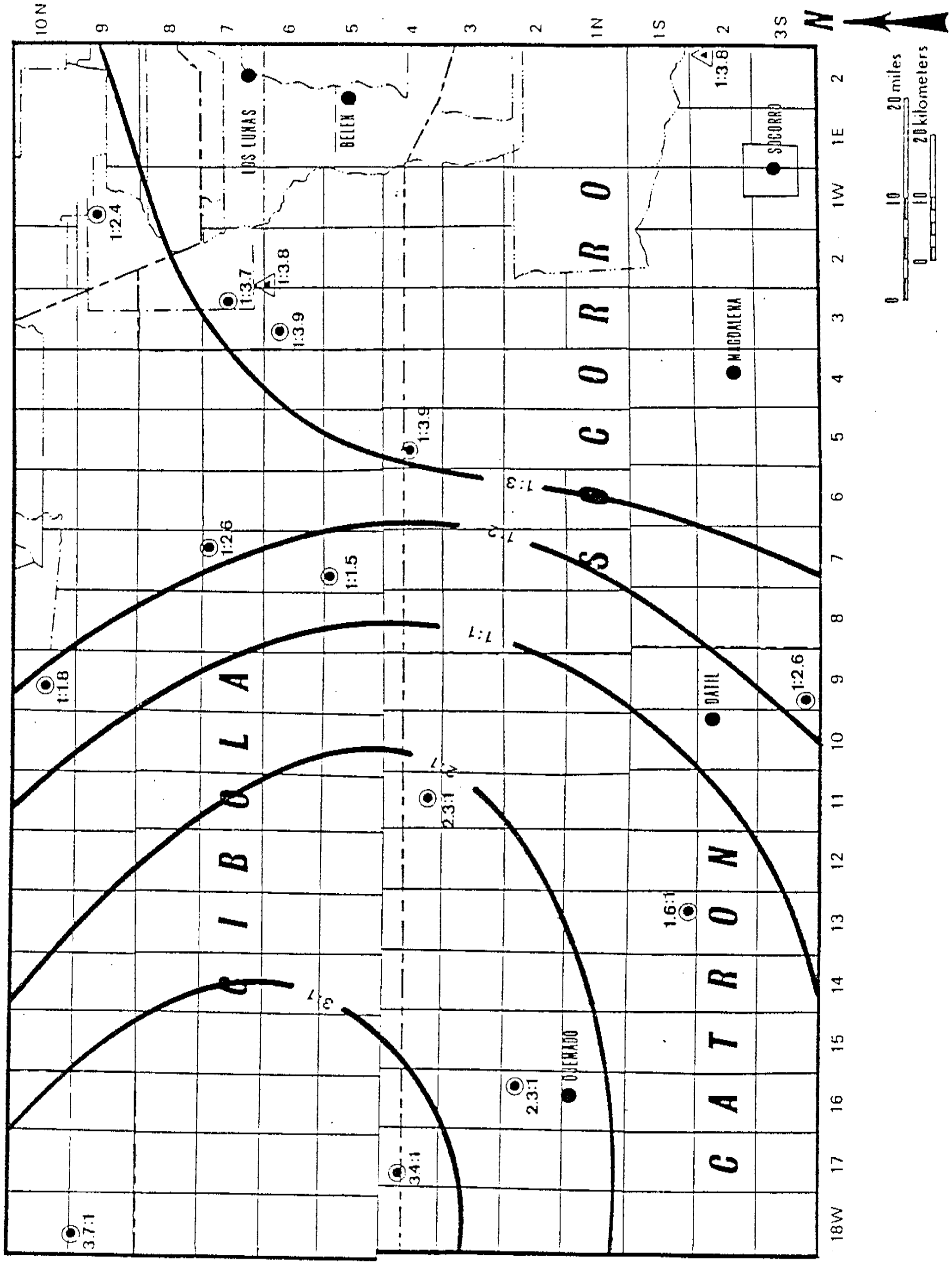


Figure 5-1. Sandstone plus siltstone to mudstone ratio map.

content to the south. Within the study area this trend is based solely on a higher sandstone plus siltstone to mudstone ratio in the Shell Oil Co. No. 1 Laguna Wilson Trust well (Plate 4), however, based on sample logs, this trend appears to continue further north as well.

Detailed percentage and interpretive logs (on file at the New Mexico Bureau of Mines and Mineral Resources petroleum records library) of the Texaco No. 1 Howard Major (Sec. 10, T13N, R3W), Brinkerhoff Drilling No. 1 Cabezon-Government (Sec. 7, T17N, R3W), Shar-Alan Oil Co. No. 1A Jicarilla (Sec. 18, T23N, R2W) and the Continental Oil Co. No. 1 South Duke (Sec. 6, T28N, R2W) wells indicate the Abo (Cutler) Formation becomes sandier to the north. These logs also show that sandstones and siltstones become more common lower in the Abo stratigraphic section to the north. This trend could not be checked south of the study area due to a lack of wells.

CHAPTER 6

LOG CURVE SHAPE ANALYSIS

Introduction

The analysis of the subsurface stratigraphy of the Abo Formation is based on the combined analysis of wire-line logs and drill cuttings. Because of the nature of drill cuttings, intrabed resolution is very poor, thereby making interpretations of depositional environments difficult. Log curve shape analysis is a method that could provide some intrabed information on sandstones and siltstones of the Abo Formation.

Log curve shape analysis was first used as a purely geometric classification of log peaks used to aid in the correlation of units (Rider, 1986). Now it is commonly used to determine vertical grain size trends in subsurface detrital units, from which subenvironments or environments of deposition can be inferred. The theory of log curve shape analysis and it's uses is discussed by numerous authors including Allen (1975), Cant (1984), Galloway and Hobday (1983), Pirson (1977), Rider (1986) and Selley (1978).

Most of the earlier discussions on the use of log curve shapes are overly simplistic and frequently correlate shapes directly to a few, oversimplified depositional environments. For an exceptional critical review of log curve shape analysis, the reader is referred to Rider (1986). The theory section of this chapter is basically a summary of Rider's discussion.

Log curve shapes have been classified into general forms which theoretically represent various grain size trends. Figure 6-1a shows the general forms and depositional settings of which they are indicative. These general forms can be described further by several specific factors such as the nature of the contacts and curve characteristics (Figure 6-1b).

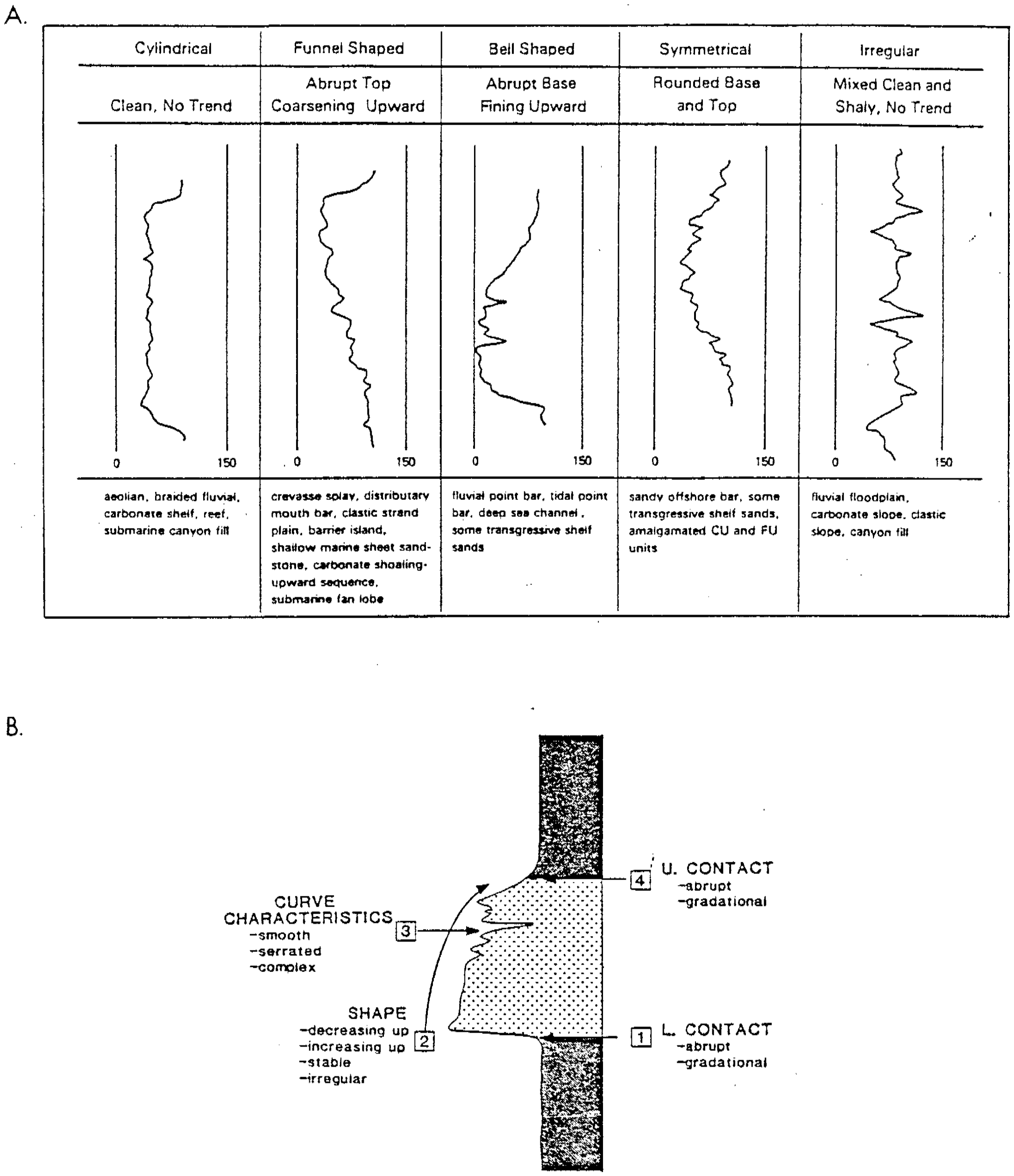


Figure 6-1. Log curve shape classification and description. (A) General forms and at least some of the depositional settings in which they can originate (From Cant, 1984). (B) Specific independent elements used along with overall shape (From Rider, 1986).

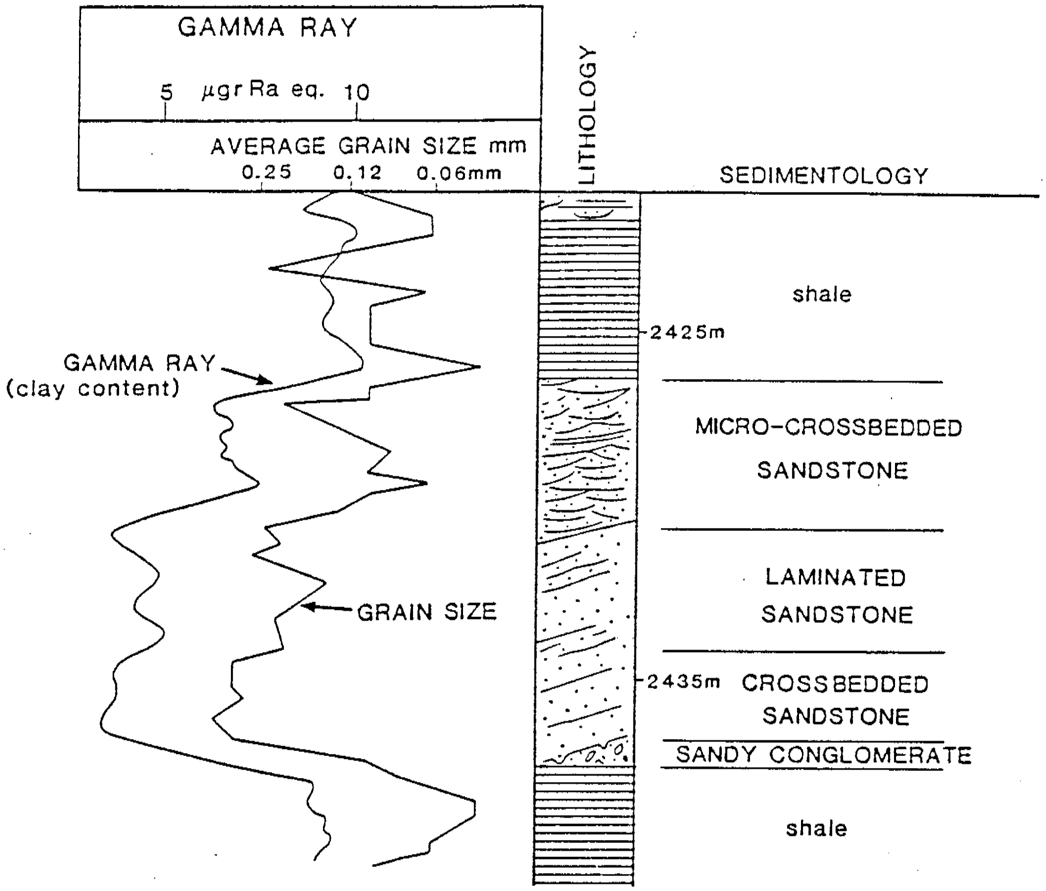
Initially, log curve shape analysis was done using the SP log because it generally responds to grain size variations. More recently, the gamma-ray log has been favored over the SP log because it shows more detail and generally has more "character" (Cant, 1984; Rider, 1986). Resistivity logs have also been used to aid in the analysis in situations where gamma-ray or SP logs are indistinct (Allen, 1975; Galloway and Hobday, 1983; Pirson, 1977). Since the gamma-ray log is the most commonly used wire- line log in log curve shape analysis, the following discussion will be based on it, however, the discussion would be very similar if SP logs were used.

Theory

As mentioned above, log curve shape analysis is based on grain size trends. Very often the gamma-ray log's responses closely mimic grain size variations in clastic sedimentary rocks (Figure 6-2). However, the gamma-ray log does not directly measure grain size. In sandstone-mudstone sequences the gamma-ray log usually reflects changes in clay content. Thus in using log curve shape analysis clay content must be assumed to be directly related to grain size.

Figure 6-3a shows the relationship between clay content and grain size for an alluvial sandstone (the Molasse) and a well-winnowed marine sandstone (the Dogger Beta). The two examples are extremes between which most sandstones lie (Pettijohn et al., 1972). The diagram indicates that clay content can vary from having a strong (the Molasse) to a weak (the Dogger Beta) dependence on grain size.

Figure 6-3b demonstrates a similar trend on a plot of quartz content versus grain size. Non-quartz elements include feldspar, rock fragments, clay matrix and accessories minerals. Along with clay, many of the constituents could potentially produce "shaley" readings on the gamma-ray log. The diagram shows a generally linear decrease in the non-quartz fraction as grain



TRIASSIC FLUVIATILE SAND BODY - POINT BAR

Figure 6-2. Gamma-ray log and corresponding core through a Triassic fluviatile sand body in the Sahara. The gamma-ray log (reading clay content) nearly parallels grain size (From Rider, 1986; after Serra and Sulpice, 1975).

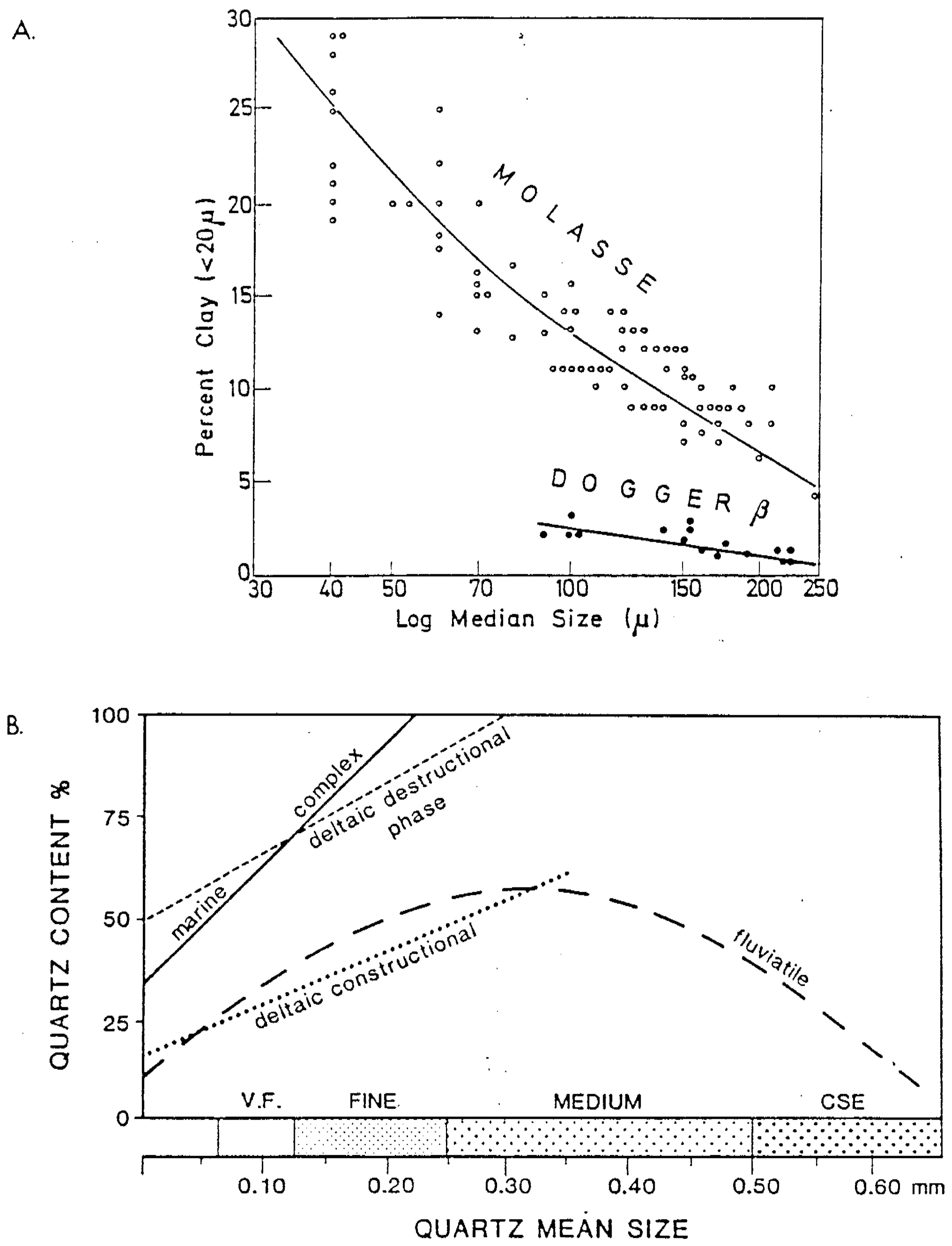


Figure 6-3. Diagrams of sandstone and siltstone composition versus grain size. (A) Clay content versus grain size for an alluvial sandstone (the Molasse) and a marine sandstone (the Dogger Beta) (From Pettijohn et al., 1972). (B) Quartz content versus grain size (From Rider, 1986: after Davies and Ethridge, 1975). Non-quartz constituents include feldspar, rock fragments, clay and accessories; constituents which commonly contain high quantities of radioactive elements.

size increases up to medium grained sandstones. In fluviatile environments this trend reverses from medium to coarse grained sandstones. This could be a source of misleading log curve shapes in coarse grained sandstones.

The relationship between grain size and gamma-ray reading is shown for two differing environments in Figure 6-4. The deltaic environment shows good separation of grain size classes and would produce log curve shapes that would accurately reflect grain size trends. Contrary to the deltaic environment, the marine environment plot shows extensively overlapping gamma-ray fields for the different grain size classes. This example could produce log curve shapes that would incorrectly represent grain size trends.

Rider (1986) attributes the differences in the relationships between clay content and grain size to hydraulic regimes present in the different depositional environments. Furthermore, he suggests that depositional flow which produces poorly winnowed sediments should generally produce accurate log curve shapes, with the possible exception of coarse grained sandstone deposits (Figure 6-3b).

As discussed in Chapter 3, other factors can also affect the gamma-ray log. Sandstones can produce "mudstone-like" readings and mudstones can produce "sandstone-like" responses on gamma-ray logs.

In conclusion, the approach to log curve shape analysis of much of the published literature is overly simplistic. The logs used (gamma-ray or SP) are assumed to reflect grain size variations when they actually reflect clay content in detrital sedimentary rocks. Occasionally the logs are adversely affected by sandstone or siltstone mineralogies or borehole factors which make the logs poor clay indicators. Even in situations where the logs are good clay indicators, clay content may not directly correspond to grain size. Thus, when using log curve shape analysis, the logs should be tested against known grain size variations to see if the response accurately reflects the physical changes. This is

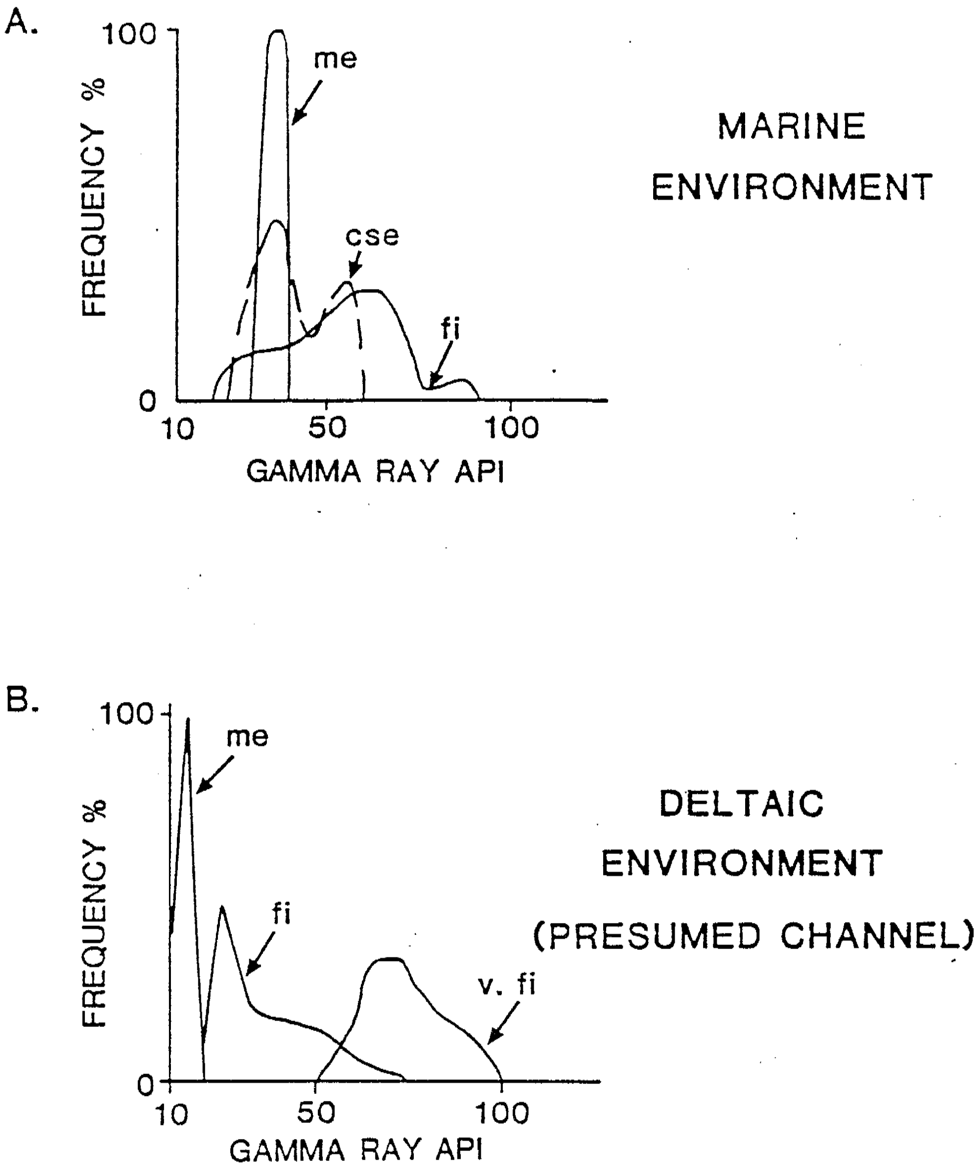


Figure 6-4. Grain size versus gamma-ray reading for (A) marine sandstones and (B) deltaic sandstones. The marine sandstones show considerable overlap of the grain size classes while the deltaic sandstones show excellant separation of classes. Average grain size measured in thinsections: cse=coarse, me=medium, fi=fine, v. fi=very fine (From Rider, 1986).

usually done by comparing log curve shapes against cores from the same interval.

Log Curve Shape Analysis of the Abo Formation

As mentioned in Chapter 3, there are no cores of the Abo Formation available from wells within the study area. To test log curve shapes through known grain grain size variations, log curve shapes of surface gamma-ray logs were tested against known grain size changes in exposed channel sandstones and siltstones (Figures 6-5 and 6-6). The surface gamma-ray logs were produced using the same methods described in Chapter 3, but readings were taken at one foot intervals to increase the detail of the log.

The two outcrops consist of siltstone point bar deposits overlying intermixed very fine and coarse grained sands and conglomeratic channel lag deposits. In one outcrop the channel lag deposits are arkosic (Figure 6-5), while in the other outcrop they are non-arkosic (Figure 6-6). The point bar deposits are fairly uniform siltstones, which megascopically do not appear to show much grain size variation. In both cases the log curve shapes would traditionally be interpreted as representing coarsening upwards sequences when they are actually fining upwards sequences.

In the Abo Formation the relationship between clay content and grain size doesn't seem to favor log curve shape analysis. The coarser grained channel lag deposits are poorly sorted and appear to contain more clay matrix than the overlying siltstones.

The composition of the coarser grained sandstones may also adversely affect gamma-ray log responses. Some of the coarse grained sandstones are arkosic. In Chapter 3 it is stated that arkosic sandstones of the Abo Formation produce gamma-ray log responses similar to non-arkosic sandstone, how-

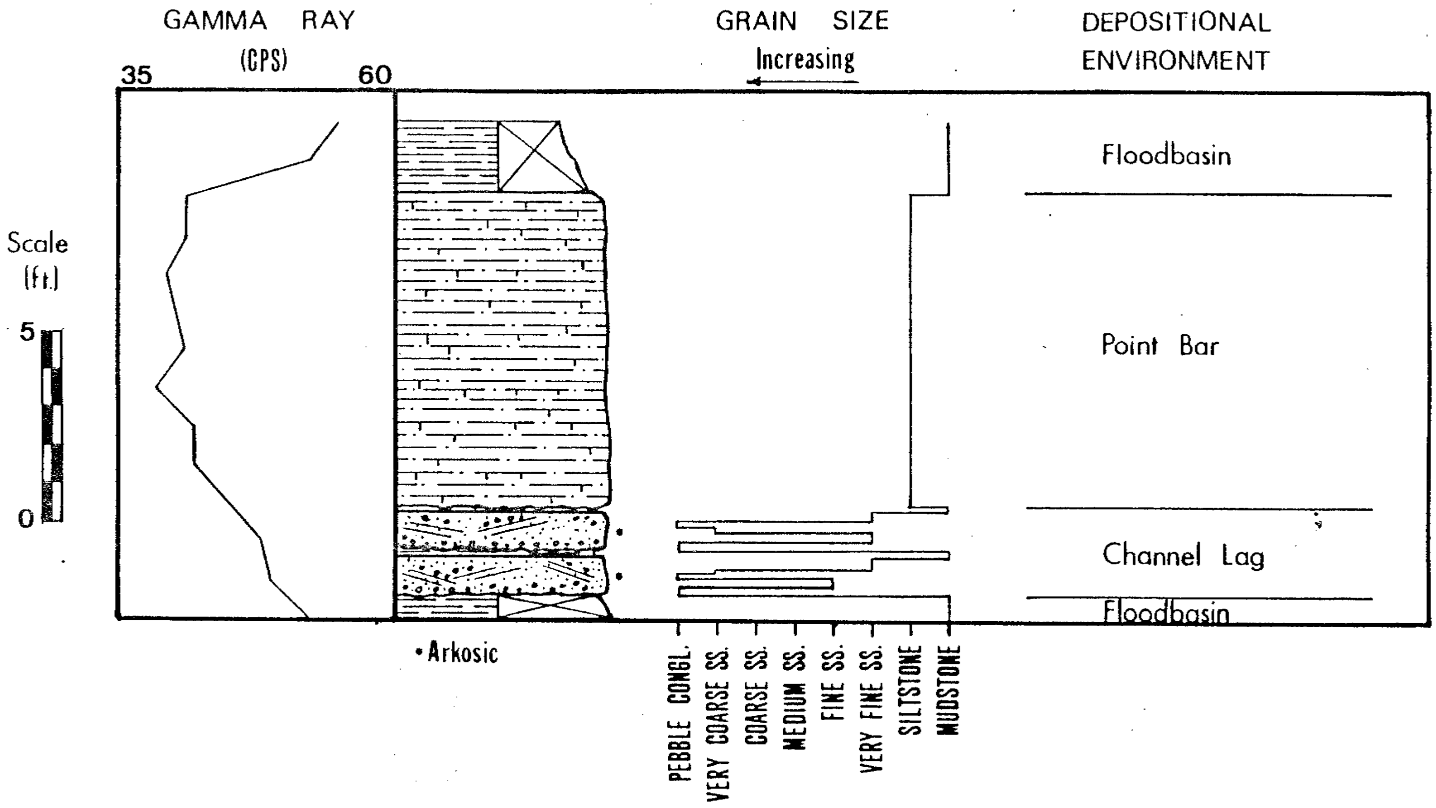


Figure 6-5. Gamma-ray versus grain size through an Abo channel exposed in Canoncito de la Uva, east of Socorro.

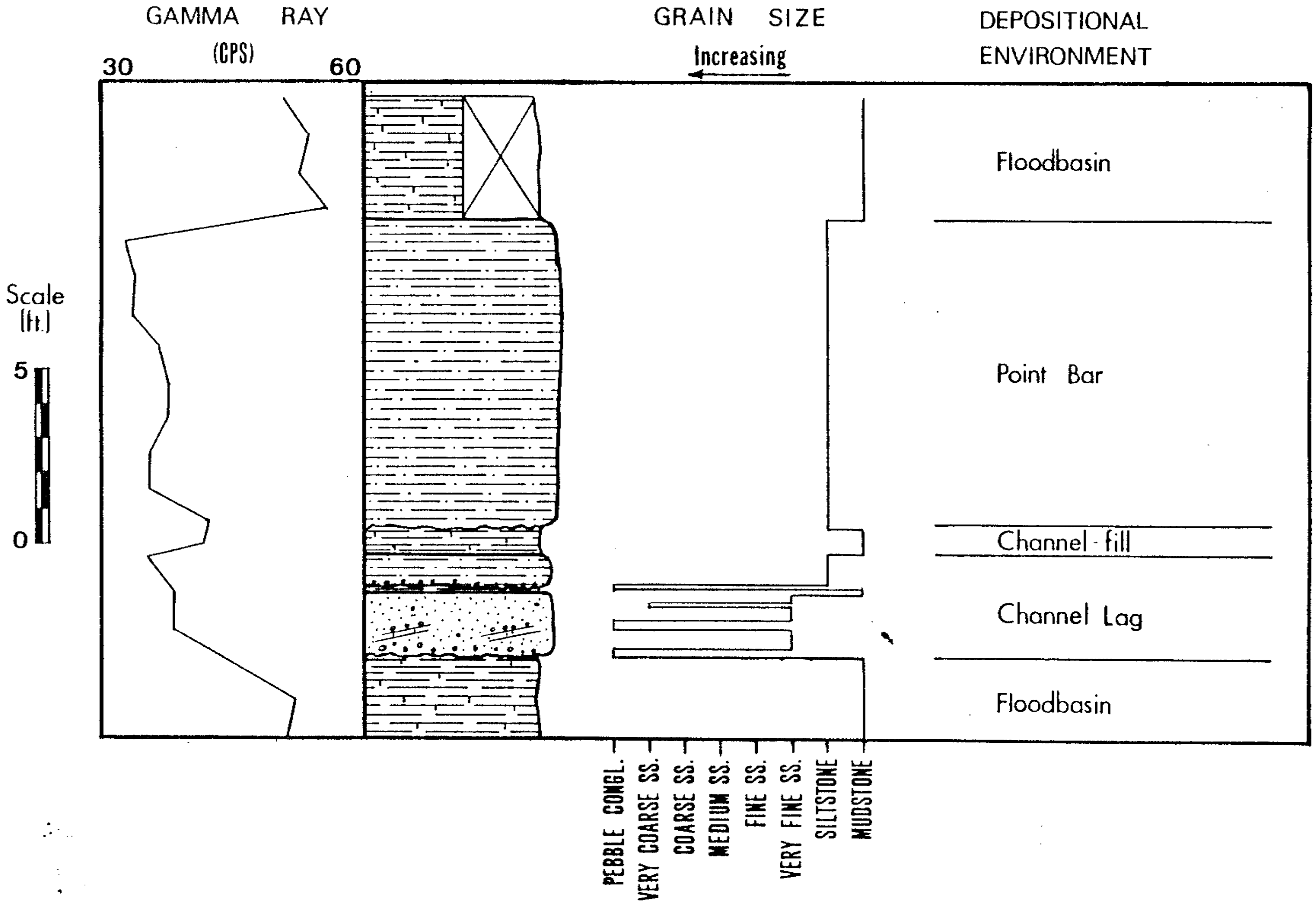


Figure 6-6. Gamma-ray versus grain size through an Abo channel exposed in Arroyo Tinajas, east of Socorro.

ever, when arkosic and non-arkosic sandstones are adjacent to one another they may differ enough to produce inaccurate log curve shapes. Although arkosic sandstones don't read like mudstones they may read slightly different from readings in non-arkosic sandstones. Furthermore, conglomeratic sandstones in the channel lag deposits of the Abo Formation frequently contain apparent intraclasts of siltstone and mudstone compositions which could also produce erroneously "fine-grained" readings on a gamma-ray log.

Finally, mudstones of the Abo Formation vary enough to produce changes in the "shale-baseline" on the gamma-ray log (Plate 22). If these variations are caused by changes in cementation or changes in clay composition, similar variations may be taking place in sandstone or siltstone beds of the Abo Formation. These changes could produce log curve shapes which may inaccurately be interpreted as grain size trends.

Because of the apparent relationship between clay content and grain size, and variations in sandstone, cement and perhaps clay compositions, log curve shapes are not considered a reliable indicator of grain size trends in the Abo Formation. Any interpretations based on log curve shapes will be equally unreliable and therefore log analysis is not considered further in this study.

CHAPTER 7

DEPOSITIONAL ENVIRONMENT

Introduction

As mentioned in chapter 1, previous workers have interpreted the Abo Formation to be of fluvial origin. Deposition of the Abo Formation is largely controlled by Pennsylvanian structural elements (Kottlowski and Stewart, 1970, McKee, 1967). Figure 7-1 shows the Pennsylvanian structural elements in New Mexico. Pennsylvanian highlands within the study area include the Zuni and Joyita uplifts. The major center of deposition is the Lucero basin. Although it contains a thick Pennsylvanian section, Martin (1971) concluded that the Lucero basin was never a deep bathymetric basin during Pennsylvanian time. This also appears to be the case during early Permian time as the Abo Formation doesn't show drastic thickening over the basin (Figure 2-7).

Paleotopography is difficult to reconstruct because of the lack of definite depositionally horizontal marker beds. Figures 7-2, 7-3 and 7-4 show cross sections of the Abo Formation and adjacent units with the top of the Meseta Blanca used as a horizontal datum. The top of the Meseta Blanca is used because the contact with the underlying Abo Formation is conformable and the overlying carbonate beds are probably as close to depositionally horizontal as any other distinguishable, regional marker beds or contacts.

Although the depositional gradients may not be accurate, the east-west cross sections do show the Abo Formation covering and sloping off the flanks of the Zuni uplift (Figures 7-2, 7-3). The north-south cross section, which is generally parallel to the Zuni uplift, shows no trend (Figure 7-4). Intrusives, such as the one in the Sun Oil Co. No. 1 Plains of San Augustine Unit well, may be fairly common in the southern portion of the study area, because it lies in the northern end of the Datil-Mogollon volcanic field.

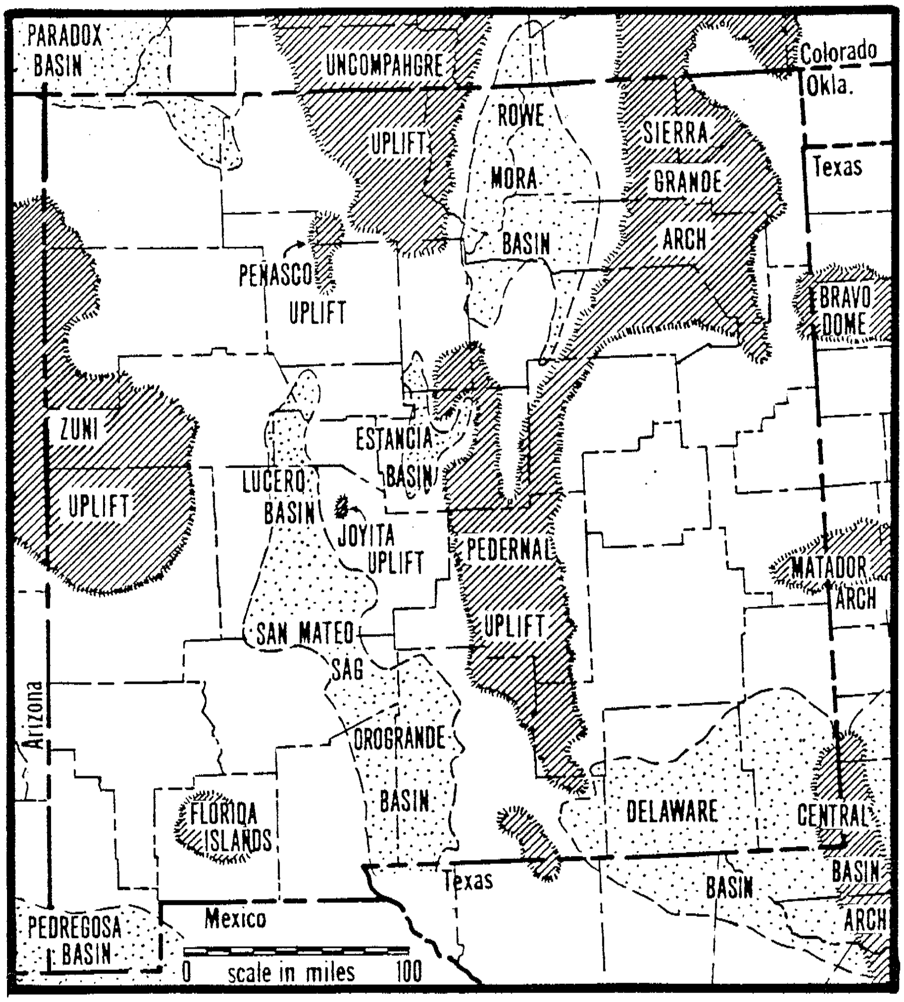


Figure 7-1. Pennsylvanian uplifts and basins of New Mexico (Modified from Kottlowski and Stewart, 1970; Martin, 1971).

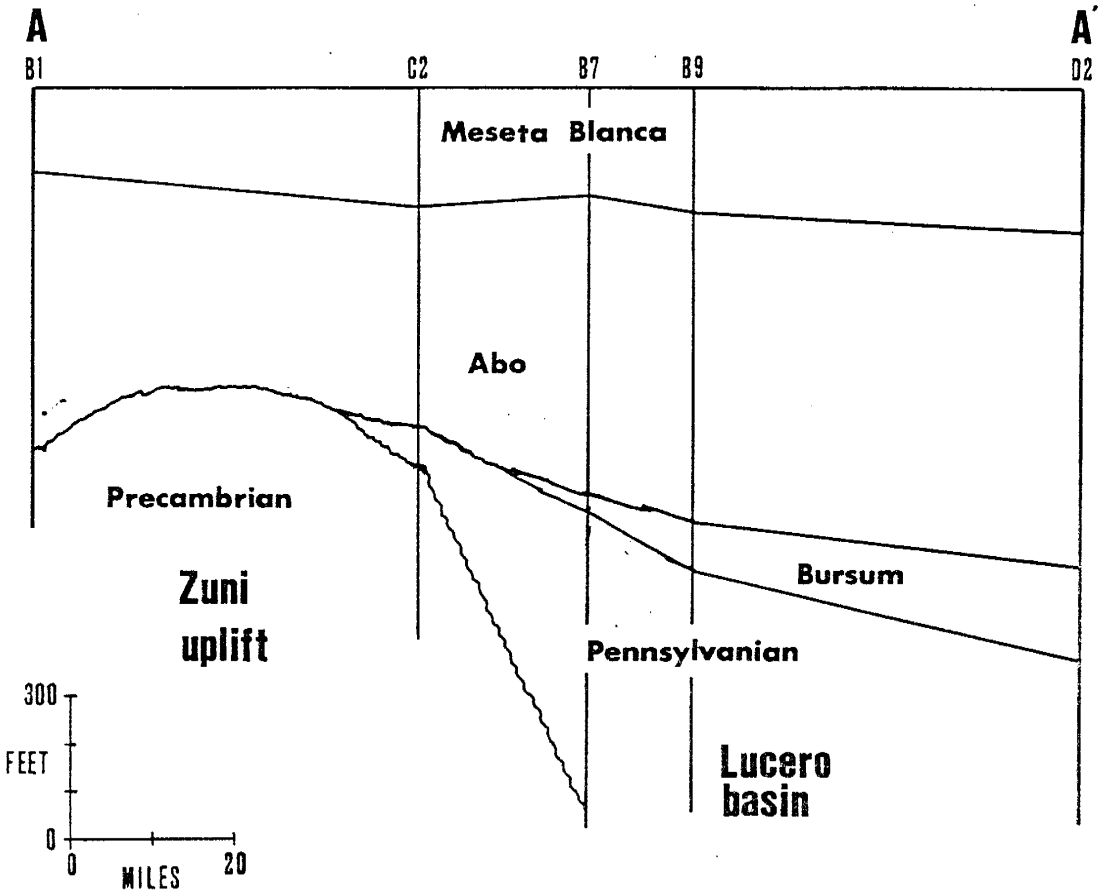


Figure 7-2. East-west cross section from the Zuni uplift to the Lucero basin. See Figure 1-2 for locations; well numbers refer to the numbers used in Figure 1-2 and Table 1-1.

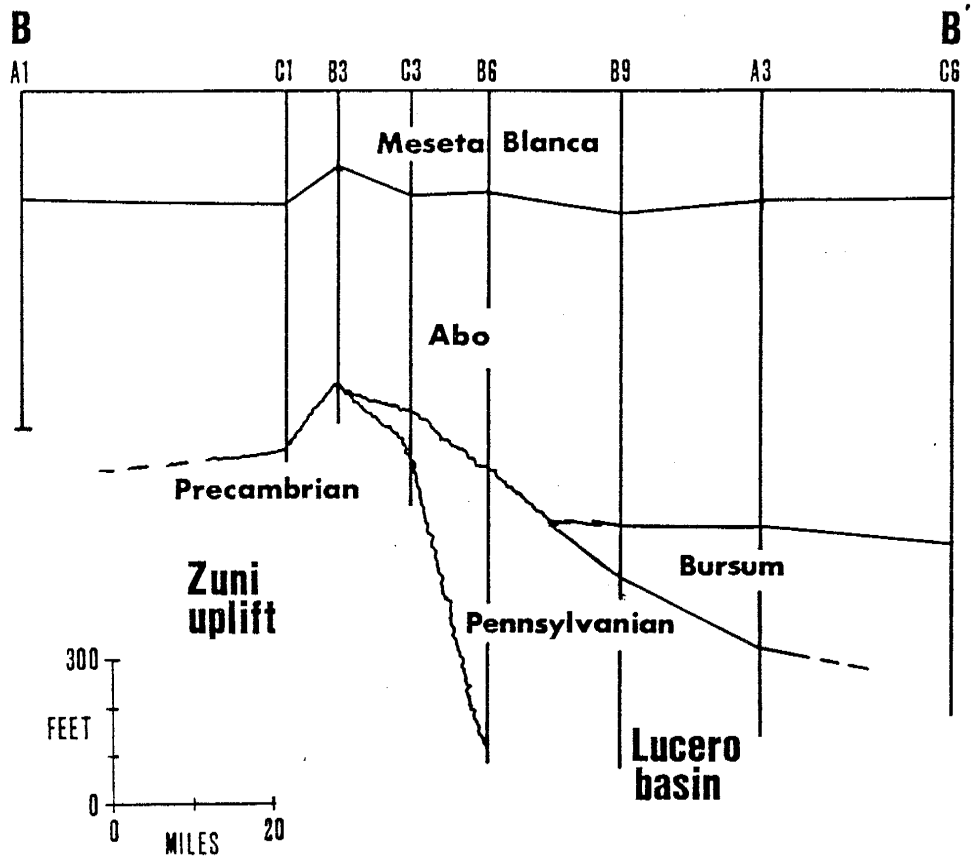


Figure 7-3. East-west cross section from the Zuni uplift to the Lucero basin. See Figure 1-2 for locations; well numbers refer to the numbers used in Figure 1-2 and Table 1-1.

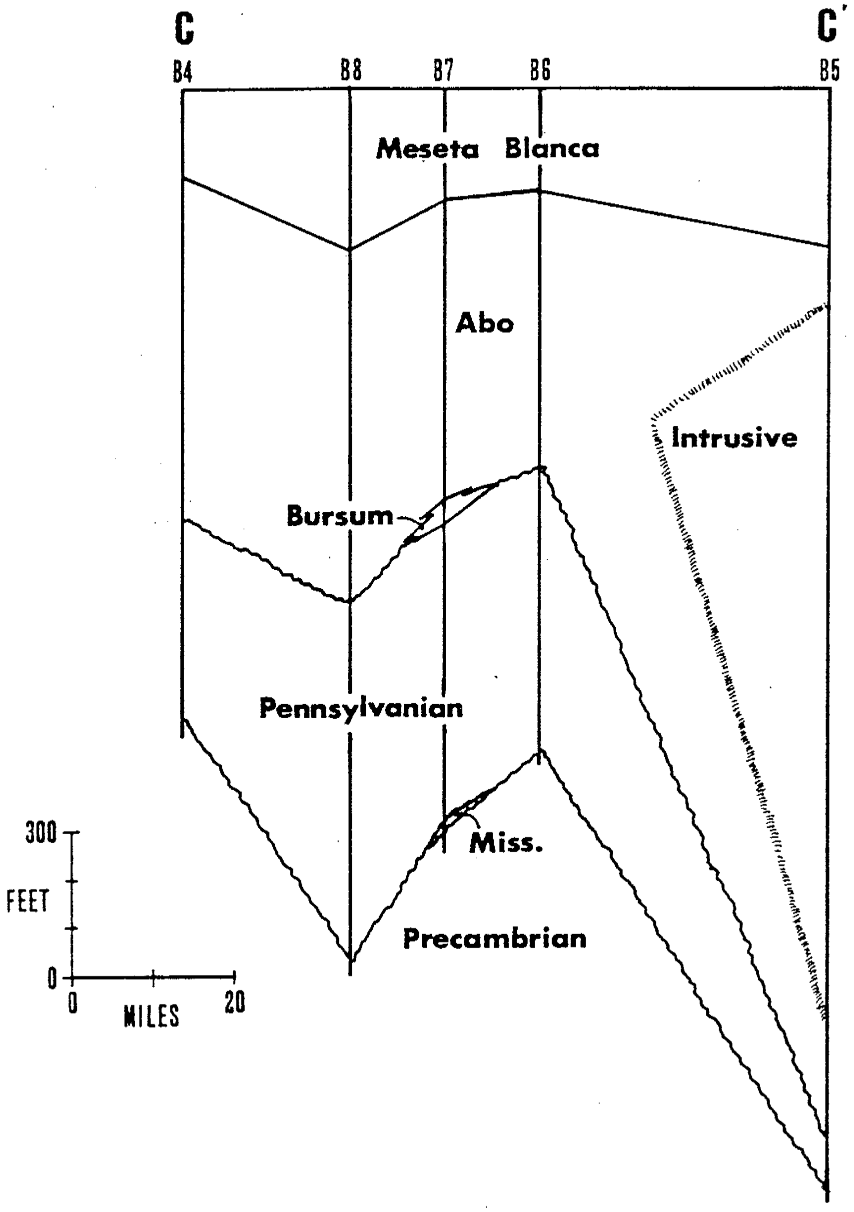


Figure 7-4. North-south cross section parallel to the eastern edge of the Zuni uplift and the Lucero basin. See Figure 1-2 for locations; well numbers refer to the numbers used in Figure 1-2 and Table 1-1.

Abo Formation Depositional Environments

Figure 5-1 shows a dramatic increase in the percentage of sandstones and siltstones in the Abo Formation over the Zuni uplift. This increase suggests that the Zuni uplift was a major source of sediment during Abo deposition. The eastern half of Figure 5-1 also shows an increase in sandstones and siltstones to the north. As discussed in Chapter 5, this northward coarsening of the Abo Formation has been verified north of the study area. Eventually the Abo grades northward into considerably coarser grained clastics of the Cutler Formation of northern New Mexico and southern Colorado.

Foster (personal communication 1986), working north of the study area, noticed an increase in arkosic sandstones up-section in the Abo Formation. In order to explain this trend, he proposes an increase in the regional gradient throughout northern New Mexico and southern Colorado during deposition of the Abo Formation. By increasing the gradient from the source area, more immature sediments can be transported farther away. Foster suggests that the increase in the gradient is due to large-scale progradation of the fluvial clastic wedge produced by sediments shed from the Uncompahgre uplift (Figure 7-5).

The eastern portion of the study area is best suited to investigate large-scale regional trends because it is farther away from the Zuni uplift, which undoubtedly influenced deposition in the area. As previously stated in Chapter 5, there are no trends in the occurrence of arkosic sandstone in either the eastern or western portions of the study area. There is, however, a general trend of increasing grain size from the lower to upper portions of the Abo Formation in the eastern Lucero region.

Galloway and Hobday (1983) describe basin-filling as occurring in one of three ways; (1) aggradation, (2) progradation and (3) lateral accretion (Figure 7-6). The grain size trend in the eastern portion of the study area is consistent

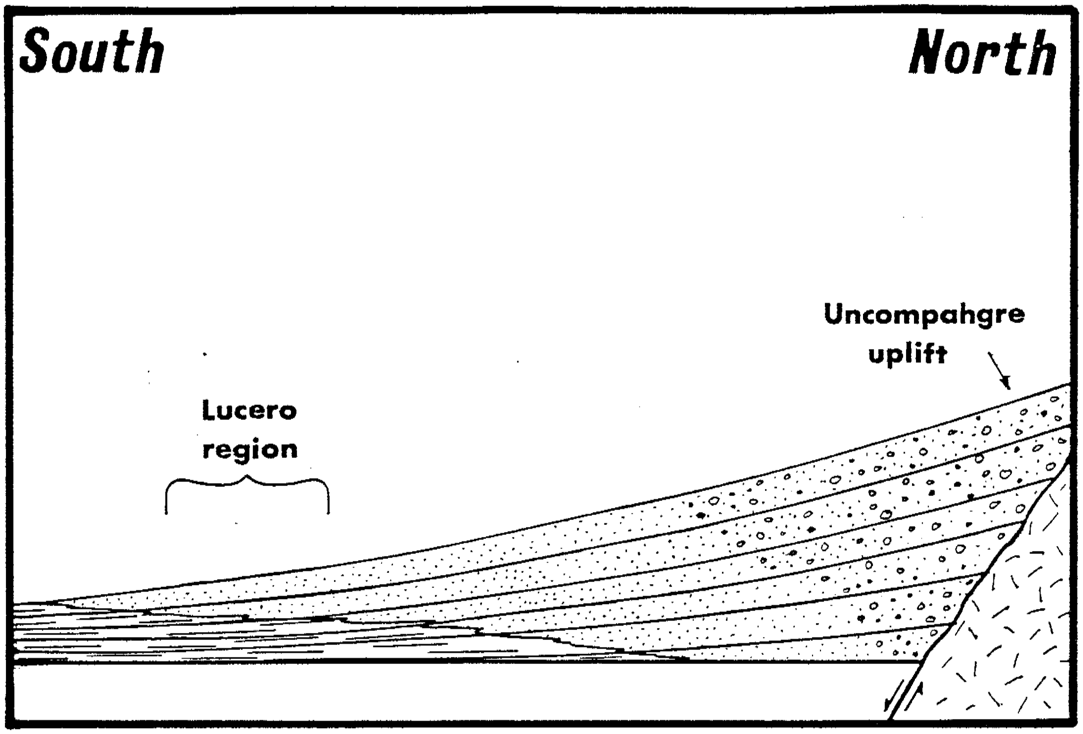
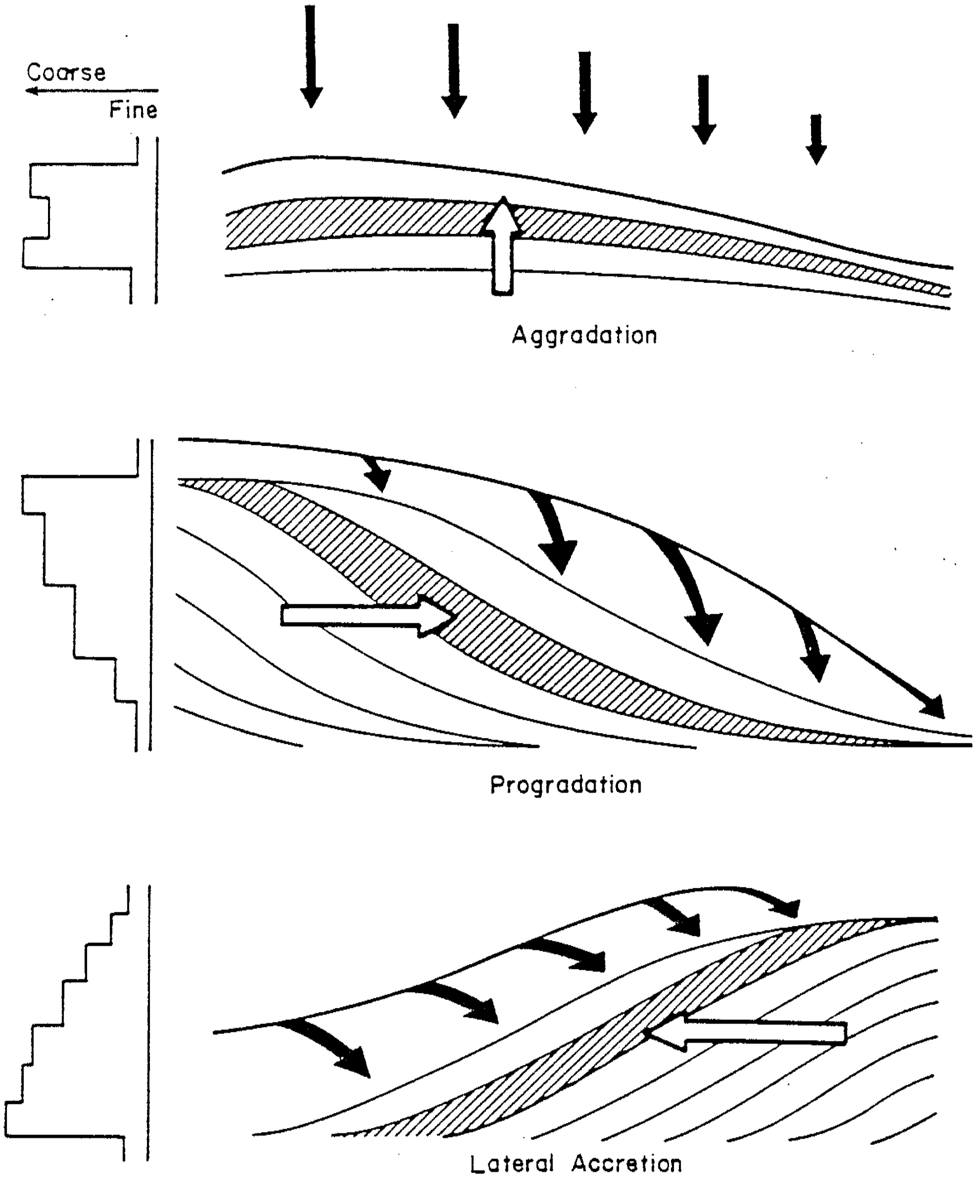


Figure 7-5. Schematic diagram of the large-scale, prograding alluvial fan model proposed by Foster (personal communication 1986). An increasing gradient enables relatively coarser and more immature sediments to be transported further away from the Uncompahgre uplift.



Aggradation

Progradation

Lateral Accretion

Figure 7-6. Three basic processes of deposition in sedimentary basins and the vertical grain-size profiles they produce (From Galloway and Hobday, 1983).

with that of a progradational depositional system.

Although there are no arkose trends as has been described by Foster (personal communication 1986), the grain size trend of the eastern Lucero region indicates a depositional process which is consistent with that proposed by Foster. Furthermore, the stratigraphic trend of the eastern portion of the study area has been found to be consistent with trends observed north of the study area and, therefore, probably reflect a greater influence of regional processes, with only minor influence from the Zuni or Joyita uplifts.

The predominant mudstone section of the lower Abo overlying deltaic deposits of the Bursum Formation (Kues and Kietzke, 1976), in the eastern Lucero region, suggests deposition in a broad, flat coastal plain environment. Locally there are coarse- grained clastics, suspected to be braided stream deposits, in the basal Abo of this area. Presumably they are from either the Joyita uplift (Cappa, 1975) or eastern sources (Lemley, 1984). The general lack of sandstones and siltstones over much of the eastern Lucero region suggests there were few channels dissecting large floodbasins. Surface exposures show few or no channels in this portion of the Abo stratigraphic section. The thick red mudstone section reflects aggradation of the floodbasin, probably in response to a rising base level. Calcareous nodules in the mudstones are pedogenic and indicate a semi-arid to arid environment (Pettijohn, 1975).

It is very difficult or impossible to determine whether flow in the Abo fluvial system was perennial or ephemeral. Likewise, it is also difficult to estimate sinuosity of the few channels of the lower Abo Formation of the Lucero region. A low gradient would usually imply meandering or tortuous channel patterns, however, this may not be the case.

Wells (1983) describes similar low gradient, sand poor, fluvial red beds of the Eocene Kuldana Formation as possessing wide, shallow, straight, anastomosing channels. He attributed the low sinuosity to rapid aggradation of the floodbasin along with frequent channel avulsion due to the ephemeral nature of the system. To explain the high mudstone content, Wells also suggested additional input of mud by other processes such as sheetflow and wind. Smith and Smith (1980) discuss similar situations where anastomosing streams were produced by high aggradation rates, which in turn were caused by an increase in base level.

As mentioned above, the Abo Formation in the eastern portion of the study area displays a dramatic increase in sandstone and siltstone content higher in the stratigraphic section. This increase in coarser clastics is interpreted to represent an increase in the number of channels. It could also be interpreted as a decrease in the rate of aggradation, which enabled channels to further erode and rework floodbasin deposits. A decrease in the rate of aggradation may also have occurred, however, outcrops do show an increase in the number of channels.

The increase in channels may be in response to a variety of factors including: (1) an increase in the gradient, (2) an increase in coarser sediment supply, (3) and an increase in the amount and/or a change in the nature of discharge. Far north of the study area, in northern New Mexico, the Abo (Cutler) Formation shows no corresponding changes. There is no evidence for a sudden climatic change that could have produced a major change in discharge (Adams, 1980). There also are no stratigraphic variations north of the study area that would suggest a sudden change in sediment supply. It appears that the increase in the number of channels is in response to an increase in gradient. Tectonically induced gradient change probably would produce a change in sediment supply. Since there is no indication of that, the gradient change is probably a sedimentation induced increase in gradient as proposed by Foster (personal communication 1986).

Classification of the channels based on sinuosity has been done for the Abo Formation in or near the eastern portion of the Lucero region. Based on bedding features, grain size distributions and paleocurrent data, Cappa (1975) interpreted the upper Abo Formation to be a meandering stream deposit. Lemley (1984), employing Schumm's (1963) classification, interpreted the upper Abo channels to vary from straight to tortuous, however, Lemley's results should be considered estimates which have limitations because of the equations from which they are based.

Lemley's (1984) sinuosity calculations are based on channel width and depth measurements using equations empirically devised by Schumm (1963). Ethridge and Schumm (1978) point out that equations used in paleohydraulic and geomorphic reconstructions are primarily based on stable alluvial streams of the western United States. The equations have rarely been tested on modern coastal plain streams, which have a greater likelihood of preservation in the rock record. Miall (1983), realizing that fluvial architecture depends on a wide variety of factors, suggests that quantitative paleohydraulic and geomorphic reconstructions from ancient deposits should be discontinued, with the possible exception of the basic meandering stream model of Allen (1965) on which the procedures are based.

The upper Abo Formation does appear to conform to the basic meandering stream model in some areas, however, flows may have been ephemeral and the environmental setting appears to been either a coastal plain or a distal portion of an alluvial fan. Thus, paleohydraulic and geomorphic reconstructions based on channel width and depth measurements probably should not be done for the Abo Formation until the equations used have been thoroughly tested in a variety of fluvial settings.

Because of the lack of data in many subsurface studies, it is not uncommon to see channel patterns inferred on the basis of percentage of fine-grained sediment in a sequence. Since the proportion of fine-grained sediments can be determined by a variety of factors other than channel pattern, Friend (1983) discourages the use of this kind of method, by itself, to infer channel sinuosity.

Probably the best way to characterize channel patterns is to combine bedding features, grain size distributions and paleocurrent data, however, not all of these are detectable or measurable by well logs and cuttings available in this study. Because of this, characterizing channel patterns is not attempted in this study.

In the western Lucero region, lower Abo beds are generally very coarse-grained and appear to be similar to sieve deposits of the basal Abo Formation, observable in road cuts in the Zuni Mountains, north of the study area. Paleocurrent data and general nature of the lower Abo beds exposed over the Zuni uplift suggest they were deposited in an alluvial fan/braided stream environment (MacMillan, 1987). Thin carbonate beds also occur locally in the lower Abo north of the study area and higher in the section within the western Lucero region (Plates 5, 10). No fossils have been found in the carbonates, which presumably were formed in small playas or by pedogenic processes.

Figure 5-1 suggests the Zuni uplift was an Abo source area in the Lucero region, however, Figures 7-2 and 7-3 show the Zuni uplift to ultimately be covered by the Abo Formation. Thus, the Zuni uplift within the study area, must only have been a source area during deposition of the lower Abo Formation. With the local sediment source covered, deposition presumably changed from proximal alluvial fan deposition to a lower gradient system, perhaps a distal portion of an alluvial fan or a coastal plain. The upper part of the Abo Formation to the west is generally similar to that of the eastern Lucero region, implying they may have had similar origins, however, higher sand and silt content in the northwest corner of the study area suggests that region was also receiving sediment from the northwest. Possible northwest sources of the sand and silt include a then still exposed portion of the Zuni uplift and the Defiance uplift of northeastern Arizona.

Adams (1980), working on the Abo Formation around the Penasco uplift, found paleocurrent directions to be radiating from the uplift during deposition of the lower Abo, however, the upper portion showed directions that were southward all around the uplift. From this, Adams concluded the Penasco uplift was a local source area that was ultimately covered by sediments derived from the Uncompahgre uplift.

Thus, it appears that the Zuni and Penasco uplifts were both local source areas that were eventually covered by a regional, southward prograding, clastic wedge derived from the Uncompahgre uplift of northern New Mexico and southern Colorado. Paleocurrents measured in this study and by Cappa (1975) support the southward regional movement of sediment in west-central New Mexico.

It is highly unlikely that the basal Abo contact is isochronous throughout the Lucero region or west-central New Mexico. Pennsylvanian uplifts were rejuvenated during the end of the Pennsylvanian in central New Mexico (Kottlowski and Stewart, 1970). Thus, the basal coarse grained Abo sandstones of the western Lucero region were most likely deposited while the Bursum Formation was being deposited further east in the Lucero basin.

Geologic History

As stated in chapters 1 and 2, exact ages for some of the units discussed are uncertain. In this study it is assumed that "Pennsylvanian rocks" (Magdelena Group) are only Pennsylvanian in age; the Bursum Formation is early Wolfcampian; the Abo Formation is both Wolfcampian and Leonardian; and the Meseta Blanca Member of the Yeso Formation is Leonardian in age. The timing of events discussed below is based on these assumptions, however, if these assumptions are later found to be incorrect, the sequence of events should remain accurate.

Martin (1971), in an in-depth study of Pennsylvanian rocks of the Lucero region, describes the Pennsylvanian depositional environment as a shallow marine shelf bounded on the west by the Zuni uplift, and separated from the Estancia basin by the Joyita uplift or platform (Figure 7-7). The Lucero basin is a basin produced by differential subsidence and never contained deep marine waters. Sedimentary rock features suggest deposition was in shallow water, nearshore and shelf-type environments. Fine- grained sediments were shed from the low lying Zuni uplift. The Joyita uplift or platform appears to have been slightly positive, supplying minor amounts of clastics and perhaps controlling carbonate deposition. Kottlowski and Stewart (1970) suggest the Joyita uplift was more likely a submarine platform, perhaps with small, low islands rather than a large landmass exposed to erosion. The Zuni uplift was at least partially covered by Pennsylvanian marine rocks which were repeatedly subjected to submarine erosion and subaerial exposure and erosion (Martin, 1971). Martin feels these apparent sea level fluctuations were due to varying basin subsidence and terrigenous sediment supply.

Beginning in late Virgilian time and continuing into early Wolfcampian time, Pennsylvanian uplifts were rejuvenated and shed vast amounts of clastics into the surrounding basins (Kottlowski and Stewart, 1970). In the Lucero region, early Wolfcampian deposition of the Bursum Formation reflects a struggle between marine and terrestrial depositional forces. The increase in clastics

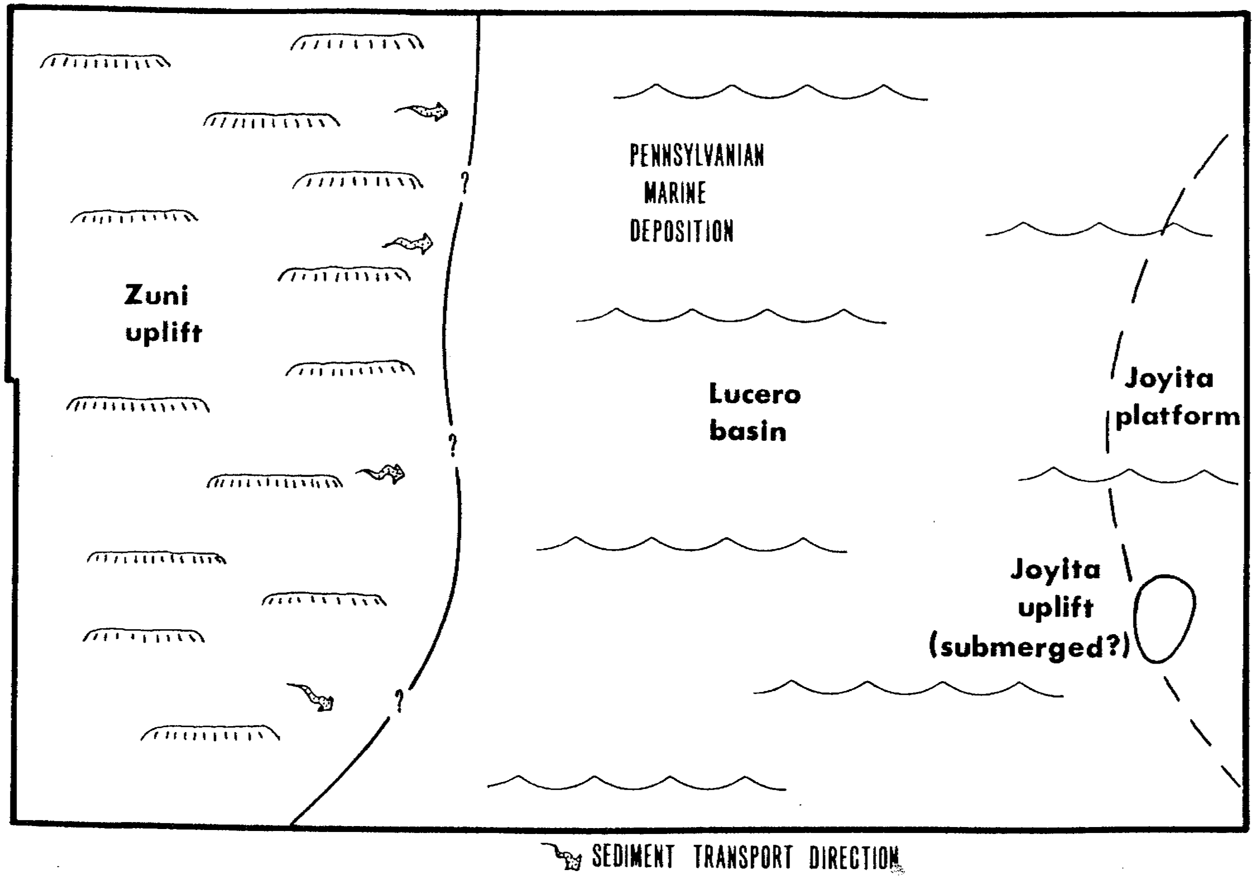


Figure 7-7. Late Pennsylvanian paleogeographic map of the Lucero region.

from rejuvenated uplifts produced prograding deltas which were periodically inundated by marine waters (Kues and Kietzke, 1976). Kues and Kietzke (1976) suggest a northerly source for a deltaic sequence near Mesa Lucero, however, the Zuni and Joyita uplifts were undoubtedly also source areas during Bursum deposition. The apparent sea level fluctuations may have been caused by two processes that Martin (1971) suspects were occurring in late Pennsylvanian time: (1) varying basin subsidence and (2) terrigenous sediment supply. However, it is very probable that sea level fluctuations were eustatic as Wilson (1967) suggests for early Wolfcampian sediments (Laborcita or Bursum Formation) in the northern Sacramento Mountains.

Both the Zuni and Joyita uplifts were exposed during early Wolfcampian time. During this time they were, along with the Uncompahgre and Penasco uplifts, major sources of sediment for the Lucero region. During relative low-stands of the Wolfcampian sea, coarse clastics, included in the Abo Formation, were being deposited by alluvial fans flanking the Zuni uplift, while fine-grained sediments, comprising the Bursum Formation, were being deposited by fluvial-deltaic systems over the eastern Lucero region (Figure 7-8). Smaller alluvial fan or fan-delta complexes probably bordered the Joyita uplift. During relative high-stands of the Wolfcampian sea, marine limestones were deposited over the eastern Lucero region, while coarse clastics continued to be deposited near the Zuni and Joyita uplifts (Figure 7-9).

Later in Wolfcampian time, the Wolfcampian sea retreated from the Lucero region for the last time (Figure 7-10). Only a small portion of the Joyita uplift was still exposed (Kottlowski and Stewart, 1970), but it appears to still have been a source of coarse grained clastics (Cappa, 1975). The Zuni uplift was still supplying sediment, however, it appears to have been retreating as none of the basal, conglomeratic sandstone sections are very thick like simi-

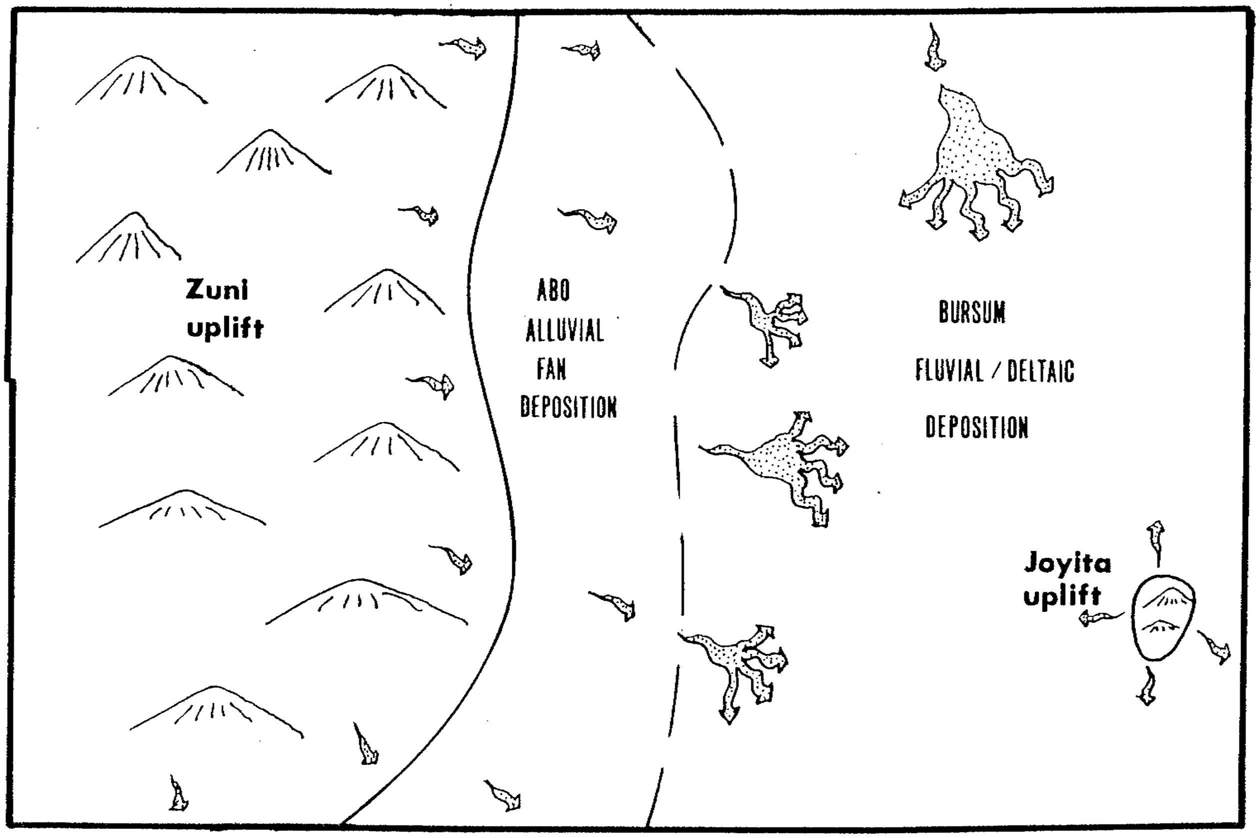


Figure 7-8. Early Wolfcampian paleogeographic map of the Lucero region. Fluvial/deltaic deposition of the Bursum Formation during eustatic low-stands.

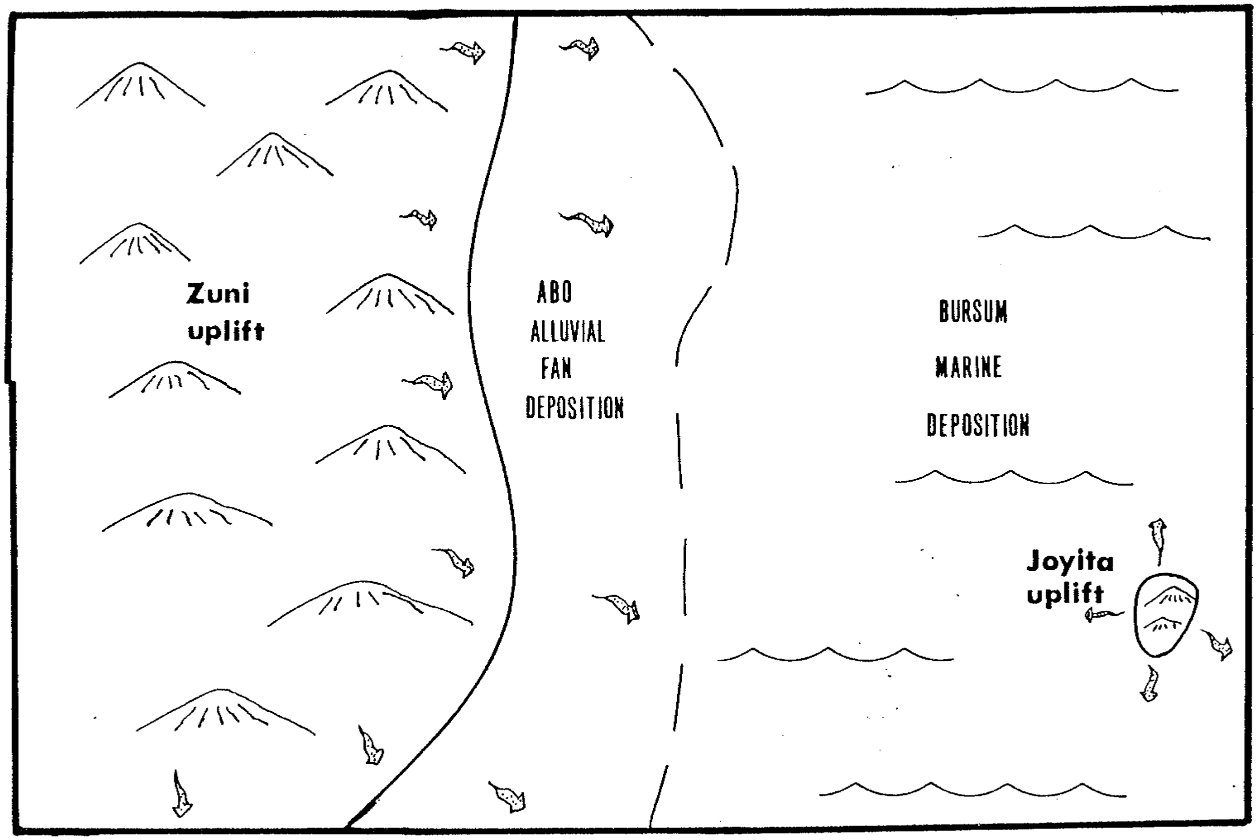


Figure 7-9. Early Wolfcampian paleogeographic map of the Lucero region. Marine deposition of the Bursum Formation during eustatic high-stands.

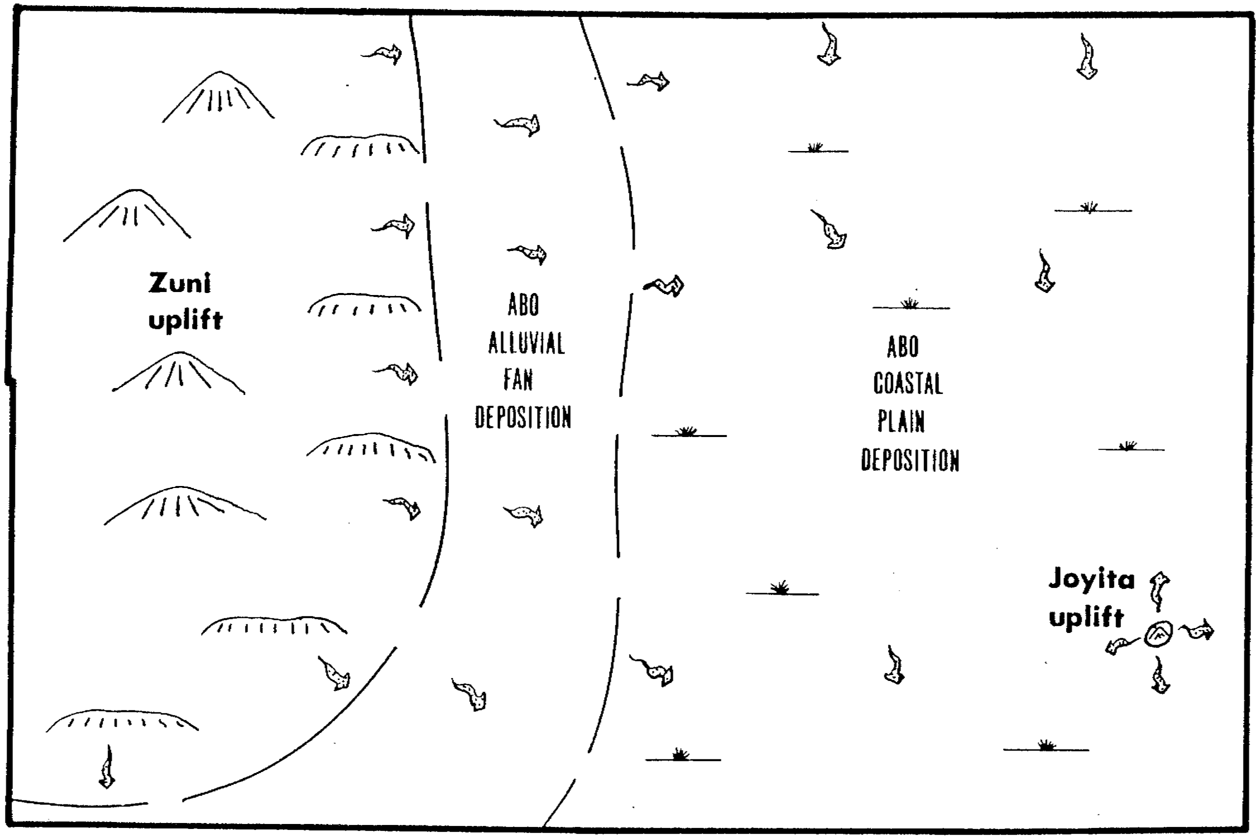


Figure 7-10. Mid-Wolfcampian paleogeographic map of the Lucero region.

lar facies surrounding the Uncompahgre or Pedernal uplifts (Baars, 1962; Broadhead, 1983a, 1984).

The eastern portion of the study area was dominated by mudstones deposited on a relatively flat coastal plain. Floodbasins dominate the coastal plain with few channels present. The floodbasins were exposed often and commonly contain mudcracks and raindrop imprints. Calcareous nodules appear to have formed extensively. They presumably formed at shallow depths below the surface (Pettijohn, 1975) and may be a major source of limestone pebbles found in channel lag deposits (Foster, personal communication 1986). The Zuni, Penasco and Uncompahgre uplifts were probably the main sources of the mud deposited on the coastal plain.

North of the study area, the Penasco uplift was breached by sediments shed from the Uncompahgre uplift, but the Penasco uplift was still a source of sediment throughout most of "Abo time" (Adams, 1980).

Even later in Wolfcampian and possibly in early Leonardian time, the Joyita uplift was covered and the Zuni uplift was being eroded down and back even further (Figure 7-11). With the Zuni uplift being eroded and covered, the Uncompahgre and Penasco uplifts probably became the primary source areas for coastal plain sediments of the eastern Lucero region.

Possibly in late Wolfcampian, but certainly by early Leonardian time, the Zuni uplift was completely covered by the Abo Formation (Figure 7-12). North of the study area, the Penasco uplift was also covered (Adams, 1980). Thus, most of the sediment being deposited in the Lucero region appears to have come from the Uncompahgre uplift, however, the northwest corner of the Lucero region may have been receiving sediment from either the Defiance uplift or part of the Zuni uplift outside of the study area. More channels, carrying sand and silt, seem to have been coming off the Uncompahgre uplift,

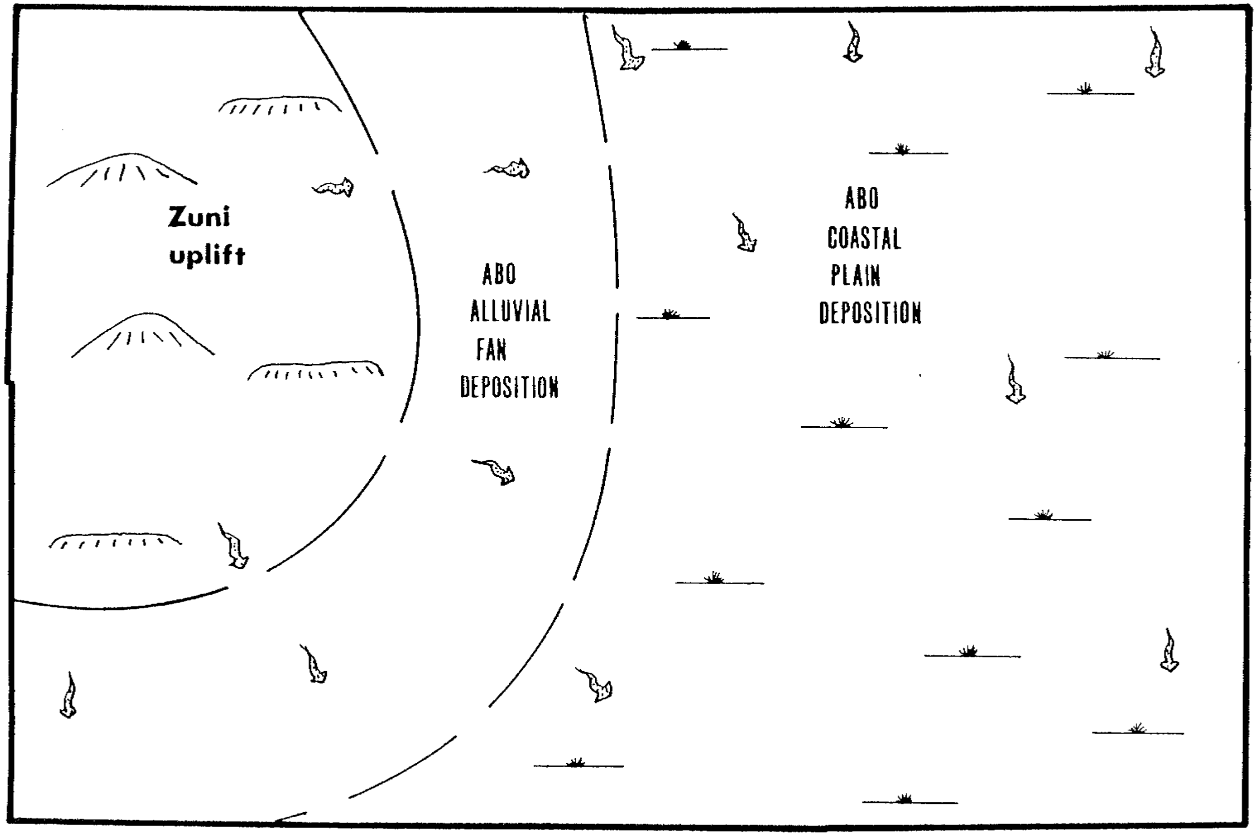


Figure 7-11. Late Wolfcampian-early Leonardian(?) paleogeographic map of the Lucero region.

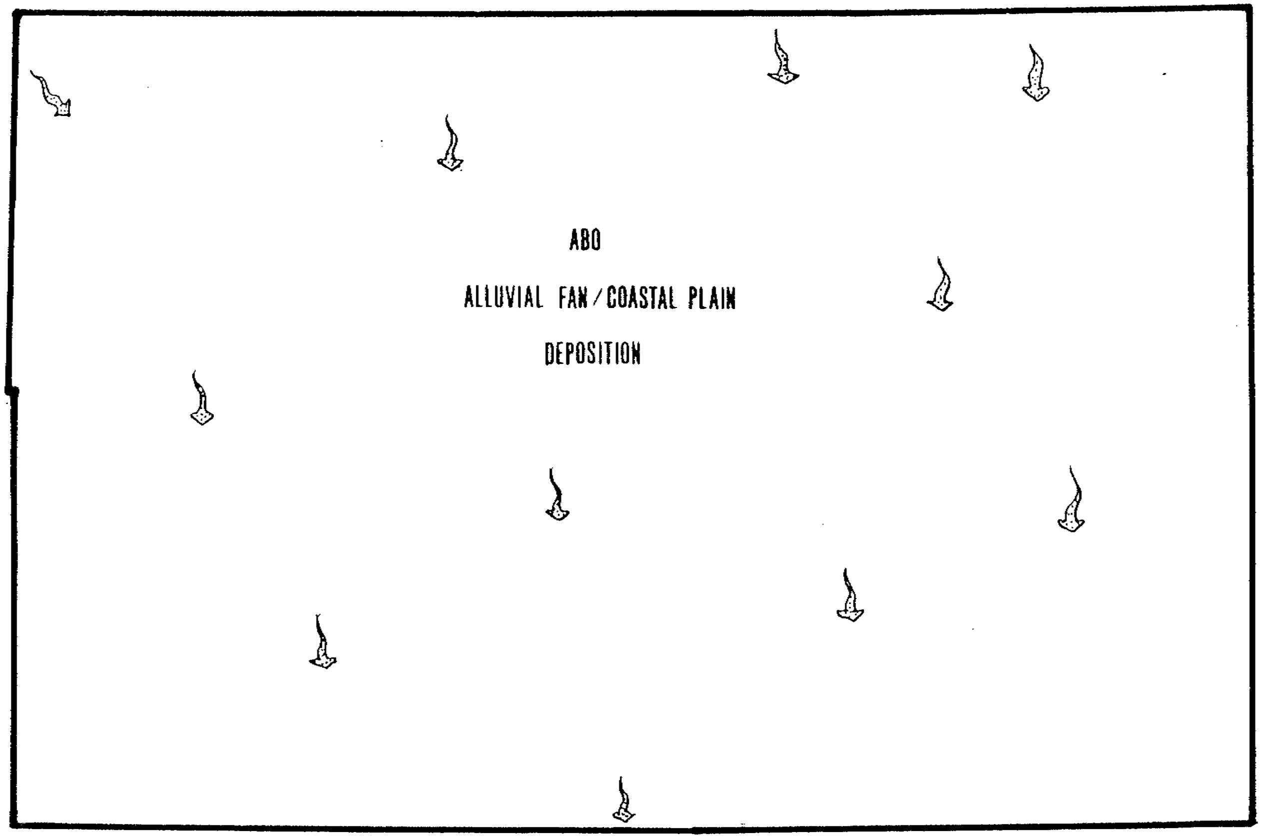


Figure 7-12. Late Wolfcampian(?)-early Leonardian paleogeographic map of the Lucero region.

presumably due to an increase in the regional gradient. The gradient change is believed to be caused by large-scale progradation of the clastic wedge produced by sediments shed off the Uncompahgre uplift as proposed by Foster (personal communication 1986). The gradient change was probably coincident with a change from a relatively flat coastal plain to either a gentle sloping coastal plain or distal portion of a large alluvial fan complex.

Later in Leonardian time, the Lucero region was inundated by marine waters depositing the Meseta Blanca Member of the Yeso Formation (Figure 7-13). Deposition took place in sandy lagoonal seas which grade into large eolian deposits north and west of the Lucero region (Baars, 1962; Kottlowski and Stewart, 1970).

Paleoecologic and biostratigraphic studies by Read and Mamay (1964) and Hunt (1983) indicate climates became drier and harsher from late Pennsylvanian to Leonardian time. Hunt (1983) suggests an arid, seasonally dry climate during Abo deposition in the Socorro area.

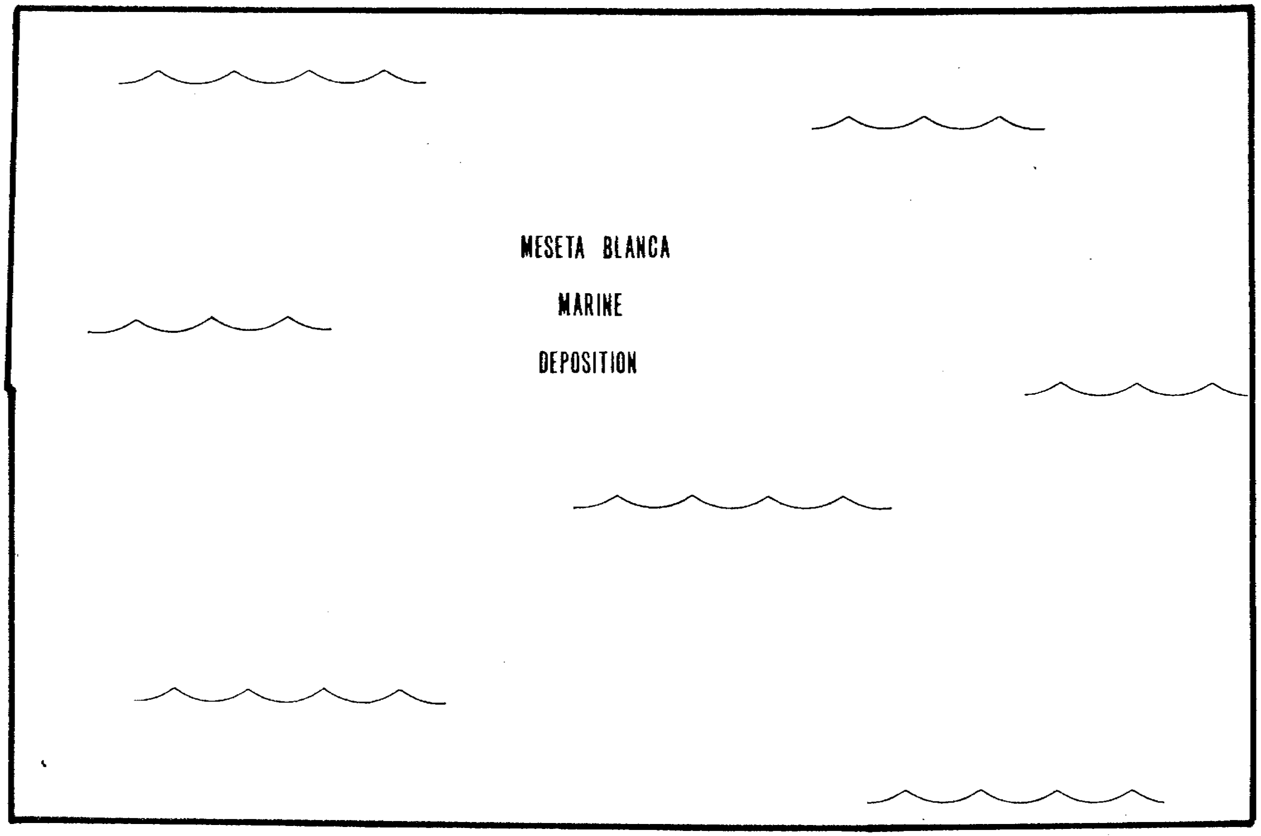


Figure 7-13. Leonardian paleogeographic map of the Lucero region.

CHAPTER 8

RESOURCE POTENTIAL

Introduction

In or near the Lucero Region, the Abo Formation has been explored for uranium, copper and petroleum. Exploration for uranium was done in the early 1950's, however, economic deposits were never found. Since economic deposits of uranium have not been found in the Abo Formation it will not be discussed in this study.

Copper

In west-central New Mexico, Abo copper deposits have been mined in the Zuni and Scholle districts. The Zuni district is located in the Zuni Mountains, just north of the study area. The Scholle district is east of the study area, near the Abo type section in Abo Canyon. In both districts, peak production took place in the 1910's and the 1920's, however, mines were operating sporadically until the early 1960's (Hatchell et al., 1982).

Surface copper deposits of the Abo Formation haven't been economic since the early 1960's and aren't expected to become economic in the near future. Copper deposits have not been found in surface exposures within the study area and the higher cost of subsurface mining would make copper prospecting in the Abo Formation even less attractive. Therefore, copper will not be discussed any further in this study. For descriptions of copper mineralization and possible origins of mineralization, the reader is referred to discussions by LaPoint (1976) and Hatchell et al. (1982).

Petroleum

Abo red beds are an important reservoir of natural gas in east-central New

Mexico. The red bed gas was first discovered in 1977 by the Yates Petroleum Corp. No. 1 McConkey well located within the Pecos slope of Chaves County (Broadhead, 1984). In 1980 the Federal Energy Regulatory Commission designated the Abo as a "tight gas" sandstone allowing producers to sell the gas at a higher regulated price. This set off a drilling boom for the Abo target.

The following information on the geology and gas production of the Pecos Slope Abo field is taken from the discussions of Broadhead (1983a, 1984).

In the Abo Formation in east-central New Mexico, natural gas is found in the distal end of a fluvial-deltaic system where mudstones are abundant, yet thick sandstones still occur. Production appears to be from natural fractures in sandstones which, otherwise, would have very low porosities and permeabilities. Mudstones, whose fractures are either closed by compaction or sealed tight by anhydrite or carbonate cements, are the seals for the fractured sandstones reservoirs.

Trapping mechanisms appear to be dominantly stratigraphic with little or no control by structures in the area. In the Pecos Slope field, the upper Abo Formation is most suited for traps because of the presence of sandstones beds within mudstones. Reservoirs probably aren't present in the middle, mudstone-rich section of the Abo because of a lack of sandstones. The lower, coarser-grained portion of the Abo Formation also contains potential reservoirs, however, they may lack a lateral trapping mechanism to prevent hydrocarbon loss up dip into overlying units to the west, over the Pedernal uplift.

Source rocks for the Abo gas are not known. Since the Abo Formation has been exposed to oxidizing conditions, it most certainly was not it's own source of gas. Other possibilities include units underlying or laterally adjacent to the red beds. The most likely two sources are the down dip dolostones of the Abo reef and the underlying and intertonguing marine mudstones and limestones of the Hueco Formation.

Recently, interest in petroleum has increased in west-central New Mexico and adjacent Arizona (Brennan, 1986; Woodward and Grant, 1986, 1987). Lease applications on state and federal lands have been filed by several petroleum companies (Brennan, 1986) and geophysical crews were seen working in the area in 1984 and 1985 (Woodward and Grant, 1986). Primary targets are believed to include Pennsylvanian and Permian sandstones and carbonates related to producers of similar ages in southeastern New Mexico (Brennan, 1986). The specific interest of this study is the resource potential of the Abo Formation. For general discussions of the petroleum potential of west-central New Mexico, the reader is referred to discussions by Black (1982), Foster (1964), and Woodward and Grant (1986, 1987).

As Broadhead (1984) concluded, the Abo Formation would not be it's own source of petroleum, therefore, if the Abo was to contain hydrocarbons, it would have to have an external source. Possible source rocks for the Abo, in the Lucero region, include Bursum marine limestones, Pennsylvanian marine limestones and mudstones, and pre-Pennsylvanian marine rocks. The Bursum Formation, like the Abo Formation, has been exposed to oxidizing conditions which produced red beds, therefore, petroleum originating from Bursum limestones is unlikely. Pennsylvanian limestones and mudstones are an obvious source which are present throughout the eastern half of the study area. Pre-Pennsylvanian rocks, including Mississippian rocks and possible Cambrian through Devonian age rocks could also potentially be source rocks. Mississippian rocks are generally limited to the southeastern corner of the Lucero region, however, Martin (1971) reported a small lens of Mississippian rocks in the Spanel and Heinze No. 1-9612 well located in section 5 of T5N and R7W (Figure 8-1). Lower Paleozoic rocks may be present south of the Lucero region, but

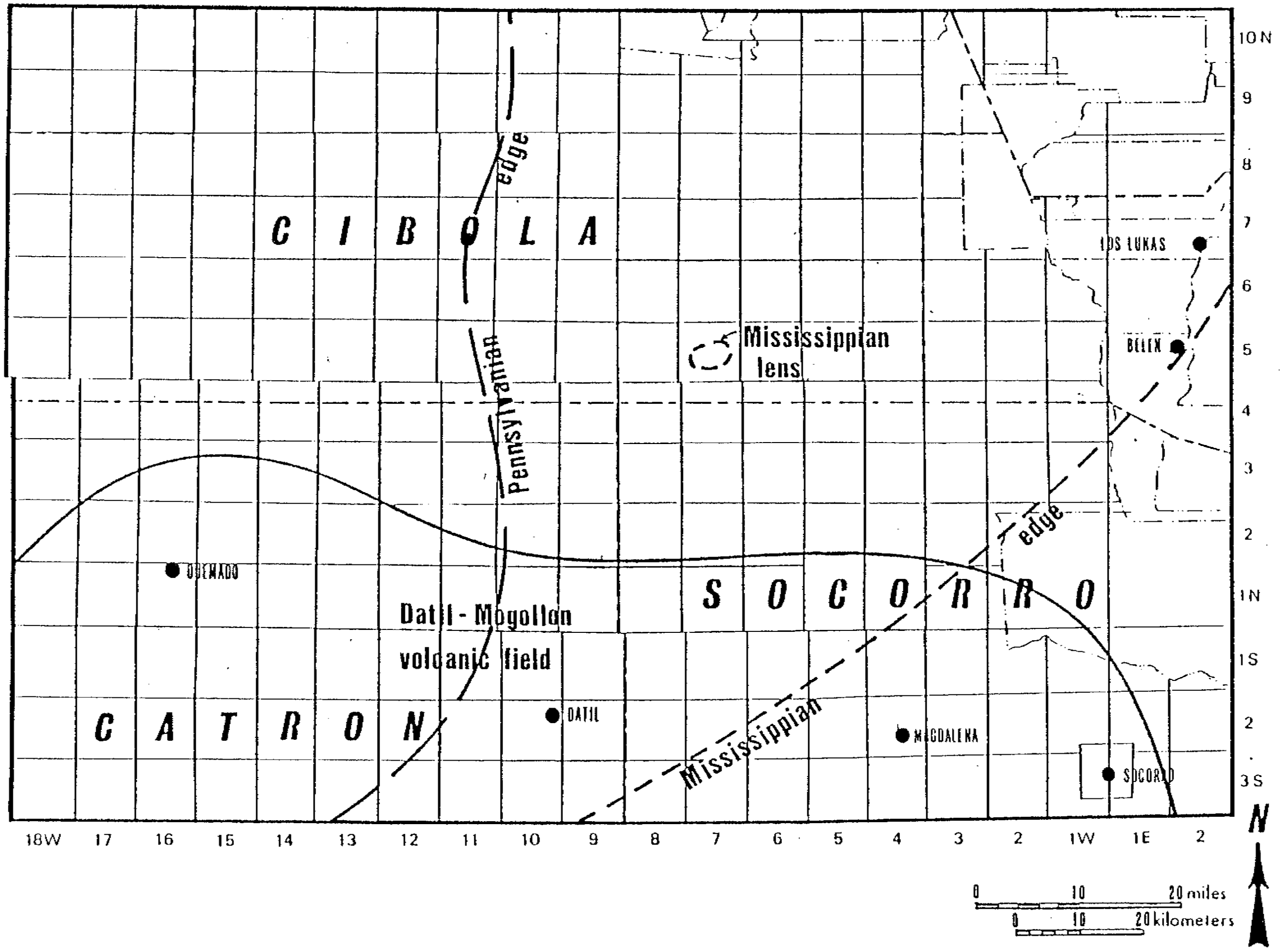


Figure 8-1. Map showing the edges of Pennsylvanian and Mississippian rocks and the Datil-Mogollon volcanic field (Modified from Foster, 1964; Woodward and Grant, 1986).

have yet to be encountered in wells (Foster, 1964; Woodward and Grant, 1986).

Previous exploration in the study area includes 28 wells which are known to have penetrated the Abo Formation (Figure 8-2). Most of these wells have been drilled where Mesozoic and Paleozoic strata are exposed (Figure 2-2), north of the Datil-Mogollon volcanic field (Figure 8-1). The wells appear to have primarily targeted anticlinal structures or the Pennsylvanian pinchout against the Zuni uplift (Figures 8-1, 8-2). A few wells also targeted structures related to the Lucero uplift and Rio Grande rift. There have been no shows of oil or gas in the Abo Formation, however, gas shows have been reported in Pennsylvanian strata in the Spanel and Heinze No. 1-9612 SF-P (Sec. 5, T5N, R7W) and in the Byron Gore No.1 NM-AR Land Co. (Sec. 27, T7N, R4W) wells.

Figure 8-2 shows structural contours of the base of the Abo Formation as determined by the wells and outcrops shown in Figure 1-2. The structural contours reflect the structural elements labelled in Figure 2-2. Possible structural traps include the untested anticlines that haven't been intruded by igneous rocks and structures related to the major uplifts in the area.

Abo gas occurrences in east-central New Mexico do not appear to be controlled by structure. Neither the Pedernal uplift nor smaller folds and buckles seem to have a major affect on the occurrence of reservoirs. Therefore, similar structures may not control petroleum occurrences, if they exist, in the Abo Formation in the Lucero region.

Broadhead's (1984) findings suggest that petroleum occurrences are most likely in thick sandstones set within abundant mudstones. This would generally exclude the lower Abo Formation of the eastern Lucero region because of the lack of sandstones. There may be exceptions to this as sandstones do occur locally in the basal Abo along the eastern side of the study area. The upper

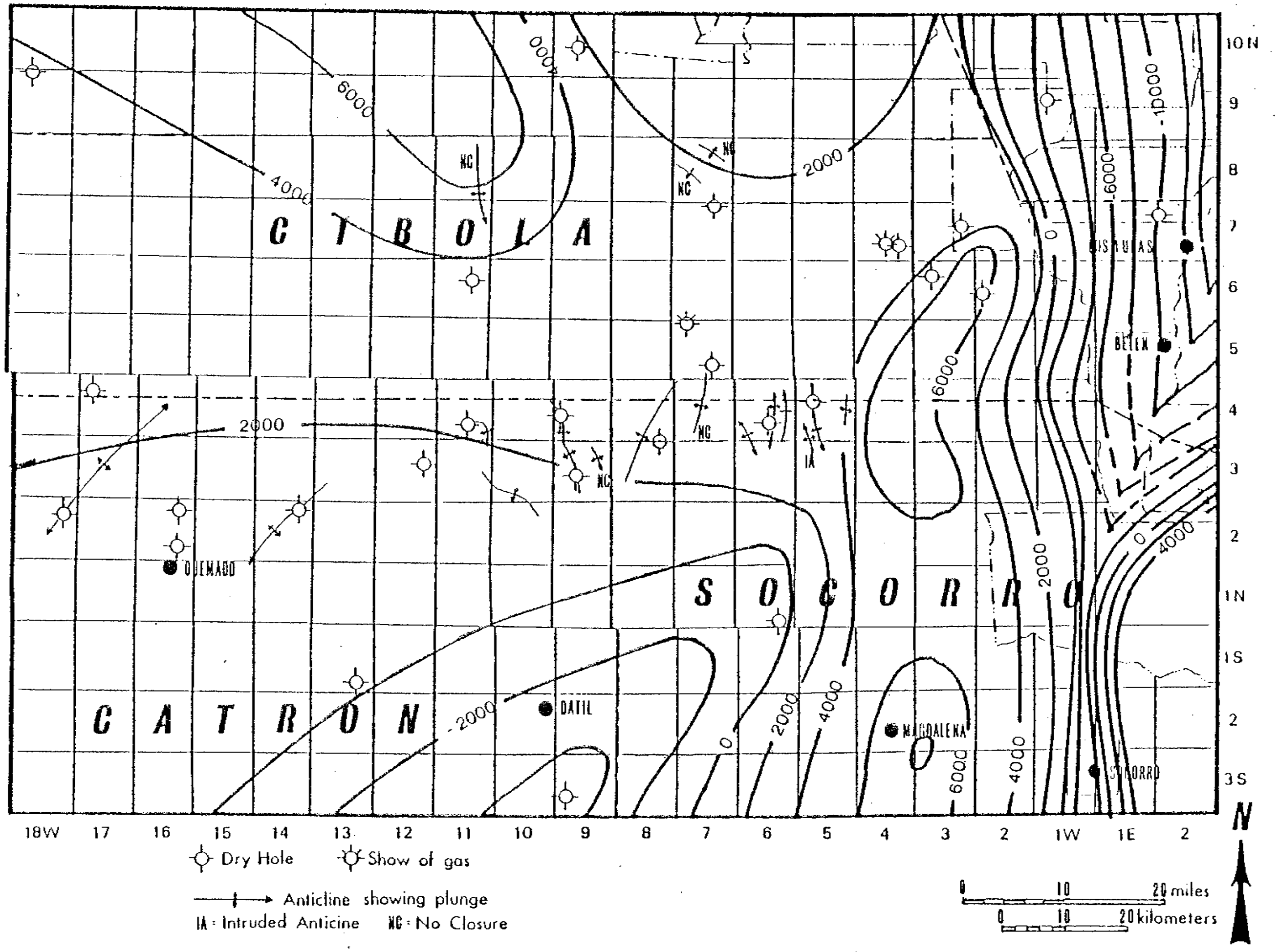


Figure 8-2. Structure contour map of the base of the Abo Formation showing wells that have penetrated the Abo Formation. Anticlines are from Foster (1964) and Woodward and Grant (1986).

portion of the Abo Formation in the eastern Lucero region is similar to the upper Abo of eastern New Mexico. Thus, relatively speaking, it would be expected to have a high potential to produce petroleum assuming the sandstones are fractured, or have sufficient matrix porosity.

In the western Lucero region, the Abo Formation is generally sandier than in the eastern part of the Lucero region. Lower conglomeratic sandstones in the Huckleberry No. 1 Federal (Sec. 11, T2N, R16W) and the Tenneco Oil Co. No. 1 Federal (Sec. 35, T1S, R13W) wells have mudstones above them to act as seals, however, the sandstones may lack a lateral trapping mechanism to prevent losses up dip, into overlying units over the Zuni uplift. The upper Abo in these two wells also show considerable amounts of mudstones, but again, lateral trapping mechanisms may be missing. Further northwest, mudstones become scarcer. With fewer mudstones to act as seals, the petroleum potential over much of the Zuni uplift appears relatively low. Not only does this discourage drilling for the Abo Formation in the northwestern portion of the Lucero region, but drilling for the Pennsylvanian pinchout in these areas may not be advisable because of the lack of potential seals.

In light of the above discussion, the most probable reservoirs of petroleum in the Abo Formation of the Lucero region are the upper sandstones in the eastern and central portions of the area. Both Foster (1964) and Woodward and Grant (1986) suggest drilling through the Cenozoic volcanics and sedimentary cover of the northern Datil-Mogollon volcanic field as they are generally very thin. Contact aureoles are expected to extend only a short distance around shallow plutons underlying the volcanics (Woodward and Grant, 1986).

If conditions are consistent with gas occurrences in Chaves County, traps should be stratigraphically controlled. However, if structures are to be tested, the anticlines and recent uplifts to the east should be preferentially tested.

Black (1982) suggests the Pennsylvanian and Permian rocks of the Rio Grande rift may also contain petroleum, but because of the deep depths at which they occur they will probably be secondary targets. Foster (1964) states that Pennsylvanian and Permian rocks in the San Augustine trough probably also warrant some testing.

CHAPTER 9

SUMMARY AND CONCLUSIONS

Summary

In the Lucero region of west-central New Mexico, the Abo Formation appears to conformably overlie the Bursum Formation and unconformably overlie Pennsylvanian and Precambrian rocks. The Meseta Blanca Member of the Yeso Formation conformably overlies the Abo throughout the study area. The Abo Formation thins to about 400 to 450 feet over the Zuni uplift, while thicknesses away from the uplift generally vary between 600 and 750 feet.

Surface testing of gamma-ray log responses to Abo lithologies found that arkosic sandstones and nonarkosic sandstones produce similar gamma-ray signatures. This appears to be due to albitization of K-feldspars by sodium-rich waters. High percentages of arkosic drill cuttings at corresponding depths with low gamma-ray peaks suggests that this is not a local phenomenon. The surface gamma-ray log also showed variable readings within thick mudstone sections. This may be due to a variety of factors including variations in the radioactive element content of the clays, and in the extent and type of cementation. The shale baseline of thick mudstone sections also shifted to lower gamma-ray readings further down-section. This shale baseline shift is also detectable in subsurface wells in the eastern portion of the study area. It appears most over limestone lithologies suggesting it is due to variations in cementation.

Paleocurrent analysis of a single sandstone bed in the upper portion of the Abo Formation, near Mesa Lucero, indicates a southerly flow direction. This is consistent with paleocurrent directions determined by other authors working in and around the Lucero region.

Analysis of wire-line logs and drill cuttings show the Abo Formation over the Zuni uplift to be significantly different from the Abo in the eastern portion of the study area. Sandstones are much more prevalent over the Zuni uplift, and are more uniformly distributed through the stratigraphic section than they are further to the east. Over the uplift itself, the Abo Formation contains more sandstone and less mudstone to the northwest. Further east, the Abo Formation consists of a distinct, mudstone- rich lower portion and an upper sandstone and siltstone-rich section. Locally, along the eastern boundary of the study area, the lower Abo contains fine and coarse-grained sandstones. A sandstone plus siltstone to mudstone ratio map illustrates the regional variation of the Abo Formation and suggests that the Zuni uplift was a substantial sediment source for the study area.

Log curve shape analysis is a common method of determining vertical grain size trends in sandstone beds. Depositional environments can be inferred from the determination of vertical grain size trends. Before this technique can be used with assurance, it should be tested on beds with known grain size variations. To test log curve shapes on Abo sandstones, a surface gamma-ray profile was checked against grain sizes measured on an outcrop. The results of these surface tests suggest that log curve shape analysis is unreliable in the Abo Formation. One source of error is an unfavorable relationship between grain size and clay content in coarse grained sandstones. Other possible sources of unreliable log curve shapes are variable compositions of framework grains, clays and cements.

Depositional environments of the Abo Formation are largely controlled by proximity to late Paleozoic uplifts. The presence of basal conglomeratic sandstones over the Zuni uplift suggest deposition by alluvial fans. Compared to similar deposits along the Pedernal uplift, the relatively thin basal conglomerates over most of the Zuni uplift suggest that the uplift was being eroded and covered.

In the eastern Lucero region, thick mudstone-rich sections, in the basal Abo Formation, overlying deltaic deposits of the Bursum Formation implies deposition on a broad, flat coastal plain. The lack of sandstones and siltstones suggests there were few channels dissecting large floodbasins.

An increase in sandstones and siltstones up-section in the eastern portion of the study area signifies an increase in the number of channels. North of the study area there are no corresponding variations in the Abo (Cutler) Formation, suggesting that the change was not due to dramatic changes in discharge or sediment supply. Thus, the increase in coarser- grained sediments is believed to represent the gradual progradation of a large-scale alluvial fan produced from the Uncompahgre uplift.

The covering of the Zuni uplift by the Abo Formation would imply that deposition in the western Lucero region changed from proximal alluvial fan deposition to either distal fan or coastal plain deposition. The general nature of the upper Abo Formation in the eastern and western portions of the study area is similar, therefore depositional environments for the two areas were probably similar. One exception to this is the upper Abo Formation in the northwest corner of the Lucero region. It contains more sandstone and less mudstone than it's equivalents to the south and east. This may reflect additional sediment input from either an uncovered portion of the Zuni uplift outside the study area or the Defiance uplift of northeastern Arizona.

Timing of the rejuvenation of the Pennsylvanian uplifts suggests that the basal contact of the Abo Formation is not isochronous. Alluvial fan deposition to the west probably began prior to deposition of the coastal plain in the eastern Lucero region.

The Abo Formation has been found to be a significant sedimentary copper and natural gas producer. The low grade of copper ores and high cost of subsurface mining makes copper prospecting in the Abo Formation unattractive. Recently, interest in the petroleum potential of west-central New Mexico has increased. Reservoir studies of the Pecos Slope Abo gas field of east-central New Mexico suggest that traps are stratigraphically controlled and that fractured sandstones within mudstone seals are the most likely producers. Within the Lucero region, the most likely productive reservoirs of the Abo Formation are the upper sandstones of the eastern and central portions of the study area. If structures are to be tested, untried anticlines and structures related to uplifts in the eastern and central portions of the study area should be tested first.

Conclusions

Analysis of wire-line logs and drill cuttings, between surface exposures, indicates that the Abo Formation thins to a thickness of 400 to 450 feet over the Zuni uplift. Elsewhere in the Lucero region, the Abo is generally between 600 and 750 feet thick. In the eastern portion of the study area the Abo consists of a lower mudstone-rich section overlain by a sandstone and siltstone-rich section. To the west, sandstones and siltstones are uniformly distributed throughout the stratigraphic section. Sandstone and siltstone content of the Abo Formation increases to the northwest corner of the Lucero region.

Depositional environments of the Abo Formation in the Lucero region reflect both local influence of the Zuni uplift and regional influence of the Uncompahgre and Penasco uplifts. Depositional environments of the eastern Lucero region are characterized by a broad, flat coastal plain succeeded by the distal portion of an alluvial fan or a gently sloping coastal plain. Western Lucero region depositional environments are characterized by proximal alluvial fan deposits overlain by the distal portion of an alluvial fan or a gently sloping coastal plain.

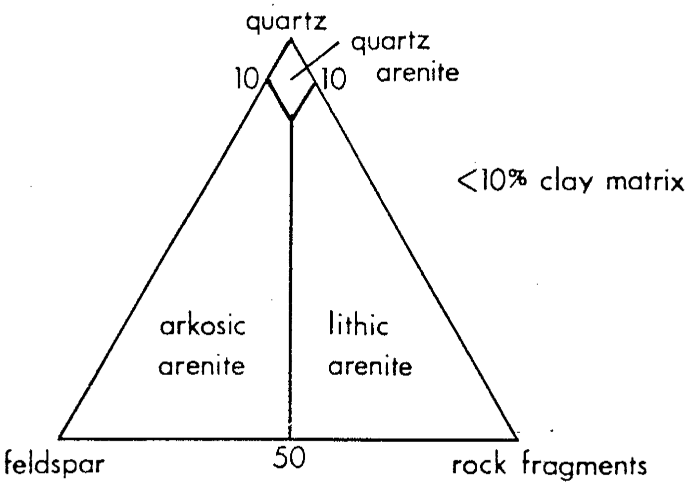
The application of log curve shape analysis as an indicator of grain size in Abo sandstones has been found to be unreliable and is not recommended as a means of determining depositional environments.

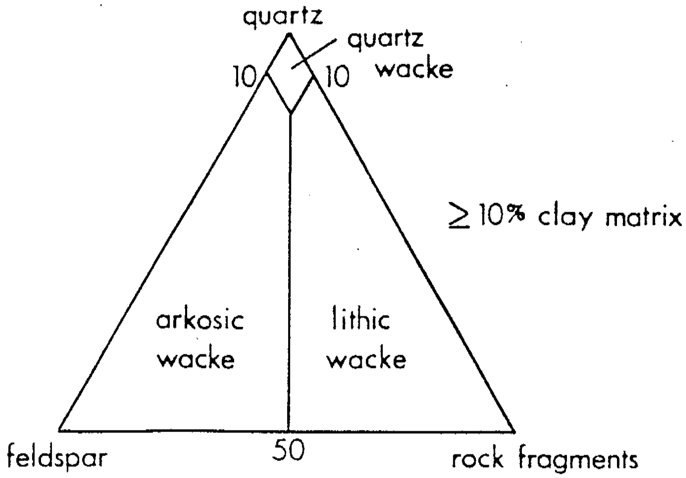
The most probable economic resource in the Abo Formation in the Lucero region appears to be petroleum. The most promising reservoirs should occur in the upper Abo sandstones in the eastern and central portions of the study area.

APPENDIX A

CLASSIFICATION SYSTEMS

Sandstone Classification System: From Broadhead (1984), modified from Dott (1964).





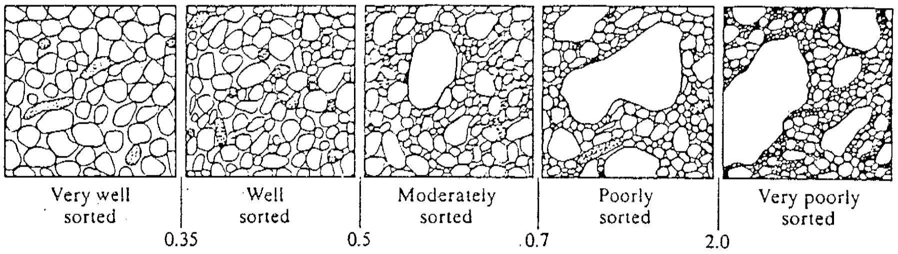
Carbonate Classification System: From Dunham (1962).

<table>
<tr><th colspan="5">DEPOSITIONAL TEXTURE RECOGNIZABLE</th><th rowspan="5">DEPOSITIONAL TEXTURE NOT RECOGNIZABLE</th></tr>
<tr><th colspan="4">Original Components Not Bound Together During Deposition</th><th rowspan="4">Original components were bound together during deposition... as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be interstices.</th></tr>
<tr><th colspan="3">Contains mud (particles of clay and fine silt size)</th><th rowspan="3">Lacks mud and is grain-supported</th></tr>
<tr><th colspan="2">Mud-supported</th><th rowspan="2">Grain-supported</th></tr>
<tr><th>Less than 10 percent grains</th><th>More than 10 percent grains</th></tr>
<tr><td>Lime <u>Mudstone</u></td><td><u>Wackestone</u></td><td><u>Packstone</u></td><td><u>Grainstone</u></td><td><u>Boundstone</u></td><td><u>Crystalline Carbonate</u>
(Subdivide according to classifications designed to bear on physical texture or diagenesis.)</td></tr>
</table>

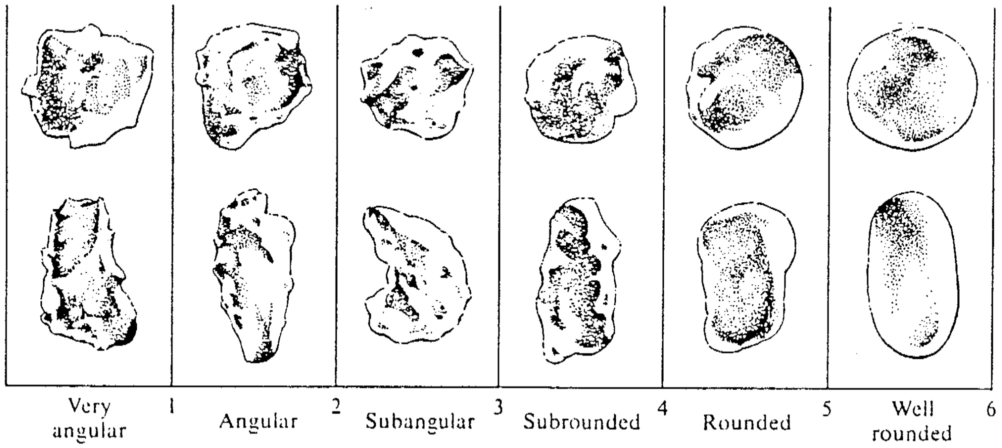
Grain Size Classification: From Blatt (1982).

	Name	Millimeters	Micrometers	ϕ
		4,096		−12
GRAVEL	Boulder			
		256		−8
	Cobble			
		64		−6
	Pebble			
		4		−2
	Granule			
		2		−1
SAND	Very coarse sand			
		1		0
	Coarse sand			
		0.5	500	1
	Medium sand			
		0.25	250	2
	Fine sand			
		0.125	125	3
	Very fine sand			
		0.062	62	4
MUD	Coarse silt			
		0.031	31	5
	Medium silt			
		0.016	16	6
	Fine silt			
		0.008	8	7
	Very fine silt			
		0.004	4	8
	Clay			
		↓	↓	↓

Classification of Grain Sorting: Visual chart used to determine grain sorting; from Compton (1962).



Grain Roundness Classification: Visual chart used to determine roundness of grains; from Blatt (1982) after Compton (1962).



Classification of Bed Thickness: From Blatt (1982).

Term	Criterion
Very thickly bedded	> 1 m
Thickly bedded	30–100 cm
Medium bedded	10–30 cm
Thinly bedded	3–10 cm
Very thinly bedded	1–3 cm
Thickly laminated	0.3–1 cm
Thinly laminated	< 0.3 cm

APPENDIX B

PALEOCURRENT DATA

Scale of Cross-Strat.	Regional Strike and Dip	Measured Strike and Dip	Measured App. Dip and Dip Direction	Corrected Dip and Dip Direction
Medium	N80W 7N		10 N72W 2 N32E	20 N75W
"	" "	N75W 12S N71W 9S N75W 7S		15 S12W
"	" "	N02E 10E N09E 9E N10E 7E		10 S47E
"	" "		11 N64E 6 N40W	7 N42E
"	" "	N69W 16S N76W 11S N68W 9S		19 S18W
"	" "		3 N67W 3 N21W	9 N62W
"	" "		13 S32W 1 S82W	21 S02E
"	" "		12 S21W 4 N81W	19 S22W
"	N85W 8N	N52W 14SW N57W 13SW N49W 10SW		18 S27W
"	" "		0 N14E 3 N81W	8 S26W
"	" "		7 N49W 7 S62E	41 N40E
"	" "		14 S05W 5 N87E	23 S16E
"	" "		5 S14W 7 N80W	14 S34W

Scale of Cross-Strat.	Regional Strike and Dip	Measured Strike and Dip	Measured App. Dip and Dip Direction	Corrected Dip and Dip Direction
Medium	N85W 8N		12 S20E 4 N45E	8 S33E
"	" "		8 N13E 4 S67E	6 S80E
Large	" "	N21W 16SW N20W 14SW N17W 14SW		19 S48W
"	" "	N65W 14SW N70W 10SW N62W 14SW		20 S16W
"			14 N34W 4 S35W	17 S85W
"	" "		7 N90W 15 S26W	22 S19W
"	" "		5 N25E 3 S67E	6 S47E
"	" "	N42W 4SW N37W 6SW N44W 3SW		11 S22W
"	" "		2 S05W 20 S80E	21 S63E
"	" "		10 S16W 5 S75E	19 S04E
"	" "		18 S09W 11 S75E	27 S12E
"	" "		16 S85E 10 N18E	16 S78E
"	" "		9 S05W 4 S87E	17 S09E
"	" "	N85E 12SE N80E 10SE N84E 11SE		19 S01E
"	" "		6 S16W 4 S38E	14 S10E

Scale of Cross-Strat.	Regional Strike and Dip	Measured Strike and Dip	Measured App. Dip and Dip Direction	Corrected Dip and Dip Direction
Large	N85W 8N		2 S10W 12 S63E	16 S44E
"	" "		4 S81W 10 N41E	12 N38W

APPENDIX C

DRILL CUTTING DESCRIPTIONS

Appendix C contains descriptions for drill cuttings logged by the author. The descriptions are reported in the same format as Broadhead (1984). Summaries of the descriptions are shown in Plates 1 - 4 and 6.

Methods and definitions used in this study are similar to those employed by Broadhead (1984). The only major difference in the methods is that whole samples were not immersed in water. Percentages were determined from dry samples, however, descriptions were done from portions of samples that were immersed in water. The main reason for not immersing the whole sample is because water commonly had destructive affects on mudstone cuttings.

Samples were originally collected at 10 foot intervals, however, occasionally they were collected at 5 foot intervals. In this study, samples were spot checked about every 50 to 100 feet in the upper Meseta Blanca. Starting about 100 feet above the Abo-Meseta Blanca contact all the samples were checked until well below the base of the Abo Formation. If the Bursum Formation was beneath the Abo, it too was completely logged.

Cuttings were examined under a 7X to 30X binocular microscope. Percentages were measured to the nearest 10% with less than 10% being reported as a trace amount. Classifications used to decribe the cuttings are shown in Appendix A. Modifiers used in the descriptions (such as calcareous, anhydritic, silty, etc.) refer to an undetermined amount (less than 50%) of that material. Presence of calcite was determined by strong effervescence in 10% HCL solution. Presence of dolomite was determined by mild effervescence in 10% HCL solution. Broadhead's (1984) definitions of induration are used and are defined as follows: Well indurated lithologies are those that are crushed only with great difficulty with tweezers; poorly indurated lithologies are those that are easily crushed with tweezers; and moderately indurated rocks fall somewhere in between.

In general, detail descriptions are given every 100 to 300 feet. The description of a rock type in any specific interval is similar to the description of that same rock type in the preceeding interval unless noted differently.

Tiger Oil Company
Unit H State No. 1
1980' FNL, 660' FEL, Sec. 8, T4N, R17W
Cibola Co., New Mexico
Elev.: 6781' (GL), 6791' (KB); T.D. 4491'

Depth (ft.) **Percent-Description**

3750-3760

Sandstone (80%): moderate reddish orange (10R 6/6) to light red (5R 6/6); very fine to fine grained; moderately sorted; subangular to subrounded grains; calcareous; quartz arenite to wacke; moderately to well indurated.

Mudstone (20%): light red (5R 6/6) to moderate red (5R4/6); argillaceous, calcareous, anhydritic; poorly indurated.

Siltstone (tr): moderate reddish orange (10R 6/6) to light red (5R 6/6); calcareous; moderately to well indurated.

Limestone (tr): greenish gray (5G 6/1); microcrystalline; lime mudstone; well indurated.

Anhydrite (tr): white (N9) to bluish white (5B 9/1) to light blue gray (5B 7/1); microcrystalline, calcareous; poorly indurated.

3780-3790

Sandstone (40%)
Siltstone (20%)
Limestone (20%)
Mudstone (20%): w/calcareous nodules
Anhydrite (tr)

3840-3850

Sandstone (80%): moderate reddish orange (10R 6/6) to light red (5R 6/6) to very light gray to pinkish gray (5YR 8/1); very fine sand to silt size grains; moderately sorted; subangular grains; calcareous; mafic grains; quartz wacke to quartz arenite, locally arkosic; moderately indurated.

Mudstone (20%): light red (5R 6/6) to moderate red (5R 4/6) to very pale green (10G 8/2); locally calcareous; poorly indurated.

Anhydrite (tr): white (N9) to pinkish gray (5YR 8/1) to bluish white (5B 9/1); microcrystalline; poorly indurated.

Limestone (tr): as above

3880-3890

Sandstone (70%): micaceous, tr. arkosic (texturally same as nonarkosic).

Mudstone (20%)

Anhydrite (10%)

3900-3910
Sandstone (80%)
Mudstone (20%)
Anhydrite (tr)
Limestone (tr)

3910-3920
Sandstone (80%)
Mudstone (20%)
Anhydrite (tr)
Limestone (tr)

3920-3930
Sandstone (60%)
Mudstone (30%)
Anhydrite (10%)

3930-3940
Sandstone (60%)
Mudstone (30%)
Anhydrite (10%)

3940-3950
Sandstone (70%)
Mudstone (20%)
Anhydrite (10%)

3950-3960
Sandstone (60%)
Mudstone (40%)
Anhydrite (tr)

3960-3970
Sandstone (80%): tr. fine-grained, tr. arkosic
Mudstone (20%)
Anhydrite (tr)

3970-3980
Sandstone (70%)
Mudstone (30%)
Anhydrite (tr)

3980-3990
Sandstone (70%)
Mudstone (30%)
Anhydrite (tr)

3990-4000
No Sample

4000-4010
Sandstone (90%)

Mudstone (10%)
Anhydrite (tr)

4010-4020
Sandstone (70%): tr. arkosic
Mudstone (30%): argillaceous
Anhydrite (tr)

4020-4030
Sandstone (70%): moderate reddish orange (10R 6/6) to moderate red (5R 5/4) to light red (5R 6/6) to pinkish gray (5YR 8/1); very fine to fine grained; moderately sorted; subangular to subrounded; calcareous; some mafic grains; quartz arenite to quartz wacke; moderately indurated.
Mudstone (30%): moderate reddish orange (10R 6/6) to moderate red (5R 5/4) to pale green (10G 8/2) to very pale green (10G 8/2); calcareous, argillaceous; poorly indurated.
Arkosic Sandstone (tr): moderate reddish orange (10R 6/6) to light red (5R 6/6) to light gray (N7) to very light gray (N8); very fine to medium grained; angular to subrounded grains; calcareous; biotite, muscovite, mafic grains, altered feldspars; arkosic arenite to arkosic wacke; poorly to moderately indurated.
Anhydrite (tr): as above.
Loose Grains (tr): loose quartz grains; medium to coarse sand size; angular to well rounded; some frosted.

4030-4040
Sandstone (70%): tr. very poorly sorted w/medium to coarse sand size quartz grains.
Mudstone (30%): about 10% is micaceous
Arkosic Sandstone (tr)
Anhydrite (tr)
Loose Grains (tr): quartz

4040-4050
Sandstone (70%): 10% w/coarser grains, locally micaceous.
Mudstone (20%): biotite and muscovite locally.
Arkosic Sandstone (10%): argillaceous
Anhydrite (tr)
Loose Grains (tr): quartz

4050-4080
No Samples

4080-4090
Sandstone (60%): about 10% is anhydritic
Mudstone (40%)
Anhydrite (tr)
Loose Grains (tr): quartz

4090-4100
Sandstone (60%)
Mudstone (40%)
Loose Grains (tr): quartz

4100-4110
Sandstone (60%)
Mudstone (30%)
Anhydrite (10%)
Loose Grains (tr): fine to coarse sand size grains of quartz.

4110-4120
Sandstone (60%): some is noncalcareous
Mudstone (40%): some is noncalcareous
Anhydrite (tr)
Arkosic Sandstone (tr)
Limestone (tr)
Loose Grains (tr): quartz

4120-4130
Sandstone (60%)
Mudstone (30%)
Loose Grains (10%): quartz
Anhydrite (tr)

4130-4140
Sandstone (60%): very fine sand to silt size grains.
Mudstone (30%)
Loose Grains (10%): quartz
Anhydritic (tr)

4140-4150
Sandstone (90%)
Mudstone (10%)
Arkosic Sandstone (tr): fine to medium sand size grains, calcareous, argillaceous.
Anhydrite (tr)
Loose Grains (tr): quartz

4150-4160
Sandstone (80%)
Mudstone (20%)
Anhydrite (tr)
Loose Grains (tr): quartz

4160-4170
Sandstone (70%)
Mudstone (20%)
Loose Grains (10%): quartz
Anhydrite (tr)
Limestone (tr)

4170-4180
Sandstone (80%): noncalcareous, about 10% if fine to medium grained.
Mudstone (20%): argillaceous, noncalcareous
Loose Grains (tr): quartz w/minor pyrite, mafic grains
Anhydrite (tr)
Limestone (tr)

4180-4190
Sandstone (70%): fine sand to silt size grains.
Mudstone (20%)
Loose Grains (10%): as above
Anhydrite (tr)
Limestone (tr)

4190-4200
Sandstone (90%)
Mudstone (10%)
Loose Grains (tr): as above
Anhydrite (tr)

4200-4210
Sandstone (80%)
Mudstone (20%)
Loose Grains (tr): as above
Anhydrite (tr)

4210-4220
Sandstone (80%)
Mudstone (20%)
Loose grains (tr): as above
Anhydrite (tr)

4220-4230
Sandstone (70%): tr. is micaceous
Mudstone (20%)
Loose Grains (10%): as above
Anhydrite (tr)
Limestone (tr)

4230-4240
Sandstone (50%)
Mudstone (40%)
Loose grains (10%): quartz w/minor pyrite and mafic grains.
Anhydrite (tr)
Limestone (tr)

4240-4250
Sandstone (40%)
Mudstone (20%)
Loose Grains (30%): as above
Anhydrite (tr)
Limestone (tr)

4250-4260

Sandstone (60%): moderate reddish orange (10R 6/6) to moderate reddish brown (10R 4/6); very fine to fine sand to silt size grains; moderately to poorly sorted; subangular grains; calcareous, tr. is micaceous; quartz wacke to quartz arenite, moderately indurated.

Mudstone (40%): moderate red (5R 5/4) to grayish red dusky red (5R 3/4) to purple (5RP 4/2) to very pale green (10G 8/2); calcareous, argillaceous; poorly indurated.

Loose Grains (tr): quartz w/minor pyrite and mafic grains.

Anhydrite (tr): white (N9) to pinkish gray (5YR 8/1) to bluish gray (5B 9/1); microcrystalline, poorly indurated.

Arkosic Sandstone (tr): same as sandstone except arkosic and contain some mafic grains.

4260-4270

Sandstone (60%)
Mudstone (40%)
Loose Grains (tr): as above
Anhydrite (tr)

4270-4280

Sandstone (60%)
Mudstone (40%)
Loose Grains (tr): as above
Anhydrite (tr)

4280-4290

Sandstone (70%)
Mudstone (20%)
Loose Grains (10%)
Anhydrite (tr)

4290-4300

Sandstone (50%)
Mudstone (50%)
Loose Grains (tr): as above
Anhydrite (tr)

4300-4310

Mudstone (70%)
Sandstone (30%)
Loose Grains (tr): as above
Anhydrite (tr)

4310-4320

Mudstone (60%)
Sandstone (30%)
Loose Grains (10%): as above
Anhydrite (tr)
Arkosic Sandstone (tr)

4320-4330
Mudstone (50%)
Sandstone (30%)
Loose Grains (10%): as above
Arkosic Sandstone (10%)
Anhydrite (tr)

4330-4340
Mudstone (50%)
Loose Grains (30%): as above
Sandstone (20%)
Anhydrite (tr)
Arkosic Sandstone (tr)

4340-4350
Mudstone (50%)
Sandstone (30%)
Loose Grains (20%)
Arkosic Sandstone (tr)

4350-4360
Sandstone (50%)
Mudstone (40%)
Loose Grains (10%): as above
Arkosic Sandstone (tr): some feldspars are altered

4360-4370
Sandstone (50%)
Mudstone (40%)
Loose Grains (10%): as above
Arkosic Sandstone (tr)

4370-4380
Mudstone (50%)
Sandstone (30%)
Loose Grains (20%): as above
Arkosic Sandstone (tr)

4380-4390
Mudstone (50%): tr. is micaceous
Sandstone (40%)
Loose Grains (10%): as above
Arkosic Sandstone (tr)

4390-4400
Mudstone (40%): tr. micaceous w./biotite
Sandstone (40%)
Loose Grains (20%): as above
Arkosic Sandstone (tr)

4400-4410
Loose Grains (40%): as above but coarser (some are very coarse sand to very fine pebbles).
Sandstone (30%)

Mudstone (30%)
Arkosic Sandstone (tr)

4410-4420
Loose Grains (30%): quartz w/minor pyrite and mafic grains; fine to very coarse sand to very fine pebble size.
Sandstone (30%)
Mudstone (30%)
Arkosic Sandstone (10%): altered feldspars; arkosic wacke.

4420-4430
Loose Grains (50%): as above
Sandstone (20%)
Mudstone (20%)
Arkosic Sandstone (10%)

4430-4440
Sandstone (60%): 10% is micaceous
Mudstone (30%)
Loose Grains (10%): as above
Arkosic Sandstone (tr)
Anhydrite (tr)

4440-4450
Loose Grains (50%): as above
Sandstone (30%)
Mudstone (20%)
Arkosic Sandstone (tr)

4450-4460
Loose Grains (40%): as above
Sandstone (30%)
Mudstone (20%)
Arkosic Sandstone (10%)

4460-4470
Loose Grains (40%): as above
Sandstone (30%)
Arkosic Sandstone (20%)
Mudstone (10%)

4470-4480
Sandstone (50%)
Loose Grains (20%): as above
Mudstone (20%)
Arkosic Sandstone (10%)

Tenneco Oil Company
Federal No. 1
1650' FNL, 1650' FEL, Sec. 35, T1S, R13W
Catron Co., New Mexico
Elev.: 8020.4' (GL), 8035' (KB); T.D. 7900

Depth (ft.) **Percent-Description**

6860-6870
Mudstone (50%): moderate orange pink (10R 7/4) to moderate reddish orange (10R 6/6) to medium light gray (N6); silty, calcareous; poorly indurated.
Siltstone (30%): moderate orange pink (10R 7/4) to moderate reddish orange (10R 6/6) to medium light gray (N6); calcareous; moderately indurated.
Limestone (20%): light gray (N7) to very light gray (N8); microcrystalline; lime mudstone; well indurated.
Anhydrite (tr): very light gray (N8) to light greenish gray (5GY 8/1); microcrystalline; poorly indurated.

6880-6890
Siltstone (50%)
Mudstone (40%)
Limestone (10%)
Anhydrite (tr)

6890-6900
Siltstone (50%)
Mudstone (30%)
Limestone (20%)
Anhydrite (tr)

6900-6910
Mudstone (50%)
Siltstone (30%)
Limestone (20%)
Anhydrite (tr)

6950-6960
Siltstone (50%): moderate reddish orange (10R 6/6) to pale reddish purple (5RP 6/2) to dark gray (N3) to medium light gray (N4); calcareous; moderately indurated.
Mudstone (40%): moderate reddish orange (10R 6/6) to pale reddish purple (5RP 6/3) to medium bluish gray (5B 5/1) to medium dark gray (N4); silty; calcareous; poorly indurated.
Limestone (10%): light gray (N7) to very light gray (N8); microcrystalline; lime mudstone; well indurated.
Anhydrite (tr): very light gray (N8) to light bluish gray (5B 7/1); microcrystalline; poorly indurated.

6990-7000
Siltstone (60%): tr. w/mafic grains
Mudstone (40%): argillaceous
Anhydrite (tr)

7000-7010
Siltstone (60%): tr. w/mafic grains
Mudstone (40%): silty
Anhydrite (tr)
Sandstone (tr): pale reddish brown (10R 4/6); very fine to fine grained; moderately sorted; subangular to subrounded grains; calcareous; quartz arenite to quartz wacke; moderately indurated.

7040-7050
Siltstone (50%)
Mudstone (50%)
Anhydrite (tr)
Sandstone (tr)

7100-7110
Mudstone (60%)
Siltstone (40%)
Sandstone (tr)
Anhydrite (tr)
Limestone (tr)

7130-7140
Siltstone (50%): moderate reddish orange (10R 6/6) to pale reddish purple (5RP 6/2); calcareous; moderately indurated.
Mudstone (50%): moderate reddish orange (10R 6/6) to pale reddish purple (5RP 6/2); silty, calcareous; poorly indurated.
Anhydrite (tr): very light gray (N8) to light bluish gray (5B 7/1); microcrystalline; poorly indurated.

7140-7150
Siltstone (50%)
Mudstone (50%)
Anhydrite (tr)

7150-7160
Mudstone (60%)
Siltstone (40%)
Anhydrite (tr)

7160-7170
Mudstone (50%)
Siltstone (50%): 10% w/mafic grains
Anhydrite (tr)

7170-7180
Siltstone (60%)

Mudstone (40%): 20% anhydritic
Anhydrite (tr)
Sandstone (tr)

7180-7190
Siltstone (50%)
Mudstone (50%)
Anhydrite (tr)

7190-7200
Siltstone (50%)
Mudstone (50%)
Anhydrite (tr)
Sandstone (tr)

7200-7210
Mudstone (50%)
Siltstone (40%)
Sandstone (10%): pale reddish brown (10R 5/4) to light greenish gray (5G 8/1); very fine to fine grained; moderately sorted; subangular to subrounded grains; calcareous; mafic grains, feldspars in about 1/3 of sandstones; quartz wacke to arkosic wacke; moderately indurated.
Anhydrite (tr)

7210-7220
Siltstone (50%): w/mafic grains
Mudstone (40%): silty
Sandstone (10%)
Anhydrite (tr)

7220-7230
Siltstone (50%)
Mudstone (40%)
Sandstone (10%)
Anhydrite (tr)

7230-7240
Siltstone (40%)
Mudstone (40%)
Sandstone (20%): 10% arkosic
Anhydrite (tr)

7240-7250
Siltstone (40%)
Sandstone (40%): 30% arkosic
Mudstone (20%)
Anhydrite (tr)

7250-7260
Mudstone (50%)
Siltstone (40%)
Sandstone (10%): arkosic

Anhydrite (tr)

7260-7270
Siltstone (40%)
Mudstone (40%)
Sandstone (20%): arkosic
Anhydrite (tr)

7270-7280
No Sample

7280-7290
Mudstone (60%): moderate reddish brown (10R 4/6) to gray red (5R 4/2) to grayish green (5G 4/2); silty, calcareous; poorly indurated.
Siltstone (40%): moderate reddish orange (10R 6/6) to moderate red (5R 4/6) to light red (5R 6/6); calcareous, micaceous; mafic grains; moderately indurated.
Sandstone (tr): moderate reddish orange (10R 6/6) to moderate reddish brown (10R 4/6); very fine to fine grained; moderately sorted; subangular to subrounded grains; calcareous; biotite, muscovite, mafic grains; arkosic wacke to arkosic arenite.
Anhydrite (tr): very light gray (N8) to light greenish gray (5GY 8/1); microcrystalline; poorly indurated.

7290-7300
Mudstone (70%)
Siltstone (30%)
Sandstone (tr)
Anhydrite (tr)

7300-7310
No Sample

7310-7320
Mudstone (70%)
Siltstone (30%)
Sandstone (tr)
Anhydrite (tr)

7320-7330
Mudstone (50%)
Siltstone (30%)
Sandstone (20%)
Anhydrite (tr)

7330-7340
Siltstone (50%)
Mudstone (40%)
Sandstone (10%)
Anhydrite (tr)

7340-7350
Siltstone (50%): nonmicaceous
Mudstone (50%)
Sandstone (tr): nonarkosic; anhydritic; still contains mafic grains and some biotite; texturally the same as the sandstone above.
Anhydrite (tr)

7350-7360
Siltstone (40%)
Mudstone (40%)
Sandstone (20%)
Anhydrite (tr)

7360-7370
Siltstone (40%)
Mudstone (30%)
Sandstone (30%)
Anhydrite (tr)

7370-7380
Mudstone (50%)
Siltstone (40%)
Sandstone (10%)
Anhydrite (tr)

7380-7390
Siltstone (60%)
Mudstone (40%)
Sandstone (tr)
Anhydrite (tr)

7390-7400
Siltstone (50%): micaceous
Mudstone (40%)
Sandstone (10%): not anhydritic
Anhydrite (tr)

7400-7410
No Sample

7410-7420
Siltstone (40%)
Mudstone (40%): argillaceous
Sandstone (20%)
Anhydrite (tr)

7420-7430
Mudstone (50%): dolomitic
Siltstone (40%)
Sandstone (10%)
Anhydrite (tr)

7430-7440

Mudstone (60%)
Siltstone (20%)
Dolostone (20%): medium gray (N5) to light gray (N7); microcrystalline; well indurated.
Sandstone (tr)
Anhydrite (tr)

7440-7450
Mudstone (50%)
Siltstone (40%)
Anhydrite (10%)
Sandstone (tr)
Dolostone (tr)

7450-7460
Mudstone (50%): anhydritic
Siltstone (30%)
Anhydrite (10%)
Sandstone (10%): 1/2 nonarkosic, 1/2 arkosic

7460-7470
Siltstone (50%)
Mudstone (30%): silty
Anhydrite (10%)
Sandstone (10%)

7470-7480
Siltstone (40%)
Mudstone (40%): calcareous
Sandstone (20%)
Anhydrite (tr)

7480-7490
Siltstone (40%)
Mudstone (40%)
Sandstone (20%)
Anhydrite (tr)

7490-7500
Siltstone (40%)
Mudstone (30%)
Sandstone (30%): 1/2 nonarkosic, 1/2 arkosic
Anhydrite (tr)

7500-7510
Mudstone (50%)
Siltstone (30%)
Sandstone (20%)
Anhydrite (tr)

7510-7520
Mudstone (60%)
Siltstone (40%)
Sandstone (tr)

Anhydrite (tr)

7520-7530

Mudstone (50%): moderate reddish brown (10R 4/6) to grayish red (5R 4/2); calcareous; moderately indurated.

Siltstone (40%): moderate reddish orange (10R 6/6) to brownish gray (5YR 4/1); calcareous; mafic grains; moderately indurated.

Sandstone (10%): moderate reddish orange (10R 6/6) to moderate reddish brown (10R 4/6); very fine to fine grained; moderately sorted; subangular to subrounded grains; calcareous; mafic grains, about 1/2 also contains biotite and feldspars (some are altered); quartz wacke to arkosic wacke to quartz arenite to arkosic arenite; moderately to poorly indurated.

Anhydrite (tr): very light gray (N8) to light greenish gray (5GY 8/1); microcrystalline; poorly indurated.

Loose Grains (tr): loose quartz grains; fine to medium sand size.

7530-7540

Mudstone (50%)
Siltstone (40%)
Sandstone (10%): 1/2 nonarkosic, 1/2 arkosic
Anhydrite (tr)

7540-7550

Mudstone (60%)
Siltstone (40%)
Sandstone (tr)
Anhydrite (tr)

7550-7560

Siltstone (50%)
Mudstone (40%)
Sandstone (10%): 1/2 nonarkosic, 1/2 arkosic; texture is the same.
Anhydrite (tr)

7560-7570

Mudstone (60%)
Siltstone (40%)
Sandstone (tr)
Anhydrite (tr)

7570-7580

Mudstone (50%)
Siltstone (50%)
Sandstone (tr)
Anhydrite (tr)

7580-7590

Mudstone (50%)

Siltstone (50%)
Sandstone (tr)
Anhydrite (tr)

7590-7600
Siltstone (50%)
Mudstone (40%): argillaceous
Sandstone (10%): about 3/4 nonarkosic, 1/4 arkosic
Anhydrite (tr)

7600-7621
No Samples

7621-24
Core Chunks
Siltstone: moderate red (5R 4/6); dolomitic, micaceous; well indurated

7624-7625
Core Chunks
Mudstone: brownish gray (5YR 4/1); anhydritic, micaceous; moderately indurated.

7625-7630
Core Chunks
Siltstone: moderate red (5R 4/6); dolomitic, micaceous; mudstone intraclasts; moderately indurated.
Lower foot (7629-7630) grades into mudstone (as above).

7630-7638
Siltstone (50%)
Mudstone (50%)
Anhydrite (tr)

7638-7645
Siltstone (50%)
Mudstone (50%): calcareous
Anhydrite (tr)

7645-7650
Siltstone (50%)
Mudstone (40%)
Sandstone (10%): nonarkosic; still a few contains mafic grains.
Anhydrite (tr)

7650-7655
Siltstone (50%)
Mudstone (40%)
Sandstone (10%)
Anhydrite (tr)

7655-7660
Mudstone (60%)

Siltstone (40%)
Sandstone (tr)
Anhydrite (tr)

7660-7665
Siltstone (60%)
Mudstone (40%)
Sandstone (tr)
Anhydrite (tr)
Loose Grains (tr): fine to medium quartz grains.

7665-7670
Siltstone (50%)
Mudstone (50%)
Sandstone (tr)
Anhydrite (tr)

7670-7675
Siltstone (50%)
Mudstone (50%)
Anhydrite (tr)
Loose Grains (tr): as above

7675-7680
Siltstone (60%)
Mudstone (40%): silty
Anhydrite (tr)

7680-7685
Siltstone (60%)
Mudstone (40%)
Anhydrite (tr)

7685-7690
Mudstone (60%): argillaceous
Siltstone (40%)
Anhydrite (tr)

7690-7695
Mudstone (60%)
Siltstone (40%)
Anhydrite (tr)

7695-7700
Mudstone (50%)
Siltstone (50%)
Anhydrite (tr)

7700-7705
Mudstone (50%): moderate reddish orange (10R 6/6) to moderate orange pink (10R 7/4) to grayish red (5R 4/2); argillaceous, calcareous; poorly indurated.
Siltstone (50%): moderate reddish orange (10R 6/6) to light red (5R 6/6); calcareous to dolomitic; mafic

grains moderately indurated.
Sandstone (tr): moderate reddish orange (10R 6/6) to light red (5R 6/6); very fine to fine grained; moderately sorted; subangular grains; calcareous, micaceous; mafic grains; lithic wacke; moderately indurated.
Anhydrite (tr): very light gray (N8); microcrystalline; poorly indurated.

7705-7710
Mudstone (60%)
Siltstone (40%)
Sandstone (tr)
Anhydrite (tr)

7710-7715
Mudstone (60%)
Siltstone (40%)
Sandstone (tr)
Anhydrite (tr)

7715-7720
Mudstone (50%)
Siltstone (40%)
Sandstone (10%)
Anhydrite (tr)

7720-7725
Mudstone (60%)
Siltstone (40%)
Sandstone (tr)
Anhydrite (tr)

7725-7730
Mudstone (60%)
Siltstone (40%)
Anhydrite (tr)

7730-7740
Mudstone (70%): anhydritic
Siltstone (30%)
Anhydrite (tr)

7740-7745
Mudstone (50%)
Siltstone (50%)
Anhydrite (tr)

7745-7750
Mudstone (50%)
Siltstone (50%)
Anhydrite (tr)
Sandstone (tr)

7750-7760
Siltstone (50%)
Mudstone (40%): silty
Sandstone (10%): very fine to fine grained lithic wacke.
Anhydrite (tr)

7760-7770
Siltstone (50%)
Mudstone (50%)
Sandstone (tr)
Anhydrite (tr)
Loose Grains (tr): loose quartz grains; very fine to medium sand size.

7770-7780
Siltstone (60%): noncalcarous
Mudstone (40%): noncalcareous
Sandstone (tr): arkosic and lithic wacke.
Anhydrite (tr)
Loose Grains (tr): as above

7780-7790
Siltstone (50%)
Mudstone (40%)
Sandstone (10%): moderate reddish orange (10R 6/6) to moderate reddish brown (10R 4/6); very fine to medium grained; poorly sorted; angular to subrounded grains; noncalcareous; biotite, muscovite, mafic grains, altered feldspars; arkosic wacke; poorly indurated.
Loose Grains (tr): as above
Anhydrite (tr)

7790-7800
Siltstone (50%): w/mafic grains, micaceous
Mudstone (40%): silty, micaceous
Sandstone (10%)
Loose Grains (tr): as above
Anhydrite (tr)

7800-7810
No Sample

7810-7820
Mudstone (60%)
Siltstone (40%)
Sandstone (tr): 1/2 is nonarkosic; quartz wacke w/minor mafic grains; texturally similar; moderately indurated.
Loose Grains (tr): as above
Anhydrite (tr)

7820-7825
Mudstone (40%)

Siltstone (40%)
Sandstone (10%): about 1/2 is arkosic wacke, 1/2 is quartz wacke; very fine to coarse grained; very poorly sorted; poorly to moderately indurated.
Loose Grains (10%): quartz grains w/ minor mafic grains.

7825-7830
Siltstone (50%)
Mudstone (30%)
Sandstone (10%): as above, mildly calcareous.
Loose Grains (10%): as above

7830-7835
Siltstone (60%)
Mudstone (20%)
Sandstone (10%): 1/2 arkosic wacke, 1/2 quartz wacke; both contain mafic grains, and some micas.
Loose Grains (10%): as above

7835-7840
Siltstone (50%)
Mudstone (30%)
Sandstone (10%)
Loose Grains (10%)
Anhydrite (tr)

7840-7845
Siltstone (50%)
Mudstone (40%)
Anhydrite (10%)
Loose Grains (tr): as above

7845-7850
Siltstone (50%): noncalcareous; mafic grains.
Mudstone (30%): silty; about 1/4 is micaceous.
Anhydrite (10%)
Loose Grains (10%): quartz w/mafic grains; fine to coarse grained; angular to rounded.
Sandstone (tr)

7850-7855
Siltstone (40%)
Loose Grains (30%): as above
Mudstone (20%)
Sandstone (10%): moderate reddish orange (10R 6/6); very fine to medium grained; poorly sorted; angular to subangular grains; noncalcareous; mafic grains, altered feldspars in about 1/3 of sandstones; quartz to arkosic wacke; poorly to moderately indurated.
Anhydrite (tr)

7855-7860
Siltstone (50%)

Mudstone (40%)
Loose Grains (10%): as above
Sandstone (tr)
Anhydrite (tr)

7860-7865
Siltstone (50%)
Mudstone (30%)
Loose Grains (20%): as above
Sandstone (tr)

7865-7870
Siltstone (40%)
Mudstone (30%)
Loose Grains (20%): as above
Sandstone (10%): 3/4 nonarkosic (quartz wacke); 1/4 arkosic (arkosic wacke); texture same as above.
Granite (tr): pinkish gray (5YR 8/1) to moderate orange pink (10R 7/4) to moderate reddish orange (10R 6/6); coarsely crystalline; quartz-rich, minor amounts of biotite, mafic grains and pyrite; quartz-rich granitoid(?).

7870-7875
Siltstone (40%)
Mudstone (40%)
Loose Grains (20%): as above
Sandstone (tr)
Granite (tr)

7875-7880
Mudstone (40%)
Siltstone (30%)
Loose Grains (20%): as above
Granite (10%)
Sandstone (tr): mostly arkosic wacke; mafic grains, micaceous.

7880-7885
Mudstone (40%)
Loose Grains (30%): mostly quartz; possibly fragments of the granite.
Siltstone (20%)
Granite (10%)
Sandstone (tr)

7885-7890
Mudstone (30%)
Siltstone (30%)
Loose Grains (30%); as above
Granite (10%)
Sandstone (tr)

7890-7895

Siltstone (30%)
Loose Grains (30%): as above
Mudstone (20%)
Granite (20%)

7895-7900
Loose Grains (40%): as above
Siltstone (30%)
Mudstone (20%)
Granite (10%)

Reese & Jones
Tecolote No. 1
1650' FSL, 1980' FEL, Sec. 8, T6N, R3W
Valencia Co., New Mexico
Elev.: 6285' (GL), 6296' (KB); T.D. 3512'

Depth (ft.) **Percent-Description**

690-700

Dolostone (100%): medium gray (N5) to medium dark gray (N4); microcrystalline; well indurated.

Sandstone (tr): grayish pink (5R 8/2) to grayish orange pink (10R 8/2); very fine to fine grained; moderately sorted; subangular to subrounded grains; dolomitic; quartz arenite to quartz wacke; moderately to well indurated.

Mudstone (tr): moderate orange pink (10R 7/4) to moderate reddish orange (10R 6/6); dolomitic, anhydritic; poorly to moderately indurated.

750-760

Sandstone (70%): moderate reddish orange (10R 6/6) to grayish orange pink (10R 8/2); very fine grained; well sorted; subangular to subrounded grains; dolomitic; quartz arenite; moderately indurated.

Siltstone (30%): pale reddish brown (10R 5/4) to reddish brown (10R 4/6); dolomitic; moderately to well indurated.

850-860

Sandstone (90%): grayish orange pink (10R 8/2) to moderate reddish orange (10R 6/6) to very light gray (N8); very fine to fine grained; moderately to well sorted; subangular to subrounded grains; slightly dolomitic; quartz arenite.

Siltstone(10%): pale reddish brown (10R 5/4) moderate reddish brown (10R 4/6) to grayish orange pink (10R 8/2); dolomitic; moderately indurated.

Mudstone (tr): moderate orange pink (10R 7/4) to moderate reddish orange (10R 6/6); silty, dolomitic; poorly to moderately indurated.

860-870

Sandstone (80%)
Siltstone (20%)
Mudstone (tr)

870-880

Siltstone (70%)
Sandstone (10%)
Mudstone (10%): also moderate reddish brown (10R 4/6); argillaceous.

Anhydrite (10%): white (N9) to very light gray (N8); microcrystalline.

880-890
Sandstone (90%)
Anhydrite (10%)
Mudstone (tr)

890-900
Sandstone (80%): w/minor mafic grains.
Mudstone (10%)
Anhydrite (10%)
Siltstone (tr)

900-910
Sandstone (40%)
Siltstone (40%)
Mudstone (10%): anhydritic
Anhydrite (10%)

910-920
Siltstone (40%)
Sandstone (30%)
Anhydrite (20%)
Mudstone (10%)

920-930
Siltstone (50%); moderate red (5R 5/4 to 5R 4/6) to very light gray (N8) to pinkish gray (5YR 8/1); calcareous; moderately indurated.
Mudstone (40%): moderate red (5R 4/6) to light red (5R 6/6) to pale green (10G 6/2); silty, calcareous; moderately to poorly indurated.
Anhydrite (10%): white (N9) to very light gray (N8); microcrystalline; poorly indurated

930-940
Siltstone (50%)
Mudstone (50%)
Anhydrite (tr)

940-950
Siltstone (50%)
Mudstone (50%)

950-960
Mudstone (60%)
Siltstone (40%)
Anhydrite (tr)

960-970
Mudstone (70%)
Siltstone (30%)
Sandstone (tr): moderate red (5 R 4/6)to pinkish gray

(5YR 8/1); very fine sand to silt size grains; moderately sorted; subangular grains; noncalcareous; mafic grains; quartz arenite to quartz wacke; moderately indurated.
Anhydrite (tr)

970-980
Mudstone (60%)
Siltstone (40%)
Anhydrite (tr)

980-990
Mudstone (60%)
Siltstone (30%)
Anhydrite (10%)

990-1000
Mudstone (80%)
Siltstone (20%)
Anhydrite (tr)

1000-1010
Mudstone (60%)
Siltstone (40%) nonmicaceous
Anhydrite (tr)

1010-1020
Mudstone (60%)
Siltstone (40%)
Anhydrite (tr)

1020-1030
Siltstone (50%)
Sandstone (40%): moderate red (5R 5/4) to very light gray (N8) to pinkish gray (5YR 8/1); very fine to fine grained; moderately sorted; subrounded to subangular grains; quartz arenite to quartz wacke; moderately indurated.
Mudstone (10%): moderate red (5R 4/6) to light red (5R 6/6) to pale green (10G 6/2); silty to argillaceous (variable), noncalcareous, locally anhydritic; poorly indurated.

1030-1040
Siltstone (50%): noncalcareous
Sandstone (30%)
Mudstone (20%)
Anhydrite (tr)

1040-1050
Mudstone (80%)
Siltstone (20%)
Sandstone (tr)
Anhydrite (tr)

1050-1060
Mudstone (70%)
Siltstone (30%)
Anhydrite (tr)

1060-1070
Siltstone (80%)
Mudstone (20%)
Anhydrite (tr)

1070-1080
Mudstone (70%)
Siltstone (30%)

1080-1090
Mudstone (90%)
Siltstone (10%)
Anhydrite (tr)

1090-1100
Mudstone (70%)
Siltstone (30%)

1100-1110
Mudstone (80%)
Siltstone (20%)
Anhydrite (tr)

1110-1120
Mudstone (50%)
Siltstone (50%)
Sandstone (tr)

1120-1130
Siltstone (60%)
Mudstone (40%): silty

1130-1140
Siltstone (50%)
Mudstone (50%)

1140-1150
Mudstone (60%)
Siltstone (40%)
Anhydrite (tr)

1150-1160
Mudstone (70%)
Siltstone (30%)
Anhydrite (tr)

1160-1170
Mudstone (70%): moderate pink (5R 7/4) to moderate red (5R 4/6) to pale green (10G 6/2); silty, calcareous;

poorly to moderately indurated.
Siltstone (30%): moderate red (5R 5/4 to 5R 4/6) to very light gray (N8) to pinkish gray (5YR 8/1); micaceous, calcareous; mafic grains; moderately indurated.
Anhydrite (tr): very light gray (N8); microcrystalline, poorly indurated.

1170-1180
Sandstone (40%): moderate red (5R 5/4) to very light gray (N8) to pinkish gray (5YR 8/1); very fine sand to silt size grains; moderately sorted; subangular to subrounded grains; calcareous, locally anhydritic; altered feldspars; arkosic arenite to arkosic wacke to quartz arenite to quartz wacke; moderately indurated.
Siltstone (30%)
Mudstone (30%)
Anhydrite (tr)

1180-1190
Sandstone (60%)
Siltstone (20%)
Mudstone (20%)

1190-1200
Siltstone (40%)
Sandstone (30%)
Mudstone (30%)
Anhydrite (tr)

1200-1210
Siltstone (60%)
Mudstone (30%)
Sandstone (10%)
Anhydrite (tr)

1210-1220
Mudstone (60%)
Siltstone (30%): nonmicaceous
Sandstone (10%): all quartz arenite.

1220-1230
Mudstone (50%)
Siltstone (30%)
Sandstone (20%)

1230-1240
Mudstone (50%)
Siltstone (30%)
Sandstone (20%)

1240-1250
Mudstone (60%)
Siltstone (30%)

Sandstone (10%): very fine grained
Anhydrite (tr)

1250-1260
Mudstone (70%)
Siltstone (30%): micaceous
Anhydrite (tr)

1260-1270
Mudstone (50%)
Siltstone (50%)
Anhydrite (tr)

1270-1280
Mudstone (70%): noncalcareous, poorly indurated
Siltstone (30%): noncalcareous
Anhydrite (tr)

1280-1290
Mudstone (50%)
Siltstone (40%)
Sandstone (10%) noncalcareous

1290-1300
Mudstone (60%)
Siltstone (40%)
Sandstone (tr)

1300-1310
No Sample

1310-1330
Poor Samples: appears to be about 80% mudstone; 20% siltstone.

1330-1340
Mudstone (90%)
Siltstone (10%)
Anhydrite (tr)

1340-1350
Mudstone (80%)
Siltstone (20%)
Anhydrite (tr)

1350-1360
Mudstone (100%)
Siltstone (tr)
Anhydrite (tr)

1360-1370
Mudstone (80%): some contains limestone nodules
Siltstone (20%)
Anhydrite (tr)

1370-1380
Mudstone (100%)
Siltstone (tr)
Anhydrite (tr)

1380-1390
Mudstone (100%)
Siltstone (tr)
Anhydrite (tr)

1390-1400
Mudstone (90%)
Siltstone (10%)
Anhydrite (tr)

1400-1410
Mudstone (90%): moderate red (5R4/6, 5R 5/4) to light red (5R 6/6) to pale green (10G 6/2); argillaceous to silty (variable); calcareous, some cuttings contain mudstone associated with limestone; poorly indurated.
Siltstone (10%): moderate red (5R 4/6) to pinkish gray (5YR 8/1) to very light gray (N8); calcareous; mafic grains; moderately indurated.
Limestone (tr): medium bluish gray (5B 5/1); microcrystalline; "dirty" (contains silt and clay); always closely associated with mudstone; moderately to well indurated.

1410-1420
Mudstone (100%): argillaceous, calcareous.
Siltstone (tr)

1420-1430
Mudstone (100%)
Siltstone (tr)
Anhydrite (tr)

1430-1440
Mudstone (90%)
Siltstone (10%)
Anhydrite (tr)

1440-1450
Mudstone (100%)
Siltstone (tr)

1450-1460
Mudstone (100%)
Siltstone (tr)

1460-1470
Mudstone (100%): silty
Siltstone (tr)

1470-1480
Mudstone (100%)
Siltstone (tr)
Anhydrite (tr)

1480-1490
Mudstone (100%)
Siltstone (tr)
Anhydrite (tr)

1490-1500
Mudstone (100%)
Siltstone (tr)
Anhydrite (tr)

1500-1510
Mudstone (100%)
Siltstone (tr)
Anhydrite (tr)

1510-1520
Mudstone (100%)
Siltstone (tr)
Anhydrite (tr)

1520-1530
Mudstone (100%): silty to argillaceous (variable).
Siltstone (tr)
Anhydrite (tr)

1530-1540
Mudstone (100%)
Siltstone (tr)
Anhydrite (tr)
Limestone (tr): medium bluish gray (5B 5/1); microcrystalline; "dirty" (contains silt and clay); closely associated with mudstone; moderately to well indurated.

1540-1550
Mudstone (100%)
Siltstone (tr)
Anhydrite (tr)
Limestone (tr)

1550-1560
Mudstone (100%)
Siltstone (tr)
Anhydrite (tr)
Limestone (tr)

1560-1570
Mudstone (80%)
Siltstone (20%)

Limestone (tr)

1570-1580
Mudstone (70%)
Siltstone (30%)
Limestone (tr)

1580-1590
Mudstone (70%)
Siltstone (30%)
Limestone (tr)
Anhydrite (tr)

1590-1600
Mudstone (50%)
Siltstone (40%)
Limestone (10%)
Anhydrite (tr)

1600-1610
Limestone (70%): light bluish gray (5 B 7/1) to medium bluish gray (5 B 5/1); microcrystalline; silty; lime mudstone; well indurated.
Siltstone (20%)
Mudstone (10%)

1610-1620
Limestone (70%)
Siltstone (20%): pinkish gray (5YR 8/1) to light red (5R 6/6); calcareous; mafic grains; moderately indurated.
Mudstone (10%): moderate red (5R 4/6) to dusky red (5R 3/4) to grayish red purple (5RP 4/2); silty to argillaceous (variable), calcareous; poorly indurated.
Anhydrite (tr): very light gray (N8); microcrystalline; poorly indurated.

1620-1630
Limestone (80%)
Siltstone (10%)
Mudstone (10%)
Anhydrite (tr)

1630-1640
Limestone (50%)
Sandstone (40%): moderate red (5R 5/4) to very light gray (N8) to pinkish gray (5YR 8/1); very fine to fine grained; moderately sorted; subangular grains; calcareous and locally anhydritic; mafic grains, biotite altered feldspars; arkosic arenite to arkosic wacke.

1640-1650
Limestone (50%)

Sandstone (40%): very fine to medium grained; poorly sorted.
Anhydrite (tr)

1650-1660
Limestone (100%)
Mudstone (tr)
Siltstone (tr)
Sandstone (tr)
Anhydrite (tr)

1660-1670
Mudstone (90%)
Limestone (10%)
Siltstone (tr)
Anhydrite (tr)

1670-1680
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

1680-1690
Mudstone (90%)
Limestone (10%)
Anhydrite (tr)

1690-1700
Mudstone (90%)
Limestone (10%)
Anhydrite (tr)

1700-1710
Mudstone (90%): silty
Limestone (10%)
Anhydrite (tr)

1710-1720
Limestone (60%)
Mudstone (40%): sandy
Anhydrite (tr)

1720-1730
Limestone (80%)
Mudstone (20%)
Anhydrite (tr)

1730-1740
Limestone (70%)
Mudstone (30%)
Anhydrite (tr)

1740-1750
Limestone (60%)

Mudstone (40%)
Sandstone (tr): very fine grained
Anhydrite (tr)

1750-1760
Limestone (90%)
Mudstone (10%): silty
Anhydrite (tr)

1760-1770
Limestone (60%)
Mudstone (40%)
Anhydrite (tr)

1770-1780
Limestone (40%)
Mudstone (30%)
Sandstone (30%): fine to medium grained; poorly sorted; angular to subangular grains; arkosic arenite arkosic wacke.
Anhydrite (tr)

1780-1790
Limestone (60%)
Mudstone (30%)
Sandstone (10%)
Anhydrite (tr)

1790-1800
Limestone (90%)
Mudstone (10%)
Sandstone (tr)
Anhydrite (tr)

1800-1810
Limestone (60%)
Mudstone (40%)
Anhydrite (tr)

1810-1820
Limestone (70%)
Mudstone (30%)
Anhydrite (tr)

1820-1830
Limestone (60%)
Mudstone (30%)
Anhydrite (10%)

1830-1840
Limestone (50%)
Mudstone (40%)
Anhydrite (10%)

1840-1850
  Limestone (60%)
  Mudstone (30%)
  Anhydrite (10%)

1850-1860
  Limestone (90%)
  Mudstone (10%)
  Anhydrite (tr)

1860-1870
  Limestone (90%)
  Anhydrite (10%)
  Mudstone (tr)

1870-1880
  Limestone (70%): silty
  Mudstone (30%)
  Anhydrite (tr)

1880-1890
  Limestone (80%)
  Mudstone (10%)
  Anhydrite (10%)

1890-1900
  Limestone (90%)
  Anhydrite (10%)
  Mudstone (tr)

Shell Oil Company
Shell Laguna Wilson Trust No. 1
1786' FNL, 2080' FWL, Sec. 8, T9N, R1W
Bernalillo Co., New Mexico
Elev.: 5394' (GL), 5415' (KB); T.D. 11107'

Depth (ft.) **Percent-Description**

7190-7200

Siltstone (50%): moderate orange pink (10R 7/4) to moderate reddish orange (10R 6/6) to light brownish gray (5YR 6/1); dolomitic; moderately indurated.

Mudstone (40%): moderate reddish orange (10R 6/6) to light red (5R 6/6); argillaceous to silty (variable), dolomitic, anhydritic; poorly to moderately indurated.

Dolostone (10%): medium gray (N5); microcrystalline; silty; well indurated.

Anhydrite (tr): very light gray (N8) to light greenish gray (5G 8/1); microcrystalline; poorly indurated.

Sandstone (tr): moderate orange pink (10R 7/4); very fine to fine grained; moderately sorted; subangular to subrounded; anhydritic; moderately indurated.

7200-7210
Mudstone (50%)
Siltstone (40%)
Sandstone (10%)
Dolostone (tr)
Anhydrite (tr)

7240-7250
Mudstone (40%)
Siltstone (40%)
Sandstone (20%)
Anhydrite (tr)

7270-7280
Siltstone (50%)
Mudstone (40%)
Sandstone (10%)
Anhydrite (tr)

7300-7310

Sandstone (40%): moderate orange pink (10R 7/4) to moderate reddish orange (10R 6/6); very fine to fine grained; moderately sorted; subangular to subrounded grains; dolomitic; mafic grains, minor feldspars in some cuttings; quartz arenite to quartz wacke (locally near a arkosic wacke); moderately indurated.

Siltstone (30%): moderate orange pink (10R 7/4) to moderate reddish orange (10R 6/6); dolomitic; some mafic grains; well indurated.

Mudstone (30%): moderate reddish orange (10R 6/6) to moderate red (5R 6/6); argillaceous, dolomitic; poorly indurated.

7340-7350
Sandstone (80%)
Mudstone (20%)
Siltstone (tr)
Anhydrite (tr)

7370-7380
Sandstone (60%)
Mudstone (20%)
Siltstone (20%)
Anhydrite (tr)

7400-7410
Sandstone (40%): moderate reddish orange (10R 6/6) to moderate orange pink (10R 7/4) to moderate reddish brown (10R 4/6); very fine to fine grained; moderately sorted; subangular to subrounded grains; dolomitic, some are anhydritic; mafic grains, feldspars in some cuttings; quartz arenite to arkosic arenite; moderately indurated.
Mudstone (40%): moderate reddish orange (10R 6/6) to moderate red (5R 5/4) to light red (5R 6/6); argillaceous to silty (variable), dolomitic, some are anhydritic; poorly to moderately indurated.
Siltstone (20%): moderate reddish orange (10R 6/6) to moderate orange pink (10R 7/4) to moderate reddish brown (10R 4/6); dolomitic; some mafic grains; moderately indurated.
Anhydrite (tr): very light gray (N8) to light greenish gray (5G 8/1); microcrystalline; poorly indurated.

7410-7420
Mudstone (40%)
Sandstone (30%)
Siltstone (30%)
Anhydrite (tr)

7420-7430
Mudstone (50%)
Siltstone (30%)
Sandstone (20%)
Anhydrite (tr)

7430-7440
Sandstone (50%): all quartz arenite to quartz wacke (no arkosic sandstone).
Mudstone (30%)
Siltstone (20%)

7440-7450
Siltstone (50%)

Mudstone (30%)
Sandstone (20%)

7450-7460
Sandstone (40%)
Siltstone (30%)
Mudstone (30%)
Anhydrite (tr)

7460-7470
Sandstone (60%)
Siltstone (20%)
Mudstone (20%)
Anhydrite (tr)

7470-7480
Siltstone (50%)
Sandstone (30%)
Mudstone (20%): 1/4 is anhydritic
Anhydrite (tr)

7480-7490
Siltstone (50%)
Mudstone (30%)
Sandstone (20%)
Anhydrite (tr)

7490-7500
Siltstone (60%)
Mudstone (30%)
Sandstone (10%)
Anhydrite (tr)

7500-7510
Siltstone (70%)
Mudstone (30%)
Sandstone (tr)
Anhydrite (tr)

7510-7520
Siltstone (60%)
Mudstone (40%)
Sandstone (tr)
Anhydrite (tr)

7520-7530
Siltstone (70%)
Mudstone (30%)
Sandstone (tr)
Anhydrite (tr)

7530-7540
Siltstone (70%): moderate reddish brown (10R 4/6); dolomitic; moderately to well indurated.

Mudstone (30%): moderate red (5R 4/6) to grayish red purple (5RP 4/2); silty, dolomitic; poorly to moderately indurated.
Anhydrite (tr): very light gray (N8) to light greenish gray (5G 8/1); microcrystalline; poorly indurated.

7540-7550
Mudstone (60%)
Siltstone (40%)
Anhydrite (tr)

7550-7560
Mudstone (50%)
Siltstone (50%)
Anhydrite (tr)

7560-7570
Siltstone (60%): pale red (10R 6/2) locally.
Mudstone (40%)
Anhydrite (tr)

7570-7580
Siltstone (60%)
Mudstone (40%)
Anhydrite (tr)

7580-7590
Siltstone (60%)
Mudstone (40%): also light greenish gray (5G 8/1).
Anhydrite (tr)

7590-7600
Siltstone (50%)
Mudstone (50%)
Anhydrite (tr)

7600-7610
Siltstone (60%)
Mudstone (40%)
Anhydrite (tr)

7610-7620
Siltstone (70%)
Mudstone (30%): silty
Anhydrite (tr)

7620-7630
Mudstone (60%): calcareous
Siltstone (40%): calcareous
Anhydrite (tr)

7630-7640
Mudstone (50%): tr. appears to have limestone nodules.
Siltstone (50%)

Anhydrite (tr)

7640-7650
Mudstone (60%)
Siltstone (40%)
Anhydrite (tr)

7650-7660
Mudstone (50%)
Siltstone (50%)
Anhydrite (tr)

7660-7670
Siltstone (60%)
Mudstone (40%)
Anhydrite (tr)

7670-7680
Siltstone (60%): w/mafic grains
Mudstone (40%)
Anhydrite (tr)

7680-7690
Siltstone (70%)
Mudstone (30%)
Anhydrite (tr)

7690-7700
Siltstone (50%)
Mudstone (50%)
Anhydrite (tr)

7700-7710
Mudstone (70%): noncalcareous
Siltstone (30%): noncalcareous
Anhydrite (tr)

7710-7720
Mudstone (70%): moderate red (5R 4/6) to grayish red purple (5RP 4/2) to light greenish gray (5G 8/1); noncalcareous, silty; poorly indurated.
Siltstone (30%): moderate reddish brown (10R 4/6) to grayish red (10R 4/2) to dark reddish brown (10R 3/4); silt size grains with very fine sand size grains locally; noncalcareous; mafic grains; moderately indurated.
Anhydrite (tr): very light gray (N8); microcrystalline; poorly indurated.

7720-7730
Mudstone (70%)
Siltstone (30%)
Anhydrite (tr)

7730-7740
Mudstone (60%)
Siltstone (40%)
Anhydrite (tr)
Sandstone (tr): moderate red (5R 5/4) to pale red (5R 6/6); very fine to fine grained; poorly to moderately sorted; subangular to subrounded grains; argillaceous, calcareous; mafic grains; arkosic wacke; moderately to well indurated.

7740-7750
Siltstone (40%)
Mudstone (30%)
Sandstone (30%)
Anhydrite (tr)

7750-7760
Mudstone (50%)
Siltstone (40%)
Sandstone (10%)
Anhydrite (tr)

7760-7770
Mudstone (50%): argillaceous, noncalcareous
Siltstone (40%)
Sandstone (10%)
Anhydrite (tr)

7770-7780
Mudstone (60%)
Siltstone (40%)
Sandstone (tr)
Anhydrite (tr)

7780-7790
Mudstone (70%): tr. appears to have limestone nodules.
Siltstone (30%)
Sandstone (tr)
Anhydrite (tr)

7790-7800
Mudstone (70%)
Siltstone (30%)
Anhydrite (tr)

7800-7810
Mudstone (60%)
Siltstone (40%)
Anhydrite (tr)

7810-7820
Mudstone (50%)
Siltstone (50%)
Anhydrite (tr)

7820-7830
Mudstone (50%)
Siltstone (50%)
Anhydrite (tr)
Sandstone (tr): calcareous

7830-7840
Mudstone (50%)
Siltstone (50%): anhydritic
Anhydrite (tr)

7840-7850
Siltstone (60%)
Mudstone (40%)
Anhydrite (tr)

7850-7860
Siltstone (50%): calcareous
Mudstone (50%): calcareous
Anhydrite (tr)

7860-7870
Mudstone (60%): silty
Siltstone (40%)
Anhydrite (tr)

7870-7880
Mudstone (80%): tr. appear to have limestone nodules
Siltstone (20%)
Anhydrite (tr)

7880-7890
Mudstone (80%)
Siltstone (20%)
Anhydrite (tr)

7890-7900
Mudstone (80%)
Siltstone (20%)
Anhydrite (tr)

7900-7910
Mudstone (100%)
Siltstone (tr)
Anhydrite (tr)

7910-7920
Mudstone (100%): dark reddish brown (10R 3/4) to very dark red (5R 2/6) to grayish brown (5YR 3/2); silty, calcareous; poorly indurated.
Siltstone (tr)

7920-7930
Mudstone (100%)

Siltstone (tr)

7930-7940
Mudstone (100%)
Anhydrite (tr)

7940-7950
Mudstone (100%): tr. w/limestone nodules

7950-7960
Mudstone (100%)

7960-7970
Mudstone (100%): noncalcareous
Anhydrite (tr)

7970-7980
Mudstone (100%)
Siltstone (tr)

7980-7990
Mudstone (100%): argillaceous, calcareous w/common limestone nodules.

7990-8000
Mudstone (100%): also some pale reddish brown (10R 5/4) and greenish gray (5GY 6/1).

8000-8010
Mudstone (100%)
Anhydrite (tr)

8010-8020
Mudstone (100%)

8020-8030
Mudstone (100%)

8030-8040
Mudstone (100%)

8040-8050
Mudstone (100%)

8050-8060
Mudstone (100%): silty and argillaceous (variable).

8060-8070
Mudstone (100%)

8070-8080
Mudstone (100%)

8080-8090

Mudstone (100%)

8090-8100
Mudstone (100%)

8100-8110
Mudstone (100%)
Anhydrite (tr)

8110-8120
Mudstone (100%)
Anhydrite (tr)

8120-8130
Mudstone (100%)

8130-8140
Mudstone (100%)
Anhydrite (tr)

8140-8150
Mudstone (100%)
Anhydrite (tr)

8150-8160
Mudstone (90%)
Limestone (10%): medium light gray (N6) to light olive gray (5Y 6/1); microcrystalline; silty; lime mudstone; well indurated.
Anhydrite (tr)

8160-8170
Mudstone (90%): dark reddish brown (5R 3/4) to moderate reddish brown (10R 6/6) to grayish red (5R 4/2); silty, calcareous w/ calcareous nodules; poorly indurated.
Limestone (10%)
Anhydrite (tr): very light gray (N8); microcrystalline; poorly indurated.

8170-8180
Mudstone (90%)
Limestone (10%)
Anhydrite (tr)

8180-8190
Mudstone (80%): also very dark red (5R 2/6) and minor amounts of medium gray (N5); silty and argillaceous (variable).
Limestone (20%)
Anhydrite (tr)

8190-8200
Mudstone (80%)

Limestone (20%)
Anhydrite (tr)

8200-8210
Mudstone (90%)
Limestone (10%)
Anhydrite (tr)

8210-8220
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)
Sandstone (tr): light brownish gray (5YR 6/1); very fine to fine grained, locally medium grained; poorly to moderately sorted; subangular grains; calcareous, micaceous; pink feldspars; arkosic wacke; moderately indurated.

8220-8230
Mudstone (90%)
Limestone (10%)
Anhydrite (tr)
Sandstone (tr)

8230-8240
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8240-8250
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8250-8260
Mudstone (90%): micaceous
Limestone (10%)
Anhydrite (tr)

8260-8270
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8270-8280
Mudstone (100%): mostly red, only minor gray color.
Limestone (tr)
Anhydrite (tr)

8280-8290
Mudstone (100%)
Limestone (tr)

8290-8300

Mudstone (90%): silty to argillaceous (variable).
Siltstone (10%): moderate reddish brown (10R 5/4); calcareous; mafic grains; moderately indurated.
Limestone (tr)

8300-8310
Mudstone (100%): more gray mudstone, still dominantly red mudstone.
Siltstone (tr)
Limestone (tr)

8310-8320
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8320-8330
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8330-8340
Mudstone (100%): mostly red mudstone
Limestone (tr)
Anhydrite (tr)

8340-8350
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8350-8360
Mudstone (80%)
Sandstone (20%): light brownish gray (5YR 6/1); very fine to medium grained; poorly sorted; subangular grains; calcareous; mafic grains, feldspars in most of the cuttings; arkosic wacke to quartz wacke; moderately indurated.
Limestone (tr)

8360-8370
Mudstone (100%): dominantly red
Sandstone (tr)
Limestone (tr)

8370-8380
Mudstone (100%): more calcareous nodules (getting more calcareous).
Sandstone (tr)
Limestone (tr)

8380-8390
Mudstone (100%): gray mudstone is more prevalent.
Sandstone (tr)

Limestone (tr)
Anhydrite (tr)

8390-8400
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8400-8410
Mudstone (90%)
Limestone (10%): medium light gray (N6) to medium gray (N5); silty; microcrystalline; lime mudstone; moderately indurated.
Anhydrite (tr)

8410-8420
Mudstone (90%): highly calcareous; almost a muddy limestone in some samples.
Limestone (10%)
Anhydrite (tr)

8420-8430
Mudstone (80%): light brownish gray (5YR 6/1) to brownish gray (5YR 4/1); argillaceous to silty (variable); calcareous; poorly indurated.
Limestone (20%)
Anhydrite (tr)

8430-8440
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8440-8450
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8450-8460
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8460-8470
Mudstone (100%)
Limestone (tr)

8470-8480
Mudstone (90%): some red mudstone; mostly gray
Limestone (10%)

8480-8490
Mudstone (70%)
Limestone (30%)

8490-8500
Mudstone (50%)
Limestone (50%)
Anhydrite (tr)

8500-8510
Mudstone (80%)
Limestone (20%)
Anhydrite (tr)

8510-8520
Mudstone (90%)
Limestone (10%)

8520-8530
Mudstone (100%): some red; dominantly gray color.
Limestone (tr)
Anhydrite (tr)

8530-8540
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8540-8550
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8550-8560
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8560-8570
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8570-8580
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8580-8590
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8590-8600
Mudstone (90%): light brownish gray (5YR 6/1) to brownish gray (5YR 4/1) to dark gray (N3) with minor dark reddish brown (10R 3/4); argillaceous,

calcareous; poorly indurated.
Limestone (10%): medium light gray (N6) to medium gray (N5) to medium dark gray (4); microcrystalline; lime mudstone; well indurated.
Anhydrite (tr): very light gray (N8) to light greenish gray (5G 8/1); microcrystalline; poorly indurated.

8600-8610
Mudstone (90%)
Limestone (10%)
Anhydrite (tr)

8610-8620
Mudstone (90%)
Limestone (10%)
Anhydrite (tr)

8620-8630
Mudstone (100%)
Limestone (tr)
Anhydrite (tr)

8630-8640
Mudstone (100%)
Limestone (tr)

8640-8650
Mudstone (90%)
Limestone (10%)

8650-8660
Mudstone (70%)
Limestone (30%)

8680-8690
Mudstone (60%): only a tr. of red mudstone.
Limestone (40%)

8690-8700
Limestone (60%)
Mudstone (40%)

No Samples until 8800'

Claude Huckleberry
Huckleberry Federal No. 1
330' FNL, 330' FEL, Sec. 11, T2N, R16W
Catron Co., New Mexico
Elev.: 7100' (GL), 7108.5' (KB); T.D. 5642'

Note: colors are generally from Foster (1964).

Depth (ft.) Percent-Description

4580-4590

Sandstone (50%): moderate brown (5YR 4/4, 5YR 3/4); very fine to medium grained; poorly to moderately sorted; subrounded to well rounded grains; dolomitic, some cuttings are anhydritic; quartz arenite to quartz wacke; moderately indurated.

Mudstone (20%): moderate (5YR 4/4, 5YR 3/4); silty, dolomitic; poorly to moderately indurated.

Anhydrite (20%): white (N9); microcrystalline; poorly indurated.

Dolostone (10%): pale yellowish brown (10YR 6/2); microcrystalline; anhydritic; lime mudstone; well indurated.

4860-4870

Sandstone (50%): moderate (5YR 4/4, 5YR 3/4); very fine to fine, locally to medium grained; moderately sorted, locally poorly sorted; subrounded to well rounded grains; dolomitic; quartz arenite to quartz wacke; moderately indurated.

Mudstone (40%): moderate (5YR 4/4, 5YR 3/4); silty, dolomitic; poorly to moderately indurated.

Anhydrite (10%): white (N9); microcrystalline; poorly indurated.

Dolostone (tr): pale yellowish brown (10YR 6/2); microcrystalline; anhydritic; lime mudstone; well indurated.

4890-4900

Sandstone (60%): moderate brown (5YR 4/4, 5YR 3/4); very fine to medium grained, locally silt size; poorly to moderately sorted; rounded grains; dolomitic; locally contains biotite and mafic grains; quartz arenite to quartz wacke; moderately indurated.

Dolostone (20%): moderate yellowish brown (10YR 4/2); microcrystalline; silty; well indurated.

Anhydrite (10%): white (N9); microcrystalline; poorly indurated.

Mudstone (10%): moderate brown (5YR 4/4, 5YR 3/4); silty, dolomitic: poorly to moderately indurated.

4900-4910

Siltstone (30%): moderate brown (5YR 4/4, 5YR 3/4);

dolomitic; mafic grains, biotite; well indurated.
Mudstone (30%)
Sandstone (20%)
Dolostone (20%)
Anhydrite (tr)

4910-4920
Siltstone (40%)
Mudstone (30%)
Sandstone (20%)
Dolostone (10%)
Anhydrite (tr)

4920-4930
Siltstone (40%)
Mudstone (40%)
Sandstone (10%)
Dolostone (10%)
Anhydrite (tr)

4930-4940
Mudstone (60%)
Siltstone (40%)
Sandstone (tr)
Dolostone (tr)
Anhydrite (tr)

4940-4950
Mudstone (70%)
Siltstone (30%)
Dolostone (tr)
Anhydrite (tr)

4950-4960
Mudstone (60%)
Siltstone (30%)
Dolostone (10%)
Anhydrite (tr)

4960-4970
Siltstone (60%)
Mudstone (40%)
Dolostone (tr)
Anhydrite (tr)

4970-4980
Siltstone (60%)
Mudstone (30%)
Sandstone (10%)
Dolostone (tr)
Anhydrite (tr)

4980-4990
Siltstone (70%): some cuttings are siliceous; well

indurated.
Mudstone (30%)
Dolostone (tr)
Anhydrite (tr)

4990-5000
Siltstone (60%)
Mudstone (30%)
Dolostone (10%)
Sandstone (tr)
Anhydrite (tr)

5000-5010
Siltstone (70%)
Mudstone (30%): silty to argillaceous (variable).
Dolostone (tr)
Sandstone (tr)
Anhydrite (tr)

5010-5020
Siltstone (80%): nondolomitic, still locally siliceous.
Mudstone (20%): nondolomitic
Dolostone (tr)
Anhydrite (tr)

5020-5030
Siltstone (70%)
Mudstone (30%)
Dolostone (tr)
Anhydrite (tr)

5030-5040
Siltstone (70%)
Mudstone (30%)
Dolostone (tr)
Anhydrite (tr)

5040-5050
Siltstone (70%)
Mudstone (20%)
Sandstone (10%)
Dolostone (tr)
Anhydrite (tr)

5050-5060
Mudstone (50%)
Siltstone (40%)
Sandstone (10%)
Dolostone (tr)
Anhydrite (tr)

5060-5070
Siltstone (40%)
Mudstone (30%)

Sandstone (30%)
Anhydrite (tr)

5070-5080
Siltstone (40%)
Sandstone (30%)
Mudstone (20%)
Anhydrite (tr)

5080-5090
Sandstone (50%): moderate brown (5YR 4/4, 5YR 3/4); very fine, locally to fine grained; well sorted; subrounded, locally subangular, locally well rounded; mafic grains in some cuttings; quartz arenite; moderately indurated.
Mudstone (30%): grayish red (10R 4/2, 5R 4/2); silty; poorly to moderately indurated.
Siltstone (20%): moderate brown (5YR 4/4, 5YR 3/4); moderately to well indurated.
Anhydrite (tr): white (N9); microcrystalline; poorly indurated.

5090-5100
Sandstone (50%)
Mudstone (40%)
Anhydrite (10%)
Dolostone (tr)

5100-5110
Sandstone (60%)
Mudstone (40%): anhydritic
Anhydrite (10%)
Dolostone (tr)

5110-5120
Sandstone (50%)
Mudstone (30%)
Anhydrite (10%)
Dolostone (10%)

5120-5130
Sandstone (50%)
Mudstone (40%)
Anhydrite (10%)
Dolostone (tr)

5130-5140
Sandstone (60%)
Mudstone (30%)
Anhydrite (10%)

5140-5150
Sandstone (70%)
Mudstone (30%): not anhydritic

Anhydrite (tr)

5150-5160
Sandstone (60%)
Mudstone (40%)
Anhydrite (tr)

5160-5170
Sandstone (50%)
Mudstone (50%)
Anhydrite (tr)

5170-5180
Sandstone (50%)
Mudstone (50%)
Anhydrite (tr)

5180-5190
Sandstone (60%)
Mudstone (40%)
Anhydrite (tr)

5190-5200
Sandstone (60%)
Mudstone (40%): silty
Anhydrite (tr)
Siltstone (tr)

5200-5210
Sandstone (50%)
Mudstone (40%)
Siltstone (10%)
Anhydrite (tr)

5210-5220
Sandstone (50%)
Mudstone (40%)
Siltstone (10%)
Anhydrite (tr)

5220-5230
Sandstone (60%)
Mudstone (40%)
Siltstone (tr)
Anhydrite (tr)

5230-5240
Mudstone (60%)
Sandstone (30%)
Siltstone (10%)
Anhydrite (tr)

5240-5250
Mudstone (70%)

Sandstone (20%)
Siltstone (10%)
Anhydrite (tr)

5250-5260
Mudstone (60%)
Sandstone (20%)
Siltstone (20%)
Anhydrite (tr)

5260-5270
Mudstone (60%)
Sandstone (30%)
Siltstone (10%)
Anhydrite (tr)

5270-5280
Mudstone (60%)
Siltstone (30%)
Sandstone (10%)
Anhydrite (tr)

5280-5290
Siltstone (50%): moderate brown (10YR 4/4, 10YR 3/4) moderate reddish brown (10R 4/6); noncalcareous; mafic grains; moderately indurated.
Mudstone (40%): grayish red (10R 4/2, 5R 4/2) to moderate reddish brown (10R 4/6) to dark reddish brown (10R 3/4); noncalcareous, silty; poorly indurated.
Sandstone (10%): moderate brown (5YR 4/4, 5YR 3/4); very fine grained; well sorted; subrounded to rounded grains; some mafic grains; quartz arenite to quartz wacke; moderately indurated.
Anhydrite (tr): white (N9); microcrystalline; poorly indurated.

5290-5300
Siltstone (70%)
Mudstone (30%)
Sandstone (tr)
Anhydrite (tr)

5300-5310
Siltstone (60%)
Mudstone (40%)
Anhydrite (tr)

5310-5320
Siltstone (50%): calcareous
Mudstone (50%): calcareous
Anhydrite (tr)

5320-5330
Mudstone (70%): argillaceous

Siltstone (30%)
Anhydrite (tr)

5330-5340
Mudstone (60%)
Siltstone (40%)
Anhydrite (tr)

5340-5350
Siltstone (50%)
Mudstone (40%): silty to argillaceous (variable)
Anhydrite (10%)

5350-5360
Mudstone (60%)
Siltstone (40%)
Anhydrite (tr)

5360-5370
Mudstone (70%)
Siltstone (30%)
Anhydrite (tr)

5370-5380
Mudstone (60%)
Siltstone (40%)
Anhydrite (tr)

5380-5390
Mudstone (50%)
Siltstone (40%)
Anhydrite (10%)
Sandstone (tr): pale red (10R 6/2, 5R 6/2); coarse to very coarse grained sand to pebble size conglomeratic (loose grains present in the sample); very poorly sorted; angular to subrounded grains; silty, mafic grains; arkosic wacke; poorly indurated.

5390-5400
Mudstone (60%)
Siltstone (40%)
Sandstone (tr)
Anhydrite (tr)

5400-5410
Siltstone (60%)
Mudstone (40%)
Sandstone (tr)

5410-5420
Mudstone (50%)
Siltstone (40%)
Sandstone (10%)
Anhydrite (tr)

5420-5430
Mudstone (60%)
Siltstone (20%)
Sandstone (20%)
Anhydrite (tr)

5430-5440
Mudstone (60%): some cuttings contain biotite.
Sandstone (30%)
Siltstone (10%)
Anhydrite (tr)

5440-5450
Sandstone (40%)
Mudstone (40%)
Siltstone (20%)
Anhydrite (tr)

5450-5460
Sandstone (40%)
Mudstone (30%)
Siltstone (20%)
Abundant Loose Grains in the sample: dominantly quartz.

5460-5470
Sandstone (50%)
Mudstone (40%)
Siltstone (10%)

5470-5480
Sandstone (60%)
Mudstone (40%)
Siltstone (tr)
Quartz Monzonite (tr)

5480-5490
Sandstone (50%)
Mudstone (40%)
Quartz Monzonite (10%)

5490-5500
Sandstone (40%)
Mudstone (30%)
Quartz Monzonite (30%)

APPENDIX D

CARRIZO ARROYO STRATIGRAPHIC SECTION

Surface Stratigraphic Section
Carrizo Arroyo (southeast of Mesa Lucero)
NW1/4, Sec. 6, T6N, R2W to
NE1/4, Sec. 1, T6N, R3W to
SE1/4, Sec. 36, T7N, R3W

Thickness	Description
11 ft. (3.35m)	Siltstone: moderate brown (5YR 4/6); noncalcareous; few mafic grains; tabular bedded; well indurated.
1 ft. (0.3m)	Mudstone: moderate reddish orange (10R 6/6); silty, noncalcareous; poorly indurated.
6 ft. (1.83m)	Siltstone: moderate brown (5YR 4/4) to light brown (5YR 5/6); locally dolomitic; few mafic grains; tabular bedding, very thickly bedded; well indurated.
0.75 ft. (0.23m)	Mudstone: moderate reddish orange (10R 6/6); silty, noncalcareous; thin silt streaks; thinly to very thinly bedded; poorly indurated.
4.5 ft. (1.37m)	Siltstone: moderate brown (5YR 4/4) to light brown (5YR 5/6) to moderate reddish orange (10R 6/6); few mafic grains; tabular bedding; very thickly bedded; moderately to well indurated.
0.5 ft. (0.15m)	Mudstone: moderate reddish orange (10R 6/6); silty; noncalcareous; poorly indurated.
11 ft. (3.35m)	Siltstone: moderate brown (10R 4/4); noncalcareous; few mafic grains; tabular bedding, very thickly bedded; well indurated.

Meseta Blanca Member of the Yeso Formation

Abo Formation (conformable contact)

8.2 ft. (2.5m)	Interbedded Siltstone and Mudstone: Siltstone; moderate brown (5YR 4/4) to moderate reddish brown (10R 4/6); noncalcareous; mafic grains; very thinly to

	thinly bedded; moderately indurated. Mudstone; moderate reddish orange (10R 6/6) to moderate reddish brown (10R 4/6); silty, noncalcareous; very thinly to thinly bedded; poorly indurated.
10.2 ft. (3.1m)	Covered Interval (Mudstone?); slope former.
1 ft. (0.3m)	Siltstone: moderate reddish orange (10R 6/6); noncalcareous; irregular bedding, very thinly to thinly bedded; moderately indurated.
7.2 ft. (2.2m)	Covered Interval (Mudstone?); slope former.
2.6 ft. (0.8m)	Siltstone: light greenish gray (5GY 8/1) to moderate reddish brown (10R 4/6); dolomitic; contains small scale cross-stratification; tabular to irregular bedding, thickly bedded; well indurated.
2 ft. (0.6m)	Mudstone: moderate reddish brown (10R 4/6); silty, calcareous; moderately to poorly indurated.
1 ft. (0.3m)	Mudstone: as above, but with calcareous nodules; grayish red (10R 4/2) to light greenish gray (5GY 8/1); moderately indurated.
22 ft. (6.7m)	Covered Interval (Mudstone?); few local mudstone exposures; slope former.
6.1 ft. (1.86m)	Siltstone: pale reddish brown (10R 5/4) to grayish red (10R 4/2); locally calcareous; mafic grains; irregularly bedding, very thickly bedded; moderately indurated.
31.2 ft. (9.5m)	Interbedded Siltstone and Mudstone: Tabular to irregular bedding, very thinly to medium bedded siltstones and laminated mudstones. Siltstone: moderate reddish orange (10R 6/6) to moderate reddish brown (10R 4/6) with light greenish gray (5GY 8/1) reduction spots; calcareous, locally micaceous; mafic grains; moderately indurated. Mudstone: moderate reddish brown (10R 4/6) to light greenish gray (5GY 8/1); silty, calcareous, locally micaceous; poorly to moderately indurated.
25.6 ft.	Siltstone: grayish red (10R 4/2) to pale

(7.8m)	reddish brown (10R 5/4); with light greenish gray (5GY 8/1) reduction spots; noncalcareous to calcareous; small scale cross-stratification; irregular bedding, very thickly bedded; moderately to well indurated.
3.1 ft. (0.9m)	Covered Interval (Mudstone?): slope former.
16.4 ft. (5.0m)	Siltstone: pale reddish brown (10R 5/4) to moderate reddish brown (10R 4/6); locally calcareous; some mafic grains; small to medium cross-stratification; soft sediment deformation; tabular to irregular bedding, very thickly bedded; moderately indurated.
14.3 ft. (4.36m)	Interbedded Siltstone and Mudstone: tabular to irregular bedding, locally lenticular; thinly to medium bedded siltstones and thinly laminated mudstones. Siltstones: moderate reddish brown (10R 4/6) with light greenish gray (5GY 8/1) reduction spots; noncalcareous, locally siliceous; moderately to well indurated. Mudstones: moderate reddish brown (10R 4/6) with light greenish gray (5GY 8/1) reduction spots; silty, noncalcareous; mudcracks; poorly to moderately indurated.
19.5 ft. (5.9m)	Mudstone: very poorly exposed, largely covered; moderate reddish brown (10R 4/6); noncalcareous; poorly indurated.
6.1 ft. (1.85m)	Siltstone: moderate reddish brown (10R 4/6) to pale reddish brown (10R 5/4); noncalcareous; some mafic grains; tabular to irregular bedding, very thickly bedded; moderately indurated.
28.6 ft. (8.7m)	Mudstone: moderate reddish brown (10R 4/6) with light greenish gray (5GY 8/1) reduction spots; silty to argillaceous, noncalcareous to locally calcareous with calcareous nodules; thinly to thickly laminated; poorly indurated.
21 ft. (6.4m)	Interbedded Siltstone and Mudstone: irregular bedding, very thinly to thinly bedded siltstones and thinly laminated mudstones. Siltstone: grayish red (10R 4/2, 5R 4/2) to yellowish gray (5Y 8/1); argillaceous, dolomitic; few mafic grains; some small scale cross-stratification; moderately to

well indurated. Mudstone: moderate reddish brown (10R 4/6) to grayish red (10R 4/2, 5R 4/2); silty, noncalcareous, locally dolomitic; poorly indurated.

9.2 ft. (2.8m)	Covered Interval (Mudstone?): slope former.
12.3 ft. (3.7m)	Siltstone: grayish red (10R 4/2) with light greenish gray (5GY 8/1) reduction spots; noncalcareous; tabular to irregular bedding, very thinly to very thickly bedded; moderately indurated.
2.6 ft. (0.8m)	Mudstone: grayish red (10R 4/2, 5R 4/2); silty, noncalcareous; poorly indurated.
13.8 ft. (4.2m)	Siltstone: grayish red (5R 4/2) to pale brown (5YR 5/2); noncalcareous to calcareous; tabular to irregular bedding, thinly to very thickly bedded; moderately indurated.
33 ft. (10m)	Covered Interval (Mudstone?): slope former.
12.3 ft. (1.2m)	Interbedded Siltstone and Mudstone: very thinly to thinly bedded siltstone and thinly laminated mudstones; mudcracks. Siltstone: moderate reddish brown (10R 4/6); calcareous, micaceous; mafic grains; moderately indurated. Mudstone: moderate reddish brown (10R 4/6) to dark reddish brown (10R 3/4); silty, calcareous; poorly indurated.
4.1 ft. (1.2m)	Covered Interval (Interbedded Mudstone and Siltstone?): slope former.
5.1 ft. (1.55m)	Interbedded Siltstone and Mudstone: very thinly to thinly bedded siltstone and thinly laminated mudstone; as above.
6.1 ft. (1.85m)	Sandstone: grayish red (5R 4/2) to dark reddish brown (10R 3/4); very fine to fine grained; moderately sorted; subangular to subrounded grains; calcareous, micaceous; mafic grains; quartz arenite to arkosic arenite; moderately indurated.
13.3 ft. (4.1m)	Covered Interval (Mudstone?): slope former.
35.9 ft. (10.9)	Sandstone: moderate reddish brown (10R 4/6) to grayish red (10R 4/2, 5R 4/2); very fine

	to fine grained to pebble size conglomeratic at channel scours; moderately to poorly sorted; angular to rounded grains; dolomitic to siliceous, locally micaceous, limestone pebbles at channel scours; quartz arenite to quartz wacke, locally lithic wacke; structureless to highly cross-stratified, large, medium and small scale cross-strata; locally displays soft sediment deformation; irregular bedding (stacked channels); very thickly bedded; well indurated. (Paleocurrents measured)
10 ft. (3.04m)	Mudstone: moderate reddish brown (10R 4/6); calcareous with calcareous nodules; poorly indurated.
28 ft. (8.5m)	Covered Interval (Mudstone?): slope former.
7 ft. (2.1m)	Mudstone: moderate reddish brown (10R 4/6) to moderate red (5R 4/6) with light greenish gray (5GY 8/1) reduction spots; silty, calcareous; poorly indurated.
15 ft. (4.6m)	Covered Interval (Mudstone?): slope former.
9.2 ft. (2.8m)	Interbedded Sandstone and Mudstone: thinly to very thickly bedded sandstone and thinly laminated mudstone; irregular bedding. Sandstone: grayish red (10R 4/2) to pale reddish brown (10R 5/4);very fine sand to silt size, locally pebble size conglomeratic at channel scours; moderately to poorly sorted; angular to rounded grains; few mafic grains; quartz arenite to quartz wacke, locally lithic wacke; moderately indurated. Mudstone: moderate reddish brown (10R 4/6); silty, calcareous; poorly indurated.
42 ft. (12.8m)	Covered Interval (Mudstone?): slope former.
13 ft. (3.9m)	Mudstone: moderate red (5R 4/6) to dark reddish brown (10R 3/4); silty, calcareous; poorly indurated.
56 ft. (17.1m)	Covered Interval (Mudstone?): slope former.
12 ft. (3.65m)	Mudstone: moderate red (5R 4/2) to dark reddish brown (10R 3/4); silty, calcareous; poorly indurated.

32 ft. (9.75m)	Covered Interval (Mudstone?): slope former.
16.4 ft. (5.0m)	Mudstone: grayish red (10R 4/2); calcareous with calcareous nodules (gray); irregular (wavey to nodular) bedding, thinly laminated to thinly bedded; poorly indurated.
25 ft. (7.62m)	Covered Interval (Mudstone?): slope former.
3.5 ft. (1.06m)	Interbedded Siltstone and Mudstone: very thinly to thinly bedded siltstone and thinly laminated mudstone, irregular, disrupted bedding (bioturbated?). Siltstone: moderate reddish brown (10R 4/6) to grayish red (10R 4/2); calcareous; few mafic grains; moderately indurated. Mudstone: moderate reddish brown (10R 4/6) with light greenish gray (5GY 8/1) reduction spots; silty, calcareous; poorly indurated.
17.7 ft. (5.4m)	Covered Interval (Mudstone?): slope former.
18.4 ft. (5.6m)	Sandstone: moderate reddish brown (10R 4/6) to dark reddish brown (10R 3/4); very fine to fine grained, to pebble size conglomeratic at channel scours; moderately to poorly sorted; subangular to rounded grains; calcareous; quartz arenite; large, medium and small scale cross-stratification; lenticular bedding (isolated channel, doesn't appear to be laterally continuous), very thickly bedded; bioturbated at top; moderately to well indurated.
16.4 ft. (5.0m)	Covered Interval (Mudstone?): slope former.
4.6 ft. (1.4m)	Siltstone: pale reddish brown (10R 5/4); calcareous; thinly to thickly bedded with very thin mudstone stringers, irregular (nodular) bedding; moderately to well indurated.
15 ft. (4.6m)	Covered Interval (Mudstone?): slope former.
12 ft. (3.65m)	Mudstone: dark reddish brown (10R 3/4) to very dark red (5R 2/6); silty, calcareous; poorly indurated.
6.4 ft.	Siltstone: moderate reddish brown (10R 4/6)

(1.95m)	to dark reddish brown (10R 3/4); calcareous; extensive burrowed, poorly preserved ripple marks; thinly to thickly bedded, irregular to tabular bedding; well indurated.

Abo Formation (conformable contact)

Bursum Formation

7.25 ft. (2.2m)	Interbedded Mudstone and Limestone: irregular bedding, thinly bedded limestone and thinly laminated to thinly bedded mudstone. Limestone: light bluish gray (5B 7/1) to light gray (N7); silty, nodular, lime mudstone; moderately to well indurated. Mudstone: dusky red (5R 3/4) to very dark red (5R 2/6) to grayish red purple (5RP 4/2) to light bluish gray (5B 7/1); silty to argillaceous, calcareous, locally with calcareous nodules; poorly indurated.
1.3 ft. (0.4m)	Limestone: light bluish gray (5B 7/1) to grayish red purple (5RP 4/2); very "muddy" (argillaceous and silty); tabular to irregular bedding; lime mudstone; moderately to well indurated.
15.1 ft. (4.6m)	Mudstone: dusky red (5R 3/4) to grayish red purple (5RP 4/2) with light bluish gray (5B 7/1) reduction spots; silty, calcareous; poorly indurated.
4.5 ft. (1.37m)	Siltstone: light bluish gray (5B 7/1) to pale red (10R 6/2); with thin streaks of grayish red purple (5RP 4/2) mudstone; calcareous; thinly bedded, tabular bedding; poorly indurated.
24.2 ft. (7.37m)	Mudstone: poorly exposed; very dark red (5R 2/6) to grayish red purple (5RP 4/2) to dusky red (5R 3/4), locally light bluish gray (5B 7/1); silty, calcareous, locally with calcareous nodules; poorly indurated.
1.9 ft. (0.6m)	Siltstone: grayish red purple (5RP 4/2) to dusky red (5R 3/4); dolomitic; tabular bedding; well indurated.
6.5 ft. (2.0m)	Mudstone: dusky red (5R 3/4); silty, calcareous with calcareous nodules; thinly laminated to thinly bedded; poorly indurated.
1 ft.	Limestone: light gray (N7); sandy, locally

(0.3m)	very sandy and containing limestone clasts; irregular bedding; sandy lime mudstone to calcirudite; well indurated.
5 ft. (1.5m)	Mudstone: poorly exposed; dusky red (5R 3/4); calcareous; poorly indurated.

BIBLIOGRAPHY

Adams, D., 1980, Late Paleozoic tectonic and sedimentologic history of the Penasco uplift, north-central New Mexico: Rice University, unpublished M.S. thesis, 79p. *(On file at the New Mexico Bureau of Mines and Mineral Resources, Information Services).*

Allen, D.R., 1975, Identification of sediments, their depositional environment and degree of compaction from well logs: *In* Compaction of coarse grained sediments, I, Chilingarian, G.V. and Wolf, K.H., (editors), Elseveir, Amsterdam, 552p.

Allen, J.R.L., 1965, A review of the origin and characteristics of recent alluvial sediments: Sedimentology, v.5, p.98-191.

Armstrong, A.K., 1955, Preliminary observations on the Mississippian of northern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circ. 39, 42p.

Asquith, G., 1982, Basic well log analysis for geologists: The American Assoc. Petrol. Geol., Tulsa, 216p.

Baars, D.L., 1961, Permian Strata of central New Mexico: New Mexico Geol. Soc. Guidebook, 12th field conference, p.113-218.

-----, 1962, Permian System of Colorado Plateau: American Assoc. Petrol. Geol. Bull., v.46, p.149-218.

Bachman, G.O., 1964, Southwestern edge of the Paleozoic landmass in southwestern New Mexico: New Mexico Geol. Soc. Guidebook, 15th field conference, p.70-72.

Bachman, G.O., and Hayes, P.T., 1958, Stratigraphy of Upper Pennsylvanian and Lower Permian in the Sand Canyon area, Otero County, New Mexico: Geol. Soc. America Bull., v. 69, p.689-700.

Bates, R.C., Wilpolt, R.H., MacAlpin, A.J. and Vorbe, G., 1947, Geology of the Gran Quivira Quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bull. 26, 57p.

Bauch, J.H.A., 1982, Geology of the central area of the Loma de Las Canas Quadrangle, Socorro County, New Mexico: New Mexico Instit. Mining and Tech., unpublished M.S. thesis, 115p.

Black, B.A., 1982, Oil and gas exploration in the Albuquerque basin: New Mexico Geol. Soc. Guidebook, 33rd field conference, p.313-324.

Blatt, H., 1982, Sedimentary petrology: W.H. Freeman and Company, San Francisco, 564p.

Brennan, D.J., 1986, Oil and gas developments in Four Corners- Intermountain area in 1983-1985: American Assoc. Petrol. Geol. Bull., v. 70, p.1315-1319.

Broadhead, R.F., 1984, Stratigraphically controlled gas production from Abo red beds (Permian), east-central New Mexico: New Mexico Bureau of Mines and Mineral Resources Circ. 183, 36p.

Broadhead, R.F., 1983a, Correlation of the Abo outcrop with the subsurface gas-producing Abo red beds of east-central New Mexico: Roswell Geological Society and New Mexico Bureau of Mines and Mineral Resources, Guidebook for trip to the Abo red beds (Permian), central and south-central New Mexico, p.45-52.

Broadhead, R.F., 1983b, Petroleum exploration in Socorro County: New Mexico Geol. Soc. Guidebook, 34th field conference, p.219- 222.

-----, Kottlowski, F.E. and MacMillan, J.R., 1983, Road log - first day - Socorro to Scholle, Priest Canyon, Cerros de Amado area, and Mesa del Yeso area: *In* Guidebook for field trip to the Abo red beds (Permian), central and south-central New Mexico: The Roswell Geological Society and New Mexico Bureau of Mines and Mineral Resources Field Trip, April 7 & 8, 1983, p.3-14.

Cant, D.J., 1984, Subsurface facies analysis: *In* Facies models (Ed. by R.G. Walker). Geoscience Canada reprint series 1, p.297- 310.

Cappa, J.A., 1975, The depositional environments, paleocurrents, provenance and dispersal patterns of the Abo Formation in part of the Cerros de Amado region, Socorro County, New Mexico: New Mexico Instit. Mining and Tech., unpublished M.S. thesis, 154p.

Colpitts, R.M., 1986, Geology of the Sierra de la Cruz area: New Mexico Instit. Mining and Tech., unpublished M.S. thesis, 166p.

Compton, R.R., 1962, Manual of field geology: John Wiley and Sons, Inc., New York, 378p.

Condie, K.C., 1976, Precambrian rocks of the Ladron Mountains, Socorro County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 38.

Condie, K.C., and Budding, A.J., 1979, Geology and geochemistry of Precambrian rocks, central and south-central New Mexico: New Mexico Bureau of Mines and Mineral Resources Mem. 35, 58p.

Cragbaugh, J.P. and MacPherson, J.G., 1984, Transitions in a fluvial system, Abo Formation, southwestern Nacimiento Mountains, New Mexico: American Assoc. Petrol. Geol. Bull., v.68, p.466- 467.

Dane, C.H. and Bachman, G.O., 1965, Geologic map of New Mexico: U.S. Geologic Survey, 1:500,000.

Davies, D.K. and Ethridge, F.G., 1975, Sandstone composition and depositional environment: American Assoc. Petrol. Geol. Bull., v.59, p.239-264.

Darton, N.H., 1928, "Red beds" and associated formations in New Mexico: U.S. Geological Survey Bull. 794, 356p.

Daut, S., 1978, Paleocurrent computor program: Iowa Geological Survey.

Dott, R.H., 1964, Wacke, graywacke and matrix--what approach to immature sandstone classification?: J. Sedim. Petrol., v.34, p.625-632.

Dunham, R.J., Classification of carbonate rocks according to depositional texture: American Assoc. Petrol. Geol. Mem. 1, p.108-121.

Ethridge, F.G. and Schumm, S.A., 1978, Reconstructing paleochannel morphologic and flow characteristics: methodology, limitations and assessment: *In* Fluvial Sedimentology, A.D. Miall (editor), Can. Soc. Petrol. Geol., Mem. 5, p.703-721.

Fenneman, N.M., 1931, Physiography of the western United States: McGraw-Hill Book Company, Inc., New York, 534p.

Fenneman, N.M., 1930, Physical divisions of the United States: (map) U.S. Geol. Survey.

Fitzsimmons, J.P., 1967, Precambrian rocks of the Zuni Mountains: New Mexico Geol. Soc. Guidebook, 18th field conference, p.119- 121.

Foster, R.W., 1964, Stratigraphy and petroleum possibilities of Catron County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bull. 85, 51p.

Foster, R.W., 1957, Stratigraphy of west-central New Mexico: Four Corners Geol. Soc. Guidebook, 2nd field conference, p.62-72.

-----, Frentress, R.M. and Riese, W.C., 1972, Subsurface geology of east-central New Mexico: New Mexico Geol. Soc. Special Publication No. 4, 22p.

Friend, P.F., 1983, Towards the field classification of alluvial architecture or sequence: *In* Modern and Ancient Fluvial Systems, Collinson, J.D. and Lewin, J., (editors), Spec. Publs. Int. Assoc. Sediment. 6, Blackwell Scientific Publications, Oxford, p. 345-354.

Galloway, W.E. and Hobday, D.K., 1983, Terrigenous clastic depositional systems: Springer-Verlag New York, Inc., New York, 423p.

Graves, W., 1986, Bit-generated rock textures and their effect on evaluation of lithology, porosity, and shows in drill-cutting samples: American Assoc. Petrol. Geol. Bull., v. 70, p.1129-1135.

Hatchell, W.O., Blagbrough, J.W. and Hill, J.M., 1982, Stratigraphy and copper deposits of the Abo Formation, Abo Canyon area, central New Mexico: New Mexico Geol. Soc. Guidebook, 33rd field conference, p.249-260.

Helander, D.P., 1983, Fundamentals of formation evaluation: Oil and Gas Consultants International, Tulsa, 332p.

Hilchie, D.W., 1982, Applied openhole log interpretation: Douglas Hilchie, Inc., Golden, 341p.

Hunt, A., 1983, Plant fossils and lithostratigraphy of the Abo Formation (lower Permian) in the Socorro area and plant biostratigraphy of Abo red beds in New Mexico: New Mexico Geol. Soc. Guidebook, 34th field conference, p.157-163.

Kelley, V.C., 1955, Regional Tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium: Univ. of New Mexico Publications in Geology, No. 5, 120p.

Kelley, V.C. and Northrop, S.A., 1975, Geology of Sandia Mountains and vicinity, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Mem. 29, 136p.

Kelley, V.C. and Silver, C., 1952, Geology of the Caballos Mountains: Univ. of New Mexico Publications in Geology, No. 4, 286p.

Kelley, V.C. and Wood, G.H., 1946, Lucero Uplift, Valencia, Socorro, and Bernalillo Counties, New Mexico: U.S. Geol. Surv. Oil and Gas Invest. Map, OM-47.

King, P.B., 1942, Permian of West Texas and southeastern New Mexico: American Assoc. Petrol. Geol. Bull., v.26, p.535-763

King, R.E., 1945, Stratigraphy and oil-producing zones of the pre-San Andres formations of southeastern New Mexico; a preliminary report: New Mexico Bureau of Mines and Mineral Resources Bull. 23, 34p.

Kottlowski, F.E., 1965, Measuring stratigraphic sections: Holt, Rinehart and Winston, New York, 253p.

Kottlowski, F.E., 1963, Paleozoic and Mesozoic strata of southwestern and south-central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bull. 79, 100p.

----- and Stewart, W.J., 1970, The Wolfcampian Joyita uplift in central New Mexico: New Mexico Bureau of Mines and Mineral Resources Mem. 23, pt.I, p.1-31.

Kues, B.S., and Kietzke, K.K., 1976, Paleontology and stratigraphy of the Red Tanks Member, Madera Formation (Pennsylvanian) Near Lucero Mesa, New Mexico: New Mexico Geol. Soc. Special Publication No. 6, p.102-108.

Lee, W.T. and Girty, G.H., 1909, The Manzano Group of the Rio Grande Valley of New Mexico: U.S. Geol. Survey Bull. 389, 141p.

LaPoint, D.J., 1976, A comparison of selected sandstone copper deposits in New Mexico: Oklahoma Geol. Survey Cir. 77, p.80-96.

Lemley, K.R., 1984, Paleocurrent analysis and paleoenvironmental interpretation of the Abo Formation, Abo Canyon area, Valencia, Torrence, and Socorro Counties, New Mexico: New Mexico Instit. Mining and Tech., unpublished M.S. thesis, 91p.

MacMillan, J.R., 1987, Paleocurrent and facies analysis of the Abo Formation along a NW-SE surface transect of New Mexico: New Mexico Geological Society, Proceedings volume, 1987 annual spring meeting, Socorro New Mexico, p.8.

Maher, J.C., 1959, The composite interpretive method of logging drill cuttings: Oklahoma Geological Survey Guidebook VIII, 48p.

Martin, J.L., 1971, Stratigraphic analysis of Pennsylvanian strata in the Lucero region of west central New Mexico: University of New Mexico, unpublished Ph.d thesis, 196p.

Maulsby, J., 1981, Geology of the Rancho de Lopez area, east of Socorro, New Mexico: New Mexico Instit. Mining and Tech., unpublished M.S. thesis, 85p.

McKee, E.D., 1967, Paleotectonic investigations of the Permian System in the United States--Arizona and western New Mexico: U.S. Geol. Survey Prof. Paper 515, p.203-223.

McKee, E.D. and Weir, G.W., 1953, Terminology for stratification and cross-stratification in sedimentary rocks: Geol. Soc. America Bull., v.64, p.381-390.

Miall, A.D., 1983, Basin analysis of fluvial sediments: *In* Modern and Ancient Fluvial Systems, Collinson, J.D. and Lewin, J., (editors), Spec. Publs. Int. Assoc. Sediment. 6, Blackwell Scientific Publications, Oxford, p.279-286.

Myers, D.A., 1977, Geologic map of the Scholle quadrangle, Socorro, Valencia, and Torrance Counties, New Mexico: U.S. Geol. Surv. Geologic Quadrangle Map GQ-1412.

Needham, C.E. and Bates, R.L., 1943, Permian type sections in central New Mexico: Geol. Soc. America Bull., v. 54, p.1653- 1667.

New Mexico Geological Society, 1963, The Abo Formation in the area around Socorro, New Mexico: New Mexico Geol. Soc. Guidebook, 14th field conference, p. 98-99.

Otte, C. Jr., 1959, Late Pennsylvanian and Early Permian stratigraphy of the northern Sacramento Mountains, Otero County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bull. 50, 111p.

Pettijohn, F.J., 1975, Sedimentary rocks: Harper and Row, Publishers, Inc., New York, 628p.

Pettijohn, F.J., Potter, P.E. and Siever, R., 1972, Sand and sandstone: Springer-Verlag, New York, 618p.

Pirson, S.J., 1977, Geologic well log analysis: Gulf Publishing Company, Houston, 377p.

Pray, L.C., 1961, Geology of the Sacramento Mountains escarpment, Otero County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bull. 35, 144p.

Pray, L.C., 1952, Stratigraphy of the escarpment of the Sacremento Mountains, Otero County, New Mexico: California Instit. Tech., Doctoral dissertation, 370p. *(On file at the New Mexico Bureau of Mines and Mineral Resources, Information Services).*

Read, C.B. and Mamay, S.H., 1964, Upper Paleozoic floral zones and floral provinces of the United States: U.S. Geol. Surv. Prof. Paper 454K, p.1-35.

Rider, M.N., 1986, The geologic interpretations of well logs: Blackie and Son, Limited, Glasgow, and John Wiley and Sons, New York, 192p.

Schlumberger Well Services, Inc., 1972, Log interpretation manual/principles, vol. I: Schlumberger Well Services, Inc., Houston, 113p.

Schumm, S.A., 1963, A tentative classification of alluvial river channels. U.S. Geol. Surv. Cir. 477, 10p.

Selley, R.C., 1978, Ancient sedimentary environments: Cornell University Press, Ithaca, 287p.

Serra, O. and Sulpice, L., 1975, Sedimentological analysis of sand-shale series from well logs, Soc. Prof. Well Log Analysts 16th Annual Symposium Transactions, Paper W, p.1-23.

Smith, C.T., 1957, geology of the Zuni Mountains, Valencia and McKinley Counties, New Mexico: *In* Geology of the southwestern San Juan Basin, Four Corners Geological Society, 2nd field conference Guidebook, p.53-61.

Smith, D.G. and Smith, N.D., 1980, Sedimentation in anastomosed river systems; examples from alluvial valleys near Banff, Alberta: J. Sedim. Petrol., v.50, p.157-164.

Speer, S.W., 1983, Abo Formation, north-central Sacramento Mountains--an onlapping fluvial clastic wedge: Roswell Geological Society and New Mexico Bureau of Mines and Mineral Resources, Guidebook for field trip to the Abo red beds (Permian), central and south-central New Mexico, p.54-72.

Swanson, R.G., 1981, Sample examination manual: The American Assoc. Petrol. Geol., Tulsa, 128p.

Thompson, M.L., 1942, Pennsylvanian System in New Mexico: New Mexico Bureau of Mines and Mineral Resources Bull. 17, 20p.

Tonking, W.H., 1957, Geology of the Puertocito quadrangle, Socorro County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bull. 41, 63p.

Wells, N.A., 1983, Transient streams in sand-poor redbeds: early- Middle Eocene Kuldana Formation of northern Pakistan: *In* Modern and Ancient Fluvial Systems, Collinson, J.D. and Lewin, J., (editors), Spec. Publs int. Ass. Sediment. 6, Blackwell Scientific Publications, Oxford, p. 393-403.

Wengerd, S.A., 1959, Regional geology as related to the petroleum potential of the Lucero region, west-central New Mexico: New Mexico Geol. Soc. Guidebook, 10th field conference, p.121-134.

Williams, J.L., and McAllister, P.E. (editors), 1979, New Mexico in Maps: Technology Application Center, University of New Mexico, 177p.

Wilpolt, R.H., Wanek, A.A., MacAlpin, A.J., Zapp, A.D., and Bates, R.L., 1951, Geology of the region from Socorro and San Antonio east to Chupadera Mesa, Socorro County, New Mexico: U.S. Geol. Survey, Prelim. Oil and Gas Invest. Map, OM-121.

Wilpolt, R.H., MacAlpin, A.J., Bates, R.L., and Vorbe, G., 1946, Geological map and stratigraphic sections of Paleozoic of Joyita Hills, Los Pinos Mountains and North Chupadera Mesa, Valencia, Torrance, and Socorro Counties, New Mexico: U.S. Geol. Survey, Prelim. Oil and Gas Invest. Map, OM-61.

Wilson, J.L., 1967, Cyclic and reciprocal sedimentation in Virgilian strata of southern New Mexico: Geol. Soc. America Bull., v. 78, p.805-818.

Woodward and Grant, 1987, Oil and gas potential of the Quemado region: Oil and Gas Journal, Feb. 23, p.75-78.

Woodward and Grant, 1986, Central-western New Mexico--an exploration frontier for oil and gas: New Mexico Geol. Soc. Guidebook, 37th field conference, p.307-314.

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