REFRACTORY CLAY RESOURCES
OF THE
BURRO CANYON(?) FORMATION-DAKOTA SANDSTONE,
NORTH-CENTRAL NEW MEXICO

by

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Abstract

A reconnaissance study of north-central New Mexico along the eastern flank of the San Juan Basin including the southern portion of the Chama Basin indicated possible refractory clays in units of the Morrison, Burro Canyon(?), Dakota, and Mancos Formations. One hundred thirty-three channel samples were collected mostly from mudstone units in this area. Preliminary screening of the samples involved using x-ray diffraction and particle-size analysis. As a result of these tests, 28 kaolinitic, fine-grained samples were selected for additional testing done at the laboratories of the U.S. Bureau of Mines (Tuscaloosa, Alabama) and New Mexico Institute of Mining and Technology. These tests included ceramic tests such as PCE (pyrometric cone equivalent), shrinkage, color, absorption, and density, which are used to describe the refractory characteristics of the clays, and chemical tests to determine the nonclay compounds (the various oxides, such as iron, calcium, and silica), which give such physical properties as dryer scum, flaking, and color to the clay. From these tests the samples from the mesas north of Youngsville are shown to be refractories. Scanning electron micrographs were taken of four samples and applied to explain the relationship of clay-particle shape and arrangement to physical properties such as density. The flint-like clay from Mesa Corral (sample B77037-040) showed fine grain size and closer packing of particles than a kaolinitic clay from one of the clay pockets found to the south.

The various sections sampled involved mudrocks formed in both marine and nonmarine environments. Examples from the literature suggest that clay-mineral trends can be used as additional criteria for indicating depositional environments. Clay minerals were determined to parts in ten

using a semiquantitative method applied to x-ray diffractograms, and the clay-mineral trends were indicated. Using these trends, in conjunction with what was reported in the literature and field data, environments for some of the clay deposits were suggested. The samples (dominantly kaolinite) from the area north of Youngsville were taken at or near the contact of Cretaceous beds (Dakota Sandstone or Burro Canyon(?) Formation) with underlying Jurassic beds (Morrison Formation). In general, the best refractory samples in the area, which may prove to be economically important, occurred near this contact. These samples appear to be lenses of mudrock in channel-type sandstones and are dominantly kaolinite. In order to discover more of these deposits, additional mapping and drilling would be needed before any economic mining is considered.

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INTRODUCTION

Purpose, Scope, and Methods

This study is mainly an economic analysis of the refractory clays occurring near the base of the Dakota Formation in a large area of New Mexico. This approach limited the amount of time allotted per location. Description of outcrops and sections were generalized and concentrated on those units immediately above or below the clay units in addition to the clays themselves. Various units were sampled and the clays were analyzed for refractory properties and characteristics. Shales, other mudrocks, and some sandstones were sampled for limited thin-section work.

There have been problems delineating the stratigraphy in this area for many years, and studies done as recently as 1977 (Owen and Siemers, 1977; Ridgley, 1977) still raise many questions on the nomenclature. I have selected the nomenclature that fits the needs of this study as will be described in the section on Stratigraphy. Since the approach here was primarily economic, this study was devoted to collecting and analyzing samples that had potential to be refractory clays and evaluating the depositional environment, to a minor extent, of the clay-bearing units and reviewing the literature on the stratigraphy of the units studied.

Refractory clays are those clays with a high resistance to heat without loss of shape (Grimshaw, 1971) and are dominantly composed of minerals of the kaolin group, $(OH)_8 (SiO)_4 Al_4O_{10}$, which include kaolinite, dickite, and nacrite, plus halloysite. Kaolins are the most refractory of the clay minerals because they are essentially hydrous alumino-silicates and contain relatively few fluxing ions. In general, the higher the alumina content, the greater the refractoriness of the clay (Crane, 1960; Elbertz, 1960).

In 1949 the American Petroleum Institute published a study of clays collected from the United States and the rest of the world to be used as standard reference clays. One sample of a kaolinite was from Mesa Corral (incorrectly identified as Mesa Alta), New Mexico. High-grade kaolinite was also reported and described by Leopold (1943), Kerr and others (1949), Bingler (1968), Reeves (1963), and Patterson (1965) from the area north of Youngsville, New Mexico (figure 1), in sedimentary beds at or near the base of Cretaceous-age rocks. These clay deposits are found for about one-half mile along the northeastern face of Mesa Corral where the kaolin mineral occurs in lenticular bodies (Reeves, 1963).

The present study correlates and locates more of the economically significant bodies in this area and the area farther south along the eastern flank of the San Juan Basin. Approximately forty days were spent in the field collecting 133 claystones, shale, siltstone, and sandstone samples from 23 locations (figure 1). The samples were taken mainly from the Dakota Sandstone (Upper Cretaceous) and the Burro Canyon(?) Formation (Lower Cretaceous). A few samples of the Morrison Formation (Upper Jurassic) and Mancos Shale (Upper Cretaceous) were also taken for comparison.

X-ray diffraction and particle-size analyses were performed on most of the 133 samples, and, based on the results of those preliminary tests, 28 were chosen for further refractory and chemical testing.

The method of semi-quantitative analysis of clays in this study is currently in use at the New Mexico Bureau of Mines and Mineral Resources and is:

The following peaks (peak intensities) were taken above background--on the initial run at 7 Å (12.4° 2θ) - K (1), at 5 Å (17.8° 2θ) - I(2), and at 4.6° to 4.8° Å (18.4 to 18.9° 2θ) - C(3); on the slow no-treatment

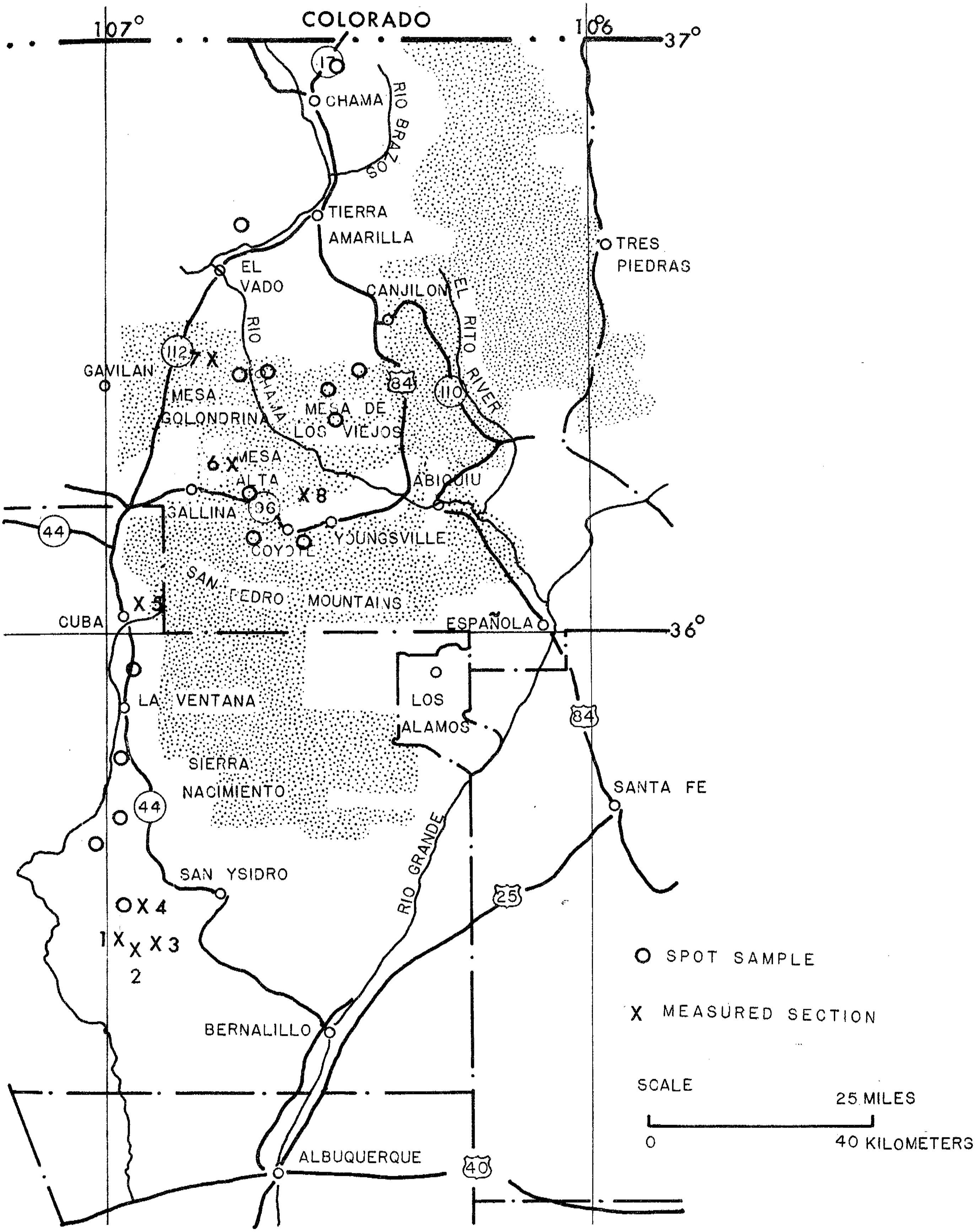


Figure 1--Location map of northern New Mexico, showing major cities, highways, mesas, and drainage systems. Carson and Santa Fe National Forests are shown by stipple pattern. Sample locations are indicated. Numbers beside locations indicate measured sections in Appendix II.

run at 3.6 Å ($24.9^\circ\ 2\theta$) - K(2) and at 3.5 Å ($25.1^\circ\ 2\theta$) - C(4); on the glycol run at 17 Å ($5.2^\circ\ 2\theta$) - S(1) and at 10 Å ($8.8^\circ\ 2\theta$) - I(1G); and on the heated run at 10 Å ($8.8^\circ\ 2\theta$) - I(1H).

The method of calculation was, and answer given, in parts in ten (10 Å (I(1H)) = counts for illite, smectite, and mixed-clay minerals):

Illite = $I(1G)/T \times 10$

Smectite = $(S(1)/4)/T \times 10$

Chlorite = $(C(3)/I(2)) \times (I(1G)/T) \times 10$

Mixed-layer clay minerals = $\{I(1H)-(I(1G)+(S(1)/4)\}/T \times 10$

Kaolinite = $K(1)/T \times 10$ or, if chlorite is present:

Kaolinite = $[(K(2)/2C(4)] \times [(C(3)/I(2)] \times [(I(1G)/T] \times 10$ where

T is equal to "total counts" and,

$T = I(1H) + K(1)$ or, if chlorite is present:

$T = I(1H) + [(C(3))(I(1G)]/I(2) + [(K(2))(C(3))(I(1G)]/[2C(4))(I(2)]$

Figure 2 shows the three x-ray traces of one of the samples.

Twenty-seven of the 28 samples were sent to the U.S. Bureau of Mines Clay Testing Laboratories in Tuscaloosa, Alabama, for refractoriness tests. Five of the 27 samples had more extensive refractory tests by the U.S. Bureau of Mines. One sample received refractory analysis in the New Mexico Bureau of Mines and Mineral Resources Laboratories. Seven of the 28 samples were analyzed chemically, and scanning-electron-microscope photographs were taken of four samples.

A summary of test procedures is in Appendix I. Appendix II contains the descriptions of eight measured sections; the generalized stratigraphic columns are included in the discussion of depositional environments. The columns also show particle size and clay mineralogy (in parts in ten).

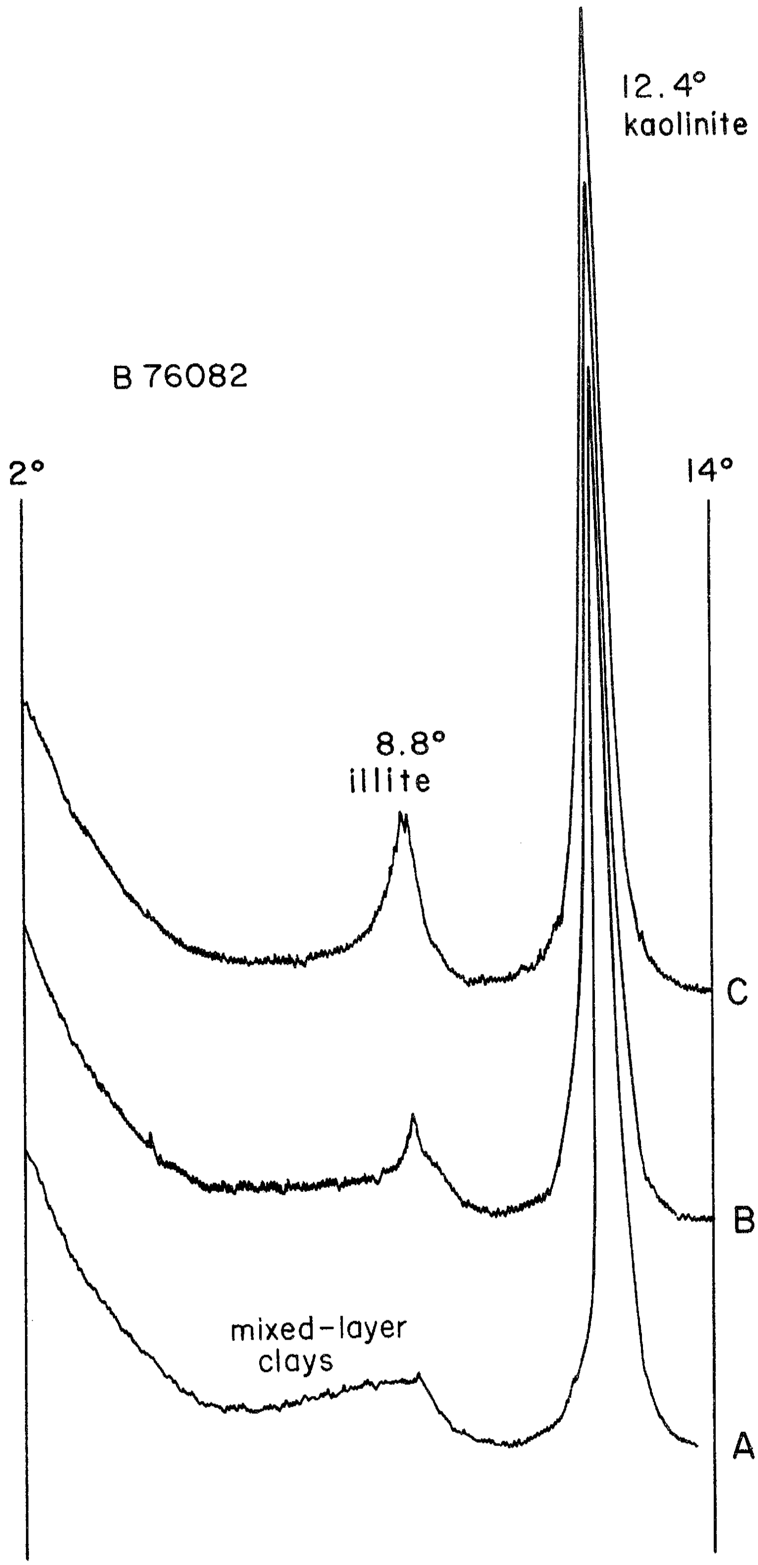


Figure 2--X-ray traces of sample B76082 showing three runs: A) untreated sample, B) slide placed over ethylene glycol and heated 1 hour at 60° C, and C) slide heated for 30 minutes at 375° C.

Also included in Appendix II are related figures such as photographs of a unit and x-ray diffractograms of four samples. Both appendices are discussed in various sections of this study.

Location of Study Area

The area of investigation includes portions of the eastern flank of the San Juan Basin, including the Gallina-Archuleta arch, and the Chama Basin. These structural features are considered to be in the eastern part of the Colorado Plateau.

The areas sampled, major highways, cities, drainage systems, and geographic features are indicated on figure 1; NM-44, NM-96, NM-112, and US-84 are the major roads through the area. A major portion of the area is in the Santa Fe and Carson National Forests, so forest service roads were extensively used for reconnaissance. Besides national forest lands and private property, land in the study area is controlled by the Bureau of Land Management and Zia and Jemez Indian Pueblos.

General Geology

On the eastern flank of the San Juan Basin both marine and nonmarine units are present in Cretaceous-age rocks. In the southern and eastern portions of the basin, the Dakota Sandstone was deposited under dominantly nearshore marine and open marine waters, but it does contain some fluvial sandstones near its base (Owen and Siemers, 1977). Farther north into the Chama Basin, the formation consists of a mixture of nearshore littoral marine deposits and fluvial, paludal, and paralic nonmarine deposits (Grant and Owen, 1974; Ridgley, 1977).

In the southern part of the eastern flank of the San Juan Basin the Dakota Sandstone and Mancos Shale intertongue, and six members have been delineated (Landis and others, 1973a,b). To the north in the Chama Basin, the Dakota can be divided into three units (Owen and Siemers, 1977). Also in the southern part of the eastern flank of the San Juan Basin, the Jackpile sandstone (informal unit of the Upper Jurassic Morrison Formation) has been recognized (Flesch, 1975; Saucier, 1974; Santos, 1975) near Cuba. A similar appearing unit, the Burro Canyon(?) Formation (also called Cedar Mountain Formation by Young, 1960) of Early Cretaceous age has been mapped in northern New Mexico (Young, 1960; Saucier, 1974; Owens and Siemers, 1977). These stratigraphic problems are discussed in more detail in the section on Stratigraphy.

In the southern portion of the study area, west of NM-44, Jurassic and Cretaceous rocks form flat-lying broad plains with elevations of about 5,600 feet. In the central portion, the Jurassic and Cretaceous rocks outcrop to the west of the Nacimiento uplift along the eastern flank of the San Juan Basin. In this portion the units are steeply dipping and locally overturned. In the northern portion, north of NM-96, these units lie on the southern boundary of the Chama Basin and along the Gallina-Archuleta arch. Along the southern end of the Chama Basin, the Dakota Sandstone caps many of the mesas east (Mesa de los Viejos and Mesa del Yeso) and west (Mesa Golondrina and Mesa Prieta) of the Rio Chama. This area is more rugged and is mostly in national forest land with elevations around 9,100 feet. The formations here are relatively flat lying and outcrops are fairly extensive. West of the Gallina fault, towards the southern end of the Gallina-Archuleta arch, the beds dip steeply to the west. The southern part of the arch merges with the Chama Basin (Woodward, 1974; Lookingbill, 1953). Figure 3 shows outcrops of the Dakota Sandstone (including the intertonguing portion of the Mancos Shale), Burro Canyon(?) Formation, and Morrison Formation in the San Juan Basin and adjacent areas.

Previous Studies

Since the area of investigation is so large, numerous previous studies have covered various parts and topics within it. However, only those studies that are pertinent to either the general structure and tectonics or Jurassic and Cretaceous stratigraphy are discussed in any detail.

Maps include those by Dane, 1948 (eastern San Juan Basin) and the geology of several quadrangles (by Woodward and others) in this area (Cuba, Holy Ghost Springs, San Pablo, La Ventana, San Ysidro, Tierra Amarilla, Cebolla, Chama). General geology and economic resources were discussed by Smith, Budding and Pitrat, 1961 (southeastern Chama Basin); Bingler, 1968 (Rio Arriba County); Reeves, 1963 (refractory clay); Patterson, 1965 (economic clays); Renick, 1931 (groundwater resources, western Sandoval County); Kelley, 1955 (tectonics, Colorado Plateau and relationship to uranium); Santos, 1975 (uranium potential of Jurassic Formations).

Structure and Tectonics

The San Juan Basin, Gallina-Archuleta arch, and Chama Basin are parts of the Colorado Plateau; the Nacimiento and Brazos uplifts are usually included with the Southern Rocky Mountains. These tectonic features attained their present structural outlines during the

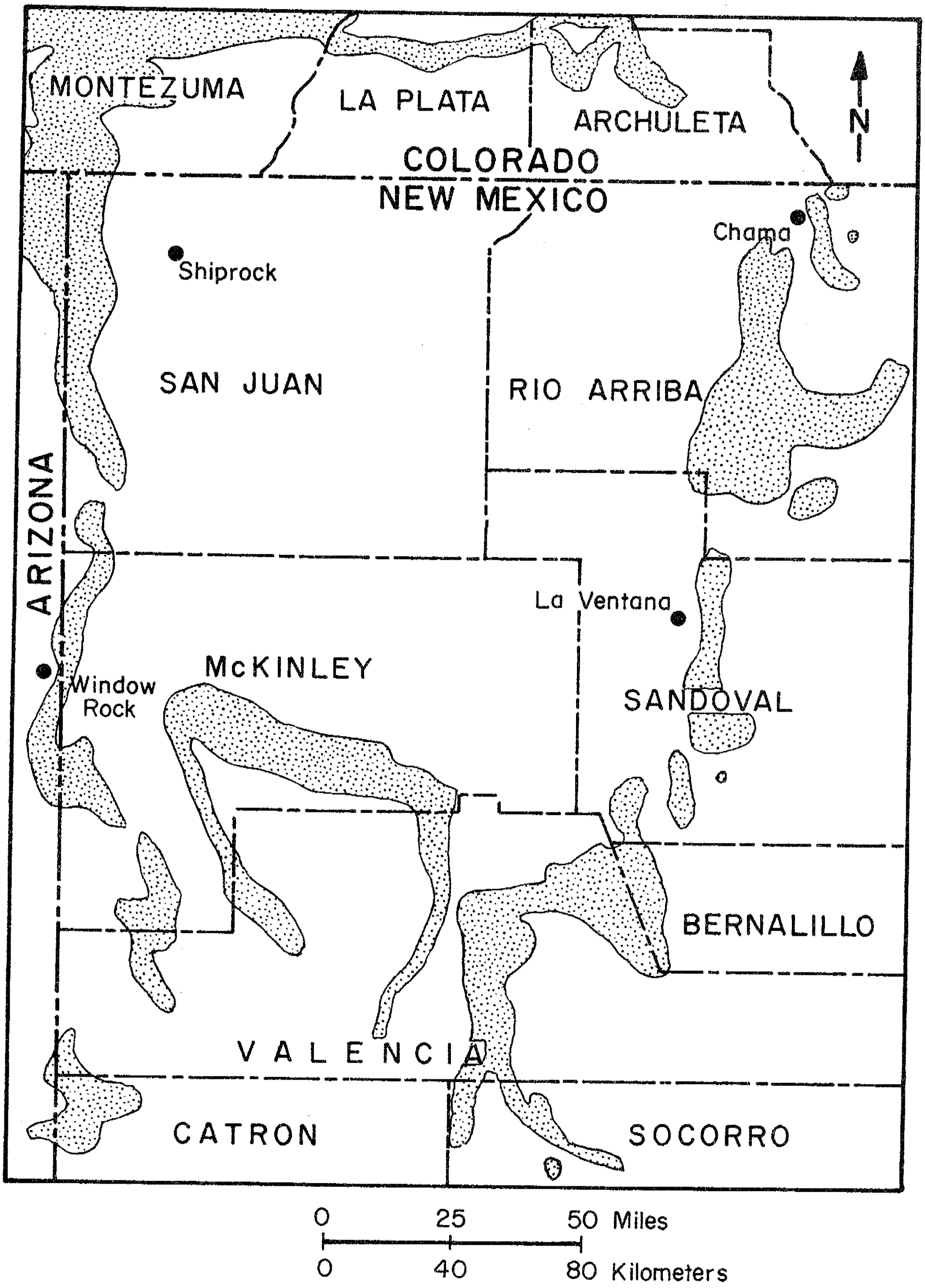


Figure 3--Stippling indicates outcrops of Dakota Sandstone (including the intertonguing portion of Mancos Shale), Burro Canyon(?) Formation, and Morrison Formation. (After Owen, 1973 and Dane and Bachman, 1965).

Laramide orogeny of Late Cretaceous and Early Tertiary. The Rio Grande rift began to form during the Miocene, and volcanism in the Jemez area began after initial development of the rift. The volcanic rocks overlie the eastern portion of the Nacimiento uplift and southern Chama Basin.

The eastern flank of the San Juan Basin is marked by a monocline along the west side of the Gallina-Archuleta arch and by marginal upthrust and reverse faults on the west side of the Nacimiento uplift. There is at least 10,000 feet of structural relief between the highest part of the Nacimiento uplift and the San Juan Basin. Several northwest-plunging, en echelon, open folds and northeast-trending, high-angle faults of small displacements are present along this portion of the San Juan Basin (Woodward, 1974).

The Gallina-Archuleta arch separates the relatively deep San Juan Basin from the shallower Chama Basin. Structural relief between the arch and the San Juan Basin is as much as 13,000 feet, whereas the Chama Basin is about 1,500 feet structurally lower than the arch. On the west the arch is bounded by a monocline with a steep westward dip at its southern end that becomes more gentle northward. The southern part of the arch merges with the shallow Chama Basin. In the northern part of the arch, numerous longitudinal, high-angle faults are present (Dane, 1948; Woodward and Callender, 1977).

The Chama Basin is structurally lower than the Gallina-Archuleta arch, and therefore could be called a platform or structural terrace (Muehlberger, 1967). The Chama Basin trends north and is about 60 miles long with widths ranging from 20 miles at the south end to about 4 miles at the north. At its southern end the basin is covered by volcanic rocks of the Jemez volcanic field. The southeastern part is separated from the Rio Grande rift by high-angle, northeast-trending faults.

The area with the most promising clay-bearing units, the Burro Canyon(?) - Dakota, occurs east of the Gallina-Archuleta arch in the Chama Basin. Tectonic activity could have caused post-Dakota erosion of the unit or may have prevented the deposition of Lower Cretaceous units south of Cuba. Faulting along the Gallina-Archuleta arch has thickened and thinned many units present in the area.

STRATIGRAPHY AND SEDIMENTATION

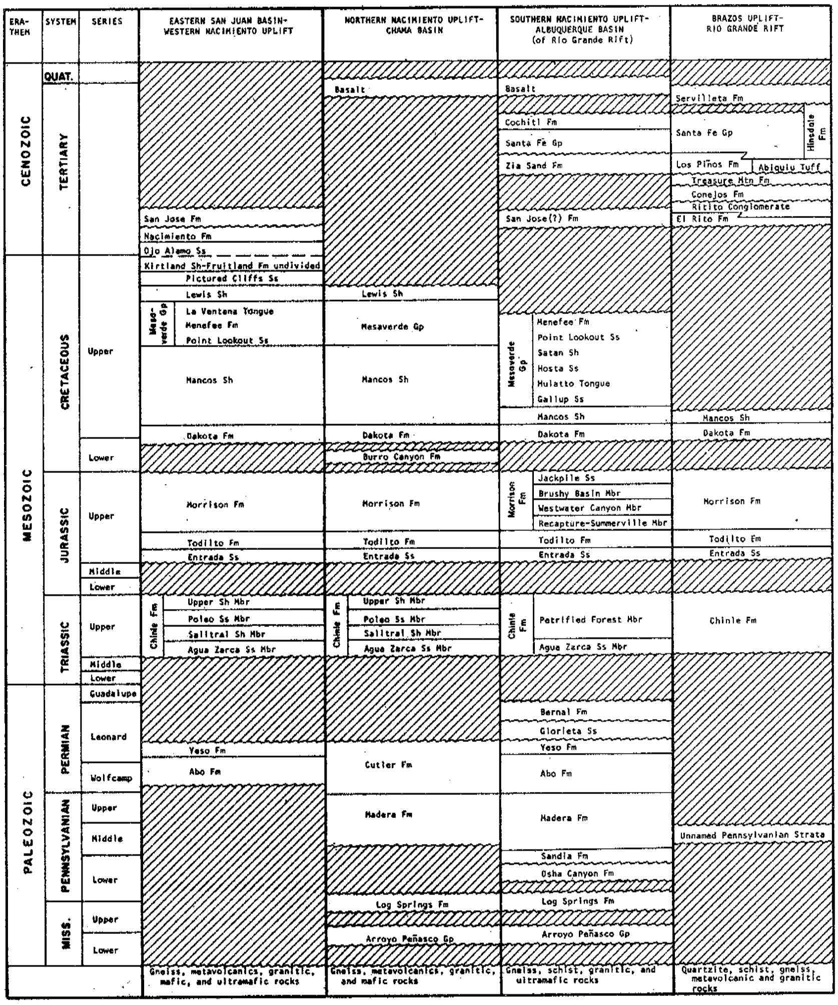
Stratigraphic Nomenclature

Only the nomenclature of the Morrison (Upper Jurassic) and Burro Canyon(?), Dakota, and lower Mancos (Cretaceous) will be discussed. This discussion summarizes previous research on these formations. Table 1 is a general summary of all formations in the study area, and table 2 summarizes the development of nomenclature of the upper Morrison and overlying Cretaceous Formations in southern and eastern San Juan Basin and Chama Basin; figure 3 shows the Jurassic and Cretaceous outcrops in the San Juan Basin and adjacent areas. Figure 4 is a photograph of a typical section in Mesa de los Viejos. The depositional environments of the units are discussed, since clay-mineral trends have been established for some environments (see section on Clay-Mineral Trends).

<u>Morrison Formation</u>--The Morrison Formation was named by Eldridge (1896) for outcrops near Morrison, Colorado. Although Eldridge is credited for naming the formation, Cross (1894, p. 2) noted the beds in the Pikes Peak area. The age of the Morrison is generally accepted as Late Jurassic (Baker and others, 1947; Imlay, 1952).

The Morrison is as much as 300 meters thick in the study area and is composed of interbedded and intertongued subarkosic, medium- to coarse-grained locally conglomeratic sandstone and interbedded sandy siltstone and variegated montmorillonitic claystone and thin microcrystalline limestone beds of high- to low-energy fluvial and lacustrine origin (Flesch, 1975; Green and Pierson, 1977; Tanner, 1968).

Table 1--Stratigraphic Nomenclature Chart (after Woodward, 1974)



ERA-THEM	SYSTEM	SERIES	EASTERN SAN JUAN BASIN-WESTERN NACIMIENTO UPLIFT	NORTHERN NACIMIENTO UPLIFT-CHAMA BASIN	SOUTHERN NACIMIENTO UPLIFT-ALBUQUERQUE BASIN (of Rio Grande Rift)	BRAZOS UPLIFT-RIO GRANDE RIFT
CENOZOIC	QUAT.		▨	▨	▨	▨
	TERTIARY		▨	Basalt	Basalt	Servilleta Fm
			▨	▨	▨	▨
			▨	▨	Cochiti Fm	Santa Fe Gp Hinsdale Fm
			▨	▨	Santa Fe Gp	
			▨	▨	Zia Sand Fm	Los Piños Fm Abiquiu Tuff
			▨	▨	▨	Treasure Mtn Fm Conejos Fm Ritito Conglomerate
			San Jose Fm	▨	San Jose(?) Fm	El Rito Fm
			Nacimiento Fm	▨	▨	▨
			Ojo Alamo Ss	▨	▨	▨
MESOZOIC	CRETACEOUS	Upper	Kirtland Sh-Fruitland Fm undivided	▨	▨	▨
			Pictured Cliffs Ss	▨	▨	▨
			Lewis Sh	Lewis Sh	▨	▨
			Mesaverde Gp La Ventana Tongue Menefee Fm Point Lookout Ss	Mesaverde Gp	Mesaverde Gp Menefee Fm Point Lookout Ss Satan Sh Hosta Ss Mulatto Tongue Gallup Ss	▨
			Mancos Sh	Mancos Sh	Mancos Sh	Mancos Sh
			Dakota Fm	Dakota Fm	Dakota Fm	Dakota Fm
		Lower	▨	▨ Burro Canyon Fm ▨	▨	▨
	JURASSIC	Upper	Morrison Fm	Morrison Fm	Morrison Fm Jackpile Ss Brushy Basin Mbr Westwater Canyon Mbr Recapture-Summerville Mbr	Morrison Fm
			Todilto Fm	Todilto Fm	Todilto Fm	Todilto Fm
			Entrada Ss	Entrada Ss	Entrada Ss	Entrada Ss
		Middle	▨	▨	▨	▨
		Lower	▨	▨	▨	▨
	TRIASSIC	Upper	Chinle Fm Upper Sh Mbr Poleo Ss Mbr Salitral Sh Mbr Agua Zarca Ss Mbr	Chinle Fm Upper Sh Mbr Poleo Ss Mbr Salitral Sh Mbr Agua Zarca Ss Mbr	Chinle Fm Petrified Forest Mbr Agua Zarca Ss Mbr	Chinle Fm
		Middle	▨	▨	▨	▨
		Lower	▨	▨	▨	▨
PALEOZOIC	PERMIAN	Guadalupe	▨	▨	▨	▨
		Leonard	▨	▨	Bernal Fm Glorieta Ss	▨
			Yeso Fm	Cutler Fm	Yeso Fm	▨
		Wolfcamp	Abo Fm		Abo Fm	▨
	PENNSYLVANIAN	Upper	▨	Madera Fm	Madera Fm	▨
		Middle	▨	▨		Unnamed Pennsylvanian Strata
		Lower	▨	▨	Sandia Fm Osha Canyon Fm ▨	▨
	MISS.	Upper	▨	Log Springs Fm ▨	Log Springs Fm ▨	▨
		Lower	▨	Arroyo Peñasco Gp ▨	Arroyo Peñasco Gp ▨	▨
			Gneiss, metavolcanics, granitic, mafic, and ultramafic rocks	Gneiss, metavolcanics, granitic, and mafic rocks	Gneiss, schist, granitic, and ultramafic rocks	Quartzite, schist, gneiss, metavolcanic and granitic rocks

Table 2--Development of Stratigraphic Nomenclature

<table>
<tr><th></th><th colspan="9">Laguna area</th><th>Acoma area</th><th>San Ysidro area (Tenorio Ranch)</th><th>LaVentana area (San Miguel Canyon)</th></tr>
<tr><th></th><th colspan="2">Hunt, 1936-map</th><th colspan="2">Hunt, 1936-text</th><th colspan="2">Moench and Schlee, 1967</th><th colspan="2">Moench, 1963</th><th>Landis, Dane, and Cobban, 1973a,b</th><th>Landis, Dane and Cobban, 1973a,b</th><th>Owen and Fassett, 1977</th><th>Landis, Dane, and Cobban, 1973b</th></tr>
<tr><td rowspan="8">CRETACEOUS</td><td rowspan="6">Mancos Shale</td><td rowspan="2">Main body</td><td colspan="2">Main body of the Mancos Sh</td><td colspan="2">Main body of the Mancos Sh</td><td rowspan="7">Mancos Shale</td><td>Main body</td><td>Main body of the Mancos Sh</td><td>Main body of the Mancos Sh</td><td>Main body of the Mancos Sh</td><td>Main body of the Mancos Sh</td></tr>
<tr><td rowspan="6">Lower part of the Mancos Shale</td><td>sandstone no. 3</td><td rowspan="6">Lower part of the Mancos Shale</td><td>upper sandstone unit</td><td>Kms_3</td><td>Twowells Sandstone Tongue of Dakota Ss</td><td>Twowells Sandstone Tongue of Dakota Ss</td><td>Twowells Sandstone Tongue of Dakota Ss</td><td>Twowells Sandstone Tongue of Dakota Ss</td></tr>
<tr><td rowspan="2">Kd_2</td><td>shale</td><td>shale unit</td><td>shale unit</td><td>Whitewater Arroyo Shale Tongue of Mancos Sh</td><td rowspan="3">Lower part of the Mancos Sh Whitewater Arroyo and Clay Mesa shale undivided</td><td>Whitewater Arroyo Shale Tongue of Mancos Sh</td><td rowspan="3">Lower part of the Mancos Sh</td></tr>
<tr><td>sandstone no. 2</td><td>middle sandstone unit</td><td>Kms_2</td><td>Paguate Sandstone Tongue of Dakota Ss</td><td>Paguate Sandstone Tongue of Dakota Ss</td></tr>
<tr><td rowspan="2">Kd_1</td><td>shale</td><td>shale unit</td><td>shale unit</td><td>Clay Mesa Shale Tongue of Mancos Sh</td><td>Clay Mesa Shale Tongue of Mancos Sh</td></tr>
<tr><td>sandstone no. 1</td><td>lower sandstone</td><td>Kms_1</td><td>Cubero Sandstone Tongue of Dakota Ss</td><td>Cubero Sandstone Tongue of Dakota Ss</td><td>Cubero Sandstone Tongue of Dakota Ss</td><td rowspan="3">? ——— ?
Main body of Dakota Ss</td></tr>
<tr><td colspan="2" rowspan="2">Dakota (?) Sandstone</td><td>sh and ss (gastropod zone)</td><td>shale unit</td><td>shale unit</td><td rowspan="2">Oak Canyon Member of Dakota Ss</td><td rowspan="2">Oak Canyon Member of Dakota Ss</td><td rowspan="2">Oak Canyon Member of Dakota Ss</td></tr>
<tr><td colspan="2">Dakota (?) Sandstone</td><td colspan="2">Dakota Sandstone</td><td colspan="2">Dakota Sandstone</td></tr>
<tr><td></td><td colspan="12">unconformity</td></tr>
<tr><td>JURASSIC</td><td colspan="2">Morrison Fm</td><td colspan="2">Morrison Fm</td><td colspan="2">Jackpile member of Morrison Fm</td><td colspan="2">Jackpile member</td><td>Jackpile member</td><td>Jurassic Sandstone</td><td>Jackpile member</td><td>Morrison (?) Fm</td></tr>
</table>

Table 2--Continued

LaVentana area (Elk Spring)	Rio Gallina area			Ghost Ranch area (SE Chama Basin)	U.S. Highway 84 (SE Chama Basin)	Southeast Chama Basin
Owen and Fassett, 1977	Swift, 1956	Dane, 1960; Lookingbill, 1953	Owen and Fassett, 1977	Saucier, 1974 Ridgely, 1977	Grant and Owen, 1974	Smith, Budding, and Pitrat, 1961
Lower part of Mancos Sh and main body of Mancos Sh	Mancos Sh undivided and/or Mancos (main body) and lower Mancos including Carlile Sh Member, Greenhorn Lms Member, and Graneros Sh Member	Mancos Sh includes Carlile Sh Member, Greenhorn Lms Member, and Graneros Sh Member	Lower part of Mancos Sh and main body of Mancos Sh	Mancos Sh	Mancos Sh	Mancos Sh includes Carlile Sh Member, Greenhorn Lms Member, and Graneros Sh Member
	?——?	?——?		?——?	?——?	?——?
Cubero Sandstone Tongue of Dakota Ss	upper sandstone of Dakota Ss	upper sandstone of Dakota Ss	Cubero Sandstone Tongue of Dakota Ss	upper unit of Dakota Ss	upper sandstone of Dakota Ss	upper sandstone of Dakota Ss
Oak Canyon Member of Dakota Ss	middle shale	middle shale	Oak Canyon Member of Dakota Ss	middle unit	middle shale	middle claystone
	lower sandstone	lower sandstone		lower unit	lower sandstone	lower sandstone
		unc.				
Burro Canyon (?) Fm	Deadman's Peak Fm		Burro Canyon (?) Fm	Burro Canyon (?) Fm		
?— and/or —?						
Jackpile member	Brushy Basin Sh Member of Morrison Fm	Morrison Fm	Jurassic	Brushy Basin Sh Member of Morrison Fm	Morrison Fm	Brushy Basin Sh Member of Morrison Fm

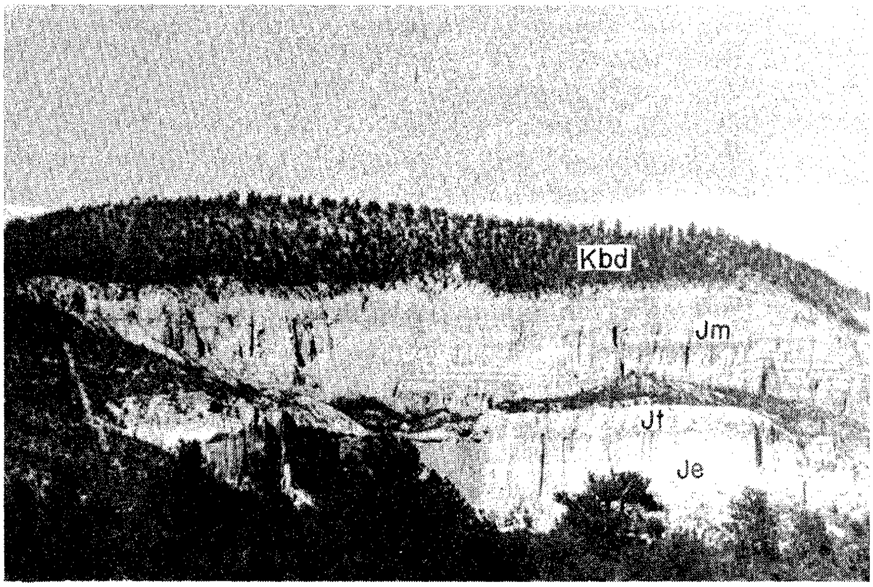


Figure 4--Photograph of a typical section in Mesa de los Viejos--Mesa Alta area, view north from NM-96. Entrada Sandstone (Je), Todilto Formation (Jt), Morrison Formation (Jm), Burro Canyon(?)-Dakota Formations (Kbd).

In the Chama Basin, the Morrison consists of three members. According to Ridgley (1977) the units are, in ascending order: the Recapture Shale Member (also known as the Summerville) composed of fine-grained sandstones, claystones, and shales; the Westwater Canyon Sandstone Member composed of sandstones and shales; and the Brushy Basin Shale Member composed of claystones and shales with minor sandstones.

Along most of the eastern and southeastern San Juan Basin there are four members of the Morrison Formation. According to Flesch (1975) the units are, in ascending order: Recapture Shale Member (also known as Summerville) composed of montmorillonitic claystones and interbedded subarkosic arenites; Westwater Canyon Sandstone Member consisting of interbedded sandstone and claystone units; Brushy Basin Shale (some intertonguing with Westwater Canyon occurs) consists of claystones, well-indurated arkosic arenites (which contain conglomerate seams, clay galls, carbonate beds, and thin volcanic ash beds); Jackpile sandstone (economic usage) consists of subarkosic arenites (fine- and medium-grained) with minor conglomerate seams, clay galls, iron nodules, carbonaceous material, and interbedded claystone. Craig and others (1955) and Cadigan (1967) have designated the source area of the Morrison in New Mexico as the Mogollon Highlands in southwest New Mexico and an area in west-central New Mexico, south of Gallup, as a more local source.

Burro Canyon(?) Formation--The presence of Lower Cretaceous age rocks in the Chama Basin has been suggested by several workers. Stokes (1944) discussed the problem of the Jurassic-Cretaceous boundary and stated that a thin layer of Lower Cretaceous rocks is probably present over much of the Rocky Mountain region. The name Cedar Mountain was proposed by Stokes (1944) for these Lower Cretaceous rocks at the north end of the San Rafael Swell northwest of Green River, Utah, and Young (1960; 1973) extended this unit to the San Juan Basin. Stokes and Phoenix (1948) applied the name Burro Canyon Formation to the same sequence in southwestern Colorado, selecting the Colorado River as the boundary between Cedar Mountain Formation and the Burro Canyon Formation. Stokes (1952) identified the Burro Canyon as Lower Cretaceous in age in its type area (150 miles northwest of this study area), but no age-diagnostic fossils have been reported in the San Juan Basin (Siemers, Flesch, and Ruetschilling, 1974; and table 3). The U.S. Geological Survey has examined palynomorphs from Cedar Mountain and Burro Canyon Formations (U.S. Geological Survey, 1977). Based on samples taken 7 meters below the base of the Dakota, an age for the Burro Canyon has been suggested to be no older than Aptian and no younger than early Albian. There appears to be an age difference between the upper Cedar Mountain and the upper Burro Canyon. In northeastern New Mexico the Purgatoire Formation, named by Stose (1912), is used for the Early Cretaceous (Comanchean).

Silver (1951, p. 105) reported: "Rocks of Early Cretaceous age have been tentatively identified by Reeside (1944) only in the northern part of the (San Juan) Basin near the town of Dolores in Montezuma County, Colorado, where they have a thickness of approximately 100 feet. They consist of white, medium- to fine-grained sandstone and green and gray shales. Similar rocks of like thickness appear to be locally present in northern New Mexico, 150 miles to the east at the head of Arroyo Canjilon in T. 25 N., R. 4 E. Subsurface information from the few wells presently drilled to that horizon indicates that these rocks are generally present in the subsurface through the north half of the basin."

Table 3--Fossils found in Jackpile sandstone and Dakota-Mancos (Siemers, Flesch, and Ruetschilling, 1974)

	STRATIGRAPHIC UNITS			
Biogenic Sedimentary Structures	Morrison Fm.	Dakota--Lower Mancos Interval		
	"Jackpile Ss"	"Lower Ss"	"Middle Ss"	"Upper Ss"
"Reed Molds"		X		
Skolithos		X	X	
Planolites	X	X	X	X
Ophiomorpha--small *Thalassinoides*		X	X	X
Teichichnus--small *Thalassinoides*			X	
Large *Thalassinoides*				X
Asterosoma				X
Arenicolites			X	
Zoophycos			X	X
Chondrites			X	X
Crossopodia			X	X
Gyrochorte			X	X
Isopodichnus				X

Saucier (1974) discussed the problems in identifying Burro Canyon rocks in the Chama Basin area. He states (p. 211): "Rocks of Lower Cretaceous age have been identified below the Dakota in southwest Utah, southwest Colorado, the extreme northeast corner of Arizona and in northwest and northeast New Mexico. In north-central New Mexico rocks of the Lower Cretaceous have not been distinguished... ." Figure 5 (from Saucier, 1974) shows the extent of units of Lower Cretaceous age in New Mexico.

Other workers have placed what has been called Burro Canyon(?), a light-gray to light-brown conglomerate to conglomeratic sandstone and red and green to gray mudstone, in either the Dakota Sandstone (Smith and others, 1961; McPeek 1965; Muehlberger, 1967; Bingler, 1968; Doney, 1968; Landis and Dane, 1967; Grant and Owen, 1974) or in the Morrison Formation (Dane, 1948, 1960; Lookingbill, 1953; Sears, 1953). Swift (1956) believed this unit to be mappable, but since he could not trace it to the Burro Canyon type section in Colorado, he named it the Deadman's Peak Formation. McPeak (1965) affirmed the presence of Burro Canyon, but not as a mappable unit. Saucier (1974), Ridgley (1977), and Owen and Siemers (1977) have separated this unit from the Dakota because they feel these beds have a distinctive lithology with contacts that can be distinguished and therefore mappable. They refer to the unit as "Burro Canyon(?)" and it is that designation that is used in this study. The lower contact of the Burro Canyon(?) with the Brushy Basin Member of the Morrison is generally an unconformable scour surface at the base of a fluvial channel-fill (Owen and Siemers, 1977) and is picked where a basal conglomerate rests on gray shales or claystones of the Brushy Basin (Ridgley, 1977). The Burro Canyon(?) is separated from the overlying Dakota Sandstone by a regional unconformity, and the

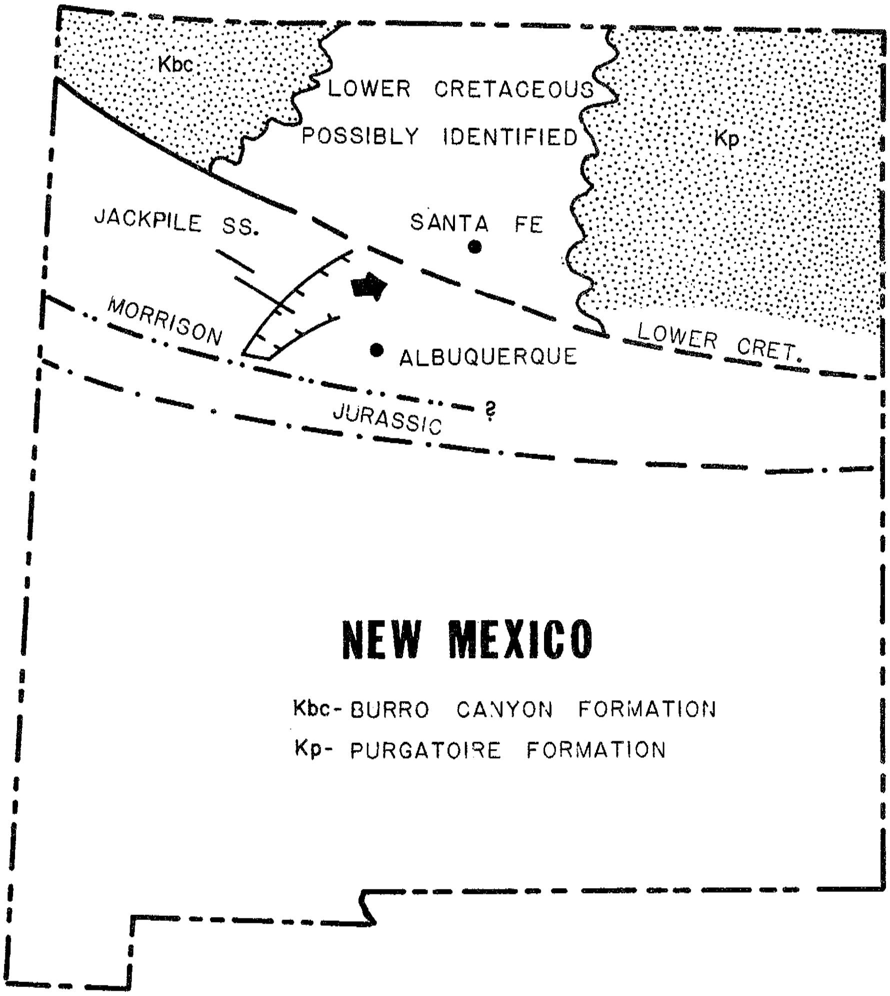


Figure 5--Sub-Dakota paleogeologic map of northern New Mexico. Stippling indicates the extent of Lower Cretaceous units which are recognized in New Mexico (from Saucier, 1974).

contact consists of sandstone on sandstone, mudstone, or shale. To the south the Burro Canyon(?) thins and it is absent south of Cuba.

Outcrops of the Burro Canyon(?) are of similar lithology throughout southwest and central Chama Basin (Saucier, 1974; Ridgley, 1977). They consist principally of conglomerate and sandstone (approximately 21-61 m thick) with thin red and green siliceous shale and mudstone lenses. The sandstones are buff to tan and locally pink to white. Chert pebbles in the conglomerate range from 1 to 6 cm in diameter (figure 6). Saucier (1974) considered these white chert pebbles to be one of the most diagnostic features of the formation. The basal sandstone of the Burro Canyon(?) is medium to fine grained and is poorly to well sorted. This sandstone consists of quartz with minor amounts of feldspar, chert, and some dark accessory minerals. Kaolinite in clay galls and disseminated particles is present throughout the unit. Samples show that the shales and mudstones within the Burro Canyon(?) contain kaolinite and illite (see section on Clay-Mineral Trends and Discussion of Depositional Environments).

Saucier (1974),and Ridgley (1977) have interpreted the Burro Canyon(?) to be deposited under fluvial conditions by a series of braided to meandering streams. Measurements of crossbeds indicate the streams flowed in directions from north-northwest to north-northeast with a source of the sediment from the southwest (Ridgley, 1977) or the Burro Canyon(?) may represent a partial reworking of the Morrison (Saucier, 1974). The upper part of this formation may be deposited by meandering streams under lower energy conditions. These conditions are reflected by finer sandstones and more shales and mudstones in the upper portion of the Burro Canyon(?).

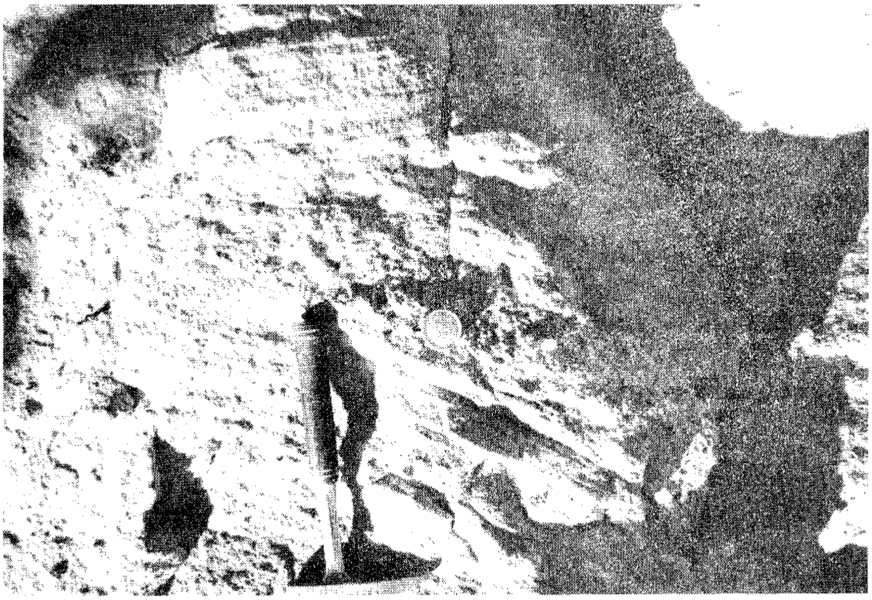


Figure 6--Photograph of conglomerate zone and crossbedding in Burro Canyon(?), Mesa Alta (Radio Tower section). Lens cap is approximately 5 cm.

Relationship of Burro Canyon(?) Formation and Jackpile sandstone--The Dakota Sandstone unconformably overlies the Burro Canyon(?) Formation in the northern part of the eastern side of the San Juan Basin and in the Chama Basin. In the southern part of the eastern side of the San Juan Basin (in the Laguna and San Ysidro areas), the Dakota overlies the Jackpile sandstone, a white kaolin-bearing fine- to medium-grained sandstone with interbedded pale-green to pale-red mudstones. Although the Jackpile cannot be traced in outcrop from the Jackpile mine (near Laguna) north to the southern end of the Nacimiento uplift because of gaps between exposures in the Rio Puerco fault zone, Owen and Siemers (1977), Saucier (1974) and Santos (1975) have correlated it across the fault zone using drill holes. Santos mapped the Jackpile north to the Nacimiento mine (near Cuba) and Young (1960) has mapped the Cedar Mountain (Burro Canyon) to its zero isopach near the Nacimiento mine. "Therefore, a sandstone called Burro Canyon, probably Lower Cretaceous, may be traced south to the Cuba area, and a sandstone called Jackpile, generally regarded as Upper Jurassic because of proximity to the Morrison mudstones (but lacking age-diagnostic fossils) may be traced north to the Cuba area. Their stratigraphic position subjacent to the Dakota and lithologic similarity indicate their correlation with one another." (Owen and Siemers, 1977, p. 180).

There are some differences between the Jackpile sandstone and the Burro Canyon(?) Formation: The basal contact of the Jackpile is usually gradational with the underlying Brushy Basin Shale Member, but the basal contact of the Burro Canyon(?) Formation is a sharp erosional contact with the Brushy Basin Member; the Burro Canyon(?) is generally conglomeratic, but the Jackpile is generally free of conglomerate beds except for locally a few pebbles near its base. So there is no positive proof that the two units are related, and the stratigraphic-age relationship of the units will need more examination before an answer is reached. For this study, they are considered as separate units.

Dakota Sandstone-Mancos Shale--The Dakota Sandstone was named by Meek and Hayden (1862) for exposures in Dakota County, Nebraska. The use of the name Dakota Sandstone in the Rocky Mountains and Colorado Plateau, although it is time-transgressive, was accepted because of similar lithology and stratigraphic position. The Mancos Shale was named by Cross and Purington (1899) from exposures in the Mancos Valley near the town of Mancos, Colorado. In the area of this study all the dark-gray marine shale tongues lying between the Dakota and the overlying Mesaverde Group (Upper Cretaceous) are considered to be Mancos.

The Dakota was deposited on a vast erosion surface in the San Juan Basin, and therefore there is a major regional unconformity at its base (Saucier, 1974). Over most of New Mexico this unconformity is angular with the strata below dipping at low angles to the north and northwest. Fassett (1974) has indicated that the Dakota section becomes generally older from east to west. As the epeiric Cretaceous seas transgressed the region, the Dakota was deposited in various environments (Landis and others, 1973b; Owen, 1973; and figure 7).

The lower part of the Dakota Sandstone is composed of fluvial, floodplain, and paludal deposits grading upward into strandline and offshore marine deposits that intertongue with the Mancos Shale (Pike, 1947; Muehlberger and others, 1960; Landis and others, 1973b; Siemers and others, 1975). In general the contact of the Dakota with the underlying beds (Burro Canyon(?) Formation, Jackpile sandstone, or Brushy Basin

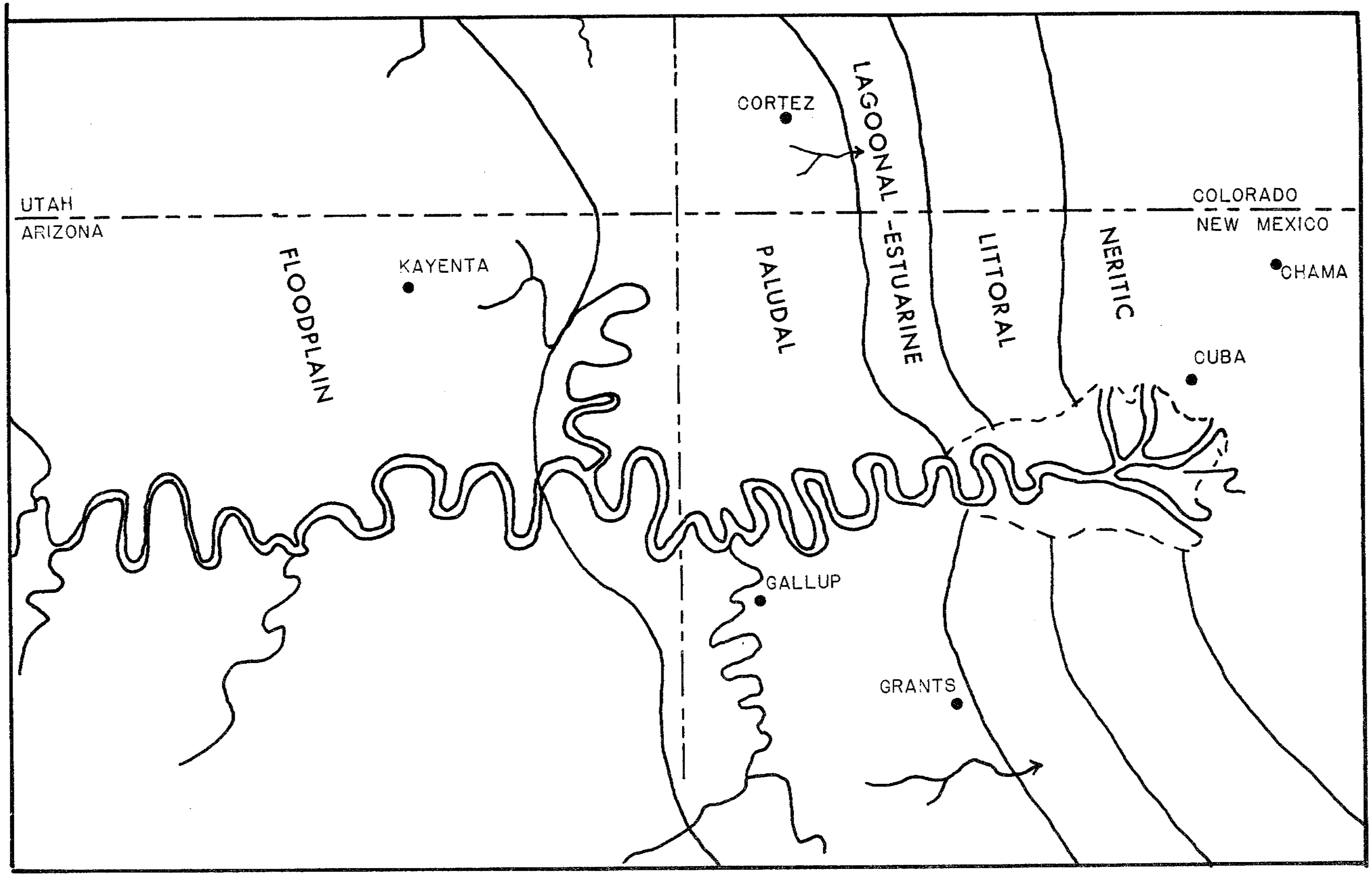


Figure 7--Schematic representation of environmental belts which migrated across the Colorado Plateau (from Young, 1973).

Shale Member is placed at the lowest occurrence of abundant carbonaceous material in the sandstone (Saucier, 1974). The Dakota intertongues with the overlying Mancos, and the Dakota-Mancos has been divided into six members along the southeastern and eastern flank of the San Juan Basin from Laguna to La Ventana (table 2). These members are, in ascending order: Oak Canyon, Cubero Sandstone Tongue, Clay Mesa Shale, Paguate Sandstone Tongue, Whitewater Arroyo Shale, and Twowells Sandstone Tongue (Owen, 1963, 1966; Dane and others, 1971; Landis and others, 1973b). North into the Chama Basin, the Dakota has a tripartite nature (figure 8) and given the informal member names of lower sandstone, middle shale, and upper sandstone. Owen and Siemers (1977) have applied the names of the two lower members of the Dakota (Oak Canyon and Cubero Sandstone) from La Ventana to El Vado (along the Gallina-Archuleta arch). As of yet, the lower two member names have not been formally applied to the Chama Basin although Saucier (1974) indicated the lower sandstone unit of the Dakota is probably the Oak Canyon Member of Landis and others (1973b).

Cobban (1977) has indicated an early Late Cretaceous age (the Twowells Sandstone and Whitewater Arroyo Shale are late Cenomanian; the rest of the units are middle Cenomanian) for the Dakota in the south and east San Juan Basin based on fossil marine mollusks which are present in all units except the lower part of the Oak Canyon Member. The lower part of the Oak Canyon was assigned an Albian age by R. H. Tschudy based on palynomorphs (Landis and others, 1973b), but Cobban (1977) revised the age to Cenomanian (based on revision of unpublished work by Tschudy).

The Dakota Sandstone was deposited in a wide range of environments (figure 7) as the shoreline moved from east to west (or northeast to southwest). Grant and Owen (1974) indicated that the Dakota is composed

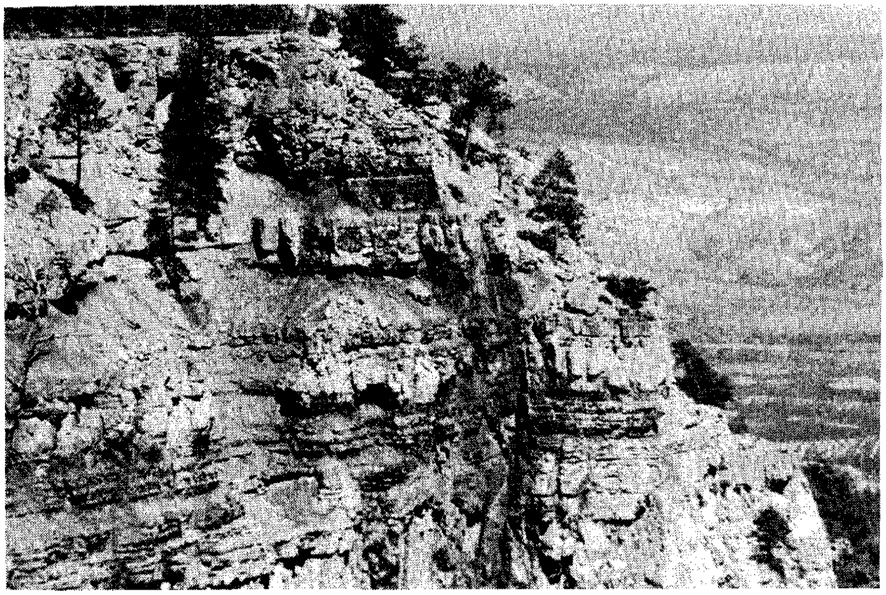


Figure 8--Photograph of typical exposure of Dakota Sandstone in northern New Mexico. Sandstone-siltstone-shale sequence is common. Photograph taken at Mesa Laguna (N½ sec. 10, T. 24 N., R. 2 E.; north of Mesa Alta).

of predominantly fluvial rocks in the northwest San Juan Basin; marine rocks in southeast San Juan Basin; and intermediate amounts of marine and nonmarine in southwest San Juan Basin and in the Chama Basin. General descriptions of the six members from bottom to top are (see section on Clay-Mineral Trends): Oak Canyon Member--This unit in most locations consists of two parts; a lower sandstone unit and an upper shale, and is a complex assemblage of fluvial, lagoonal, estuarine, and open-marine deposits. The lower part is composed of coarse- to very fine-grained sandstone, locally conglomeratic, and in places silty. There are no megafossils present, but there are some trace fossils. The unit unconformably overlies nonmarine rocks. Rocks of this lower part were deposited marginal to the shoreline (lagoonal, littoral, or shallow marine) as the Cretaceous shoreline retreated and(or) advanced. The local basal conglomeratic sandstones may be fluvial deposits shoreward of the strandline. The upper unit is composed mostly of mud-shale and silt-shale with bentonite beds. This part grades upward into the sandstones of the Cubero Sandstone Tongue. The upper part is largely deposited in a marine environment during transgression of the sea.

Cubero Sandstone Tongue--This unit is mostly composed of very fine- to fine-grained sandstone that is silty and carbonaceous in part (Landis and others, 1973b). It commonly is a resistant ledge-former (especially in the upper part). Generally, the lower portion is coarser grained and unfossiliferous except for abundant burrows (probably Ophiomorpha and Thalassinoides). The environment of deposition was probably shallow marine.

Clay Mesa Shale Member--This unit is composed of medium- to dark-gray, silty clay-shale. The upper part includes some sandy beds. This unit forms gentle slopes between the ledge-forming sandstone tongues of the

Dakota (which define the top and bottom of the Clay Mesa). This tongue is fossiliferous, and the fauna indicate changes in depositional conditions. The finer grained, middle part of the unit (samples B76042 and B76027) contains ammonites and is an open-marine, deeper water deposit while the siltier upper and lower portions contain oysters and clams and are probably shallower water deposits (Landis and others, 1973b).

Paguate Sandstone Tongue--This unit is similar to the Cubero Sandstone although generally thicker, very fine-grained, and contains dark-brown calcareous concretions. North from the San Ysidro area it intertongues with shales of the Mancos and gradually wedges out into the Mancos. The thicker Paguate is highly bioturbated making distinction of trace fossils difficult. In general it represents a mixture of open-marine shelf sandstones and nearshore marine siltstones and sandstones. Its basal contact with the Clay Mesa is gradational; its upper contact may be disconformable with the Whitewater Arroyo Shale.

Whitewater Arroyo Shale--This unit is composed of soft, slope-forming shale and siltstone with bentonite beds. The fauna in this unit indicates a shallow-water marine shelf with part being deposited in quieter and perhaps deeper water.

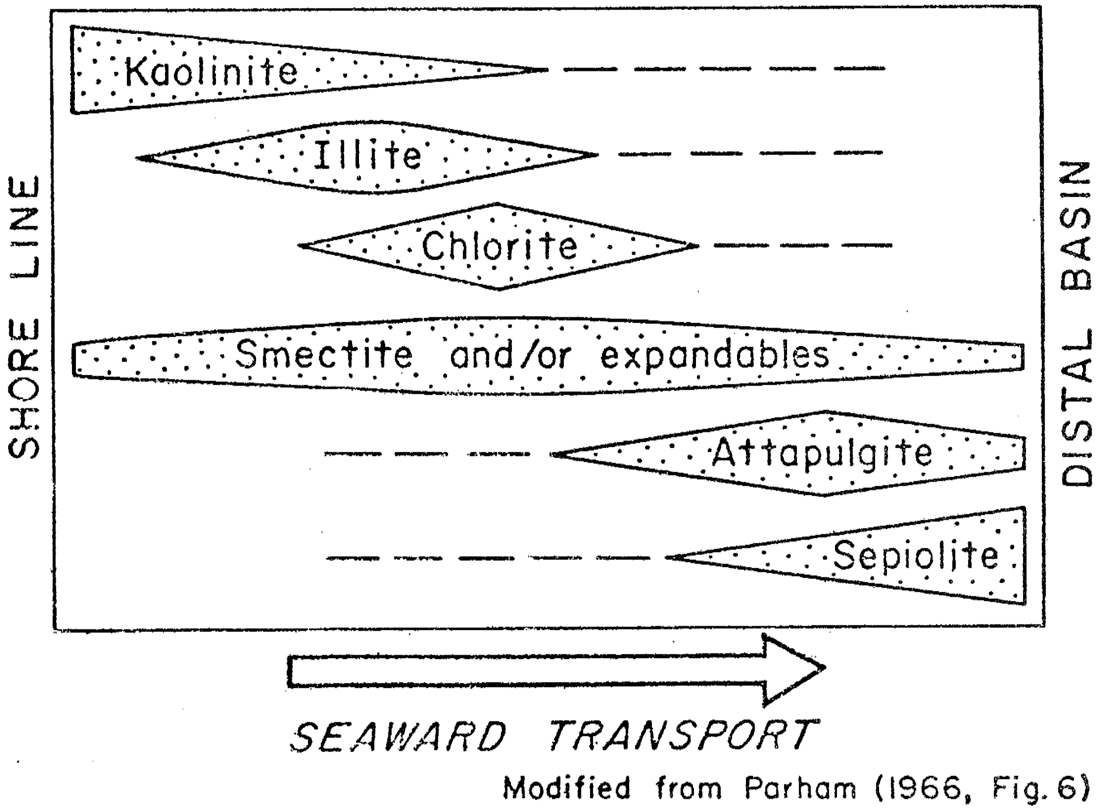
Twowells Sandstone Tongue--This unit differs from the other sandstone tongues in that it is coarser grained, with a few pebbles, glauconitic, and contains some beds with well-developed crossbedding. It is believed to be an extensive off-shore shallow-water marine shelf sandstone derived from a source area to the southwest (Dane and others, 1971; Owen, 1963).

Clay-Mineral Trends and Associated Depositional Environments

As indicated in the Stratigraphic Nomenclature section, many of the shales that were sampled represent transition zones (nonmarine-marine) as the Cretaceous shoreline advanced. Many of the Dakota-Mancos shale members were deposited in nearshore environments. I sampled some of the clay-bearing units occurring in the Jackpile sandstone (nonmarine) unit of the Morrison Formation, Burro Canyon(?) (nonmarine), and the Oak Canyon and Clay Mesa Members (nonmarine-marine) of the Dakota-Mancos Formations. Even though many of these samples are not economically useful as refractory clays, they provide an interesting look at clay-mineral trends of these units.

Several studies of clay mineralogy in recent and ancient environments that are well documented have indicated a predictable variation in clay-mineral trends (figure 9) for various sedimentation patterns (deltas, lagoons), lithologies, and depositional environments (Brown and others, 1977; Gibbs, 1977; Grim, 1968; Keller, 1970; Lee and Chaudhuri, 1976; Parham, 1966; Pryor and Glass, 1961; Smoot, 1960; Weaver, 1967a, 1967b).

Discussed here are eight measured sections with the accompanying descriptions and figures in Appendix II. In the figures the particle size and clay-mineral composition are plotted. A summary of these sections are: Oak Canyon Member (figure 10)--The clay-mineral suites and particle size of samples B76033 - B76039 (see figure 1, locality 3; and figure 11) indicate a gradational zone from nearshore nonmarine and marine to deeper marine. The exact depositional environment is difficult to postulate. The lower Oak Canyon Sandstone is probably deposited in a meandering stream grading into a paralic shale. Shale is the dominant lithology, although the samples grade into siltstone. Up section (in middle) smectite increases (as a result of the bentonite layers), illite remains relatively constant, and the mixed-layer (illite-smectite)



Modified from Parham (1966, Fig. 6)

Figure 9--Generalized lateral variations in clay-mineral assemblages.

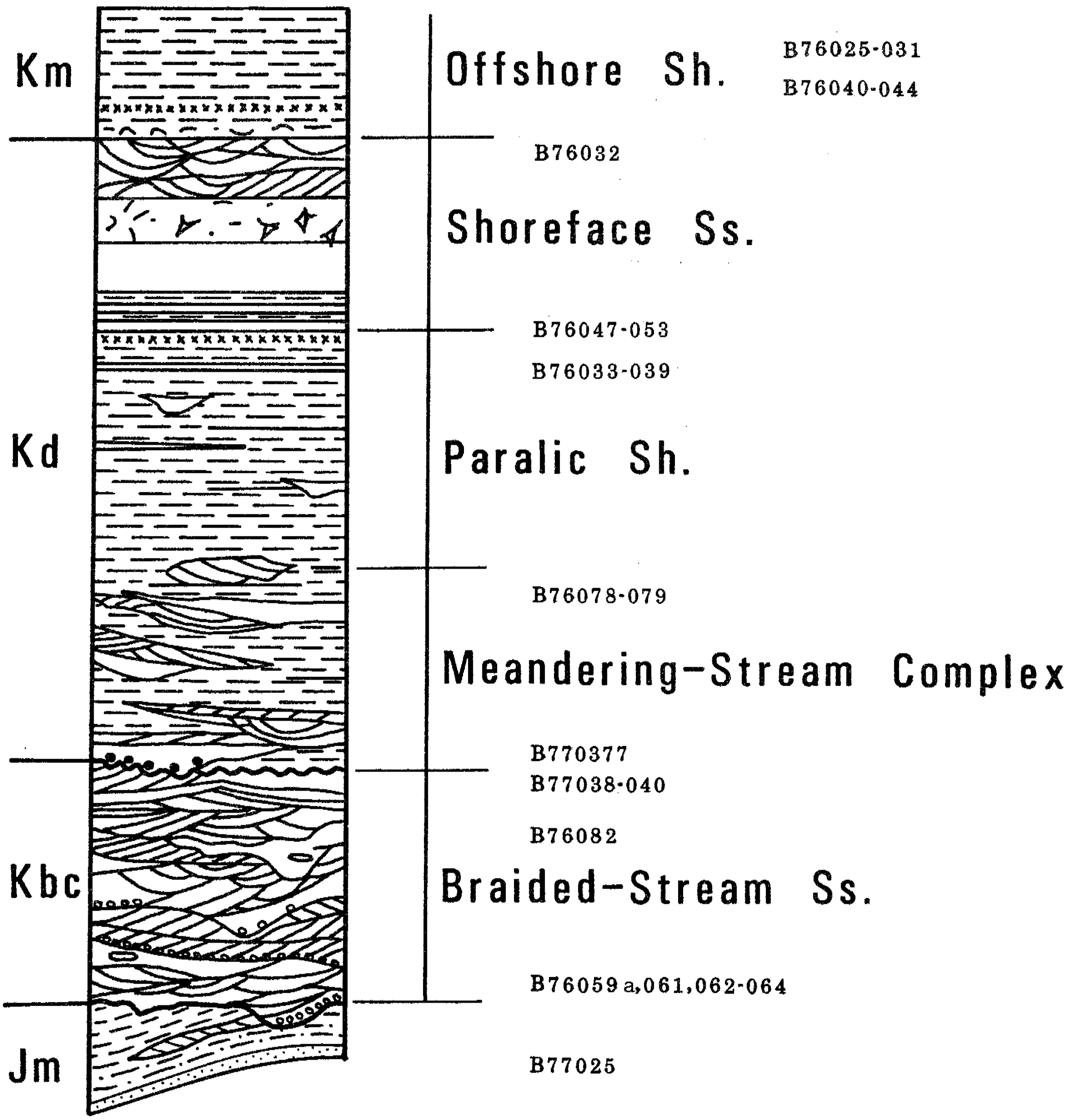
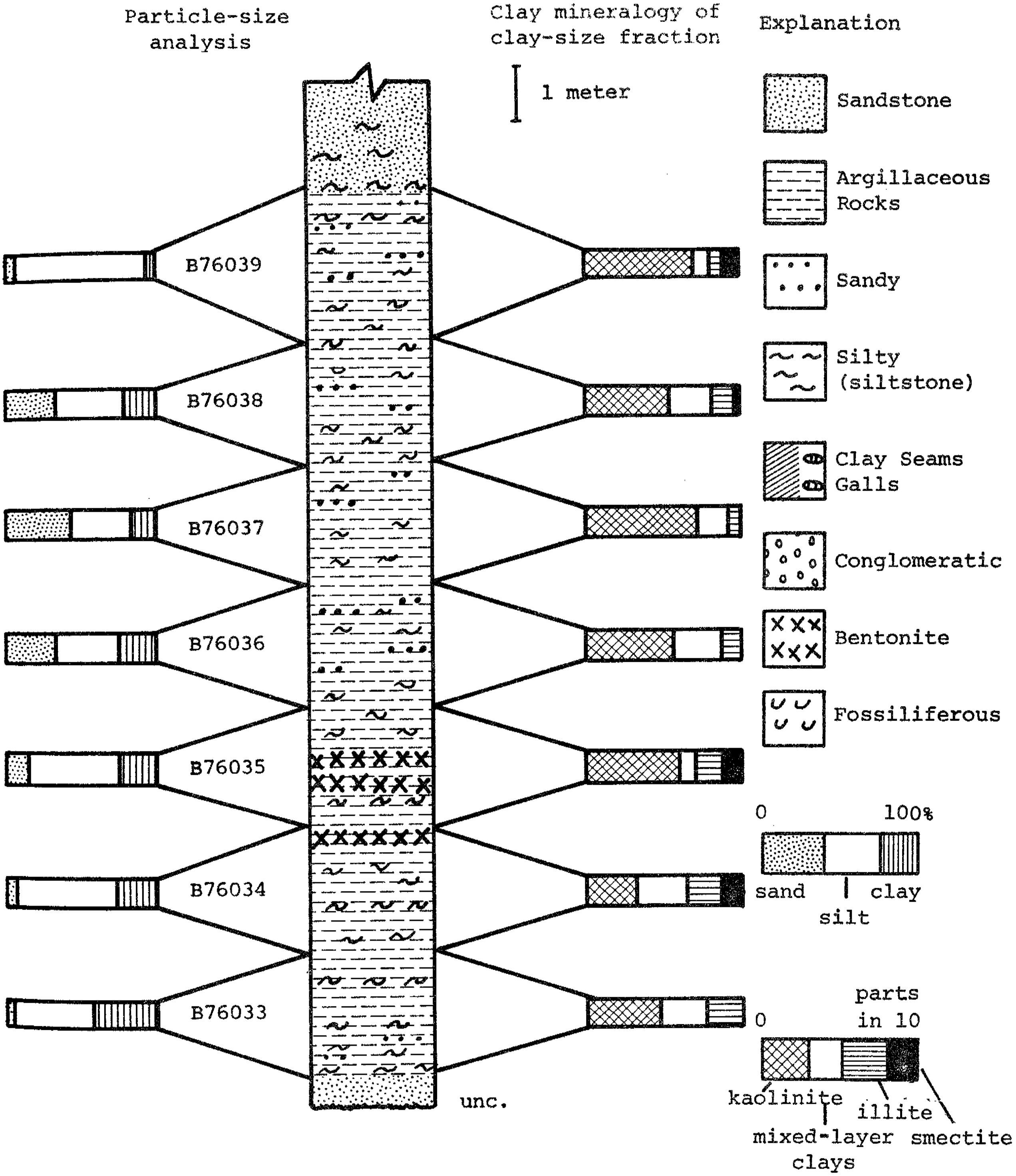


Figure 10--Location of the samples within an idealized depositional model of Dakota Sandstone-Mancos Shale and Burro Canyon(?) Formation. (After Owen, written communication, 1979.)

Figure 11--Measured Section

CAÑADA DE LAS MILPAS SECTION - OAK CANYON MEMBER (3)
SEC. 32ac T. 15 N., R. 1 E.
SKY VILLAGE NE QUADRANGLE



clay minerals fluctuate throughout (decrease in sample B76035, where smectite increases). Kaolinite fluctuates irregularly but does increase at the top. These variations indicate a trend of nearshore deposition gradually becoming more marine in the center of the section (possibly as a result of transgression) with a shallowing occurring during deposition of the top of the section.

In samples B76047 - B76053 (figure 1, locality 1; and figure 12), the clay-mineral trend indicates the presence of smectite in all samples, with kaolinite and illite varying some; and the mixed-layer (illite-smectite) clays vary directly with the variations in smectite. This indicates an environment similar to samples B76033 - B76039--dominantly nearshore grading to deeper marine then with shallowing occurring near the top of the section.

Clay Mesa Shale (figure 10)--In samples B76025 - B76032 (figure 1, locality 4; and figure 13) and B76040 - B76044 (figure 1, locality 2; and figure 14), kaolinite abundance remains relatively constant, illite increases towards the middle of the section and mixed-layer (illite-smectite) clay minerals decrease. This would indicate that the upper and lower portions may be shallow marine and the middle portion (samples 026-027 and 041-042) deeper marine.

Basal Dakota or Burro Canyon(?) (figure 10)--These samples (figure 1, localities 5, 6, 7, and 8; and figures 15-18) are dominantly deposited in marsh, fluvial, or other nonmarine environments. The particle size is dominantly clay size with kaolinite being the only or at least principal clay mineral, and with only minor amounts of illite and mixed-layer clays. The absence of smectite and predominance of kaolinite would indicate a more nearshore or a nonmarine environment. In samples B77038-40

Figure 12--Measured Section

BERNALILLTO MESA SECTION - OAK CANYON MEMBER (1)
SEC. 27 line ab T. 15 N., R. 1 W.
SKY VILLAGE NW QUADRANGLE

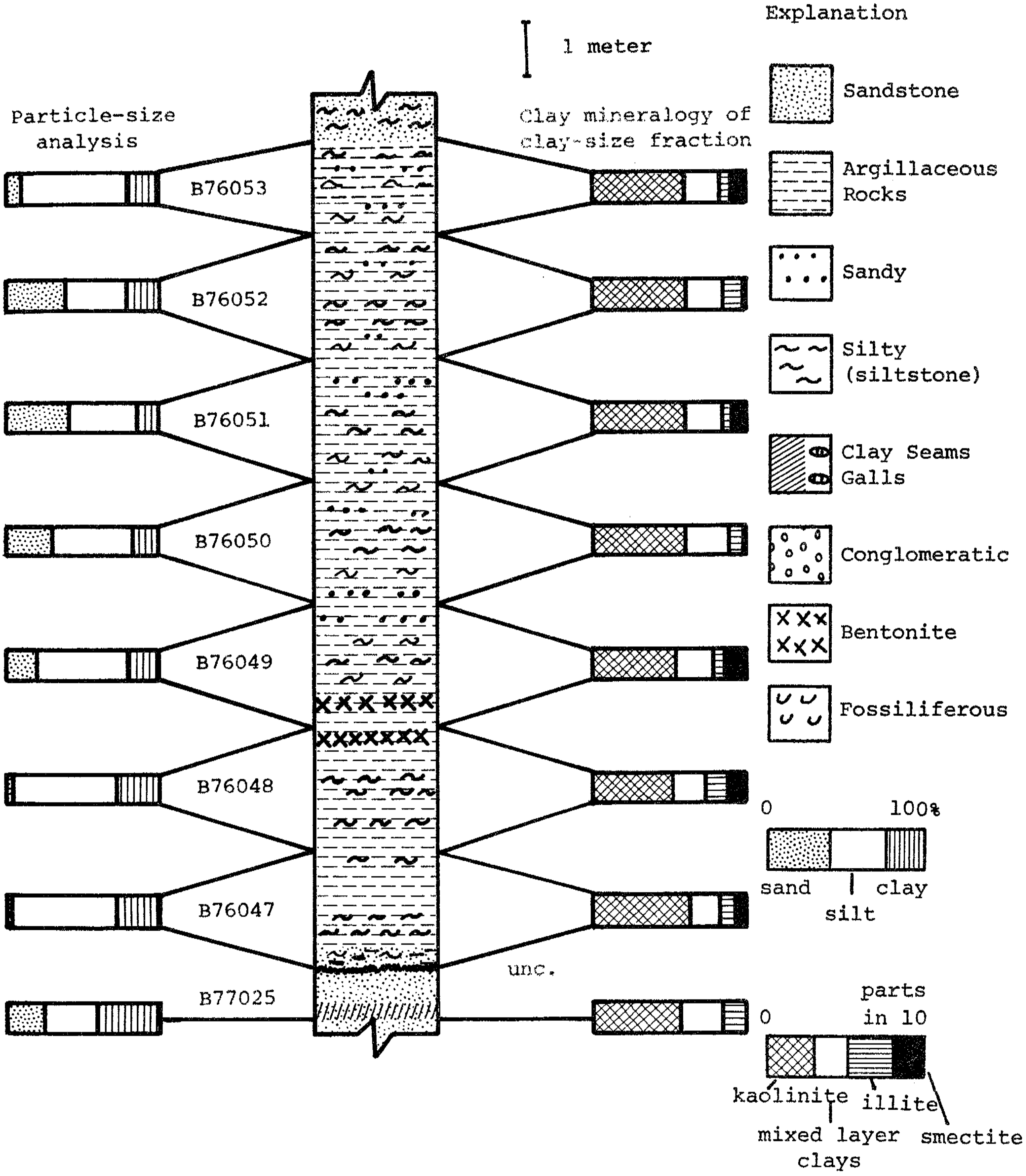


Figure 13--Measured Section

CLAY PIT SECTION - CLAY MESA SHALE - PAGUATE SANDSTONE(4)
SEC. 26bd T. 15 N., R. 1 E.
SAN YSIDRO QUADRANGLE

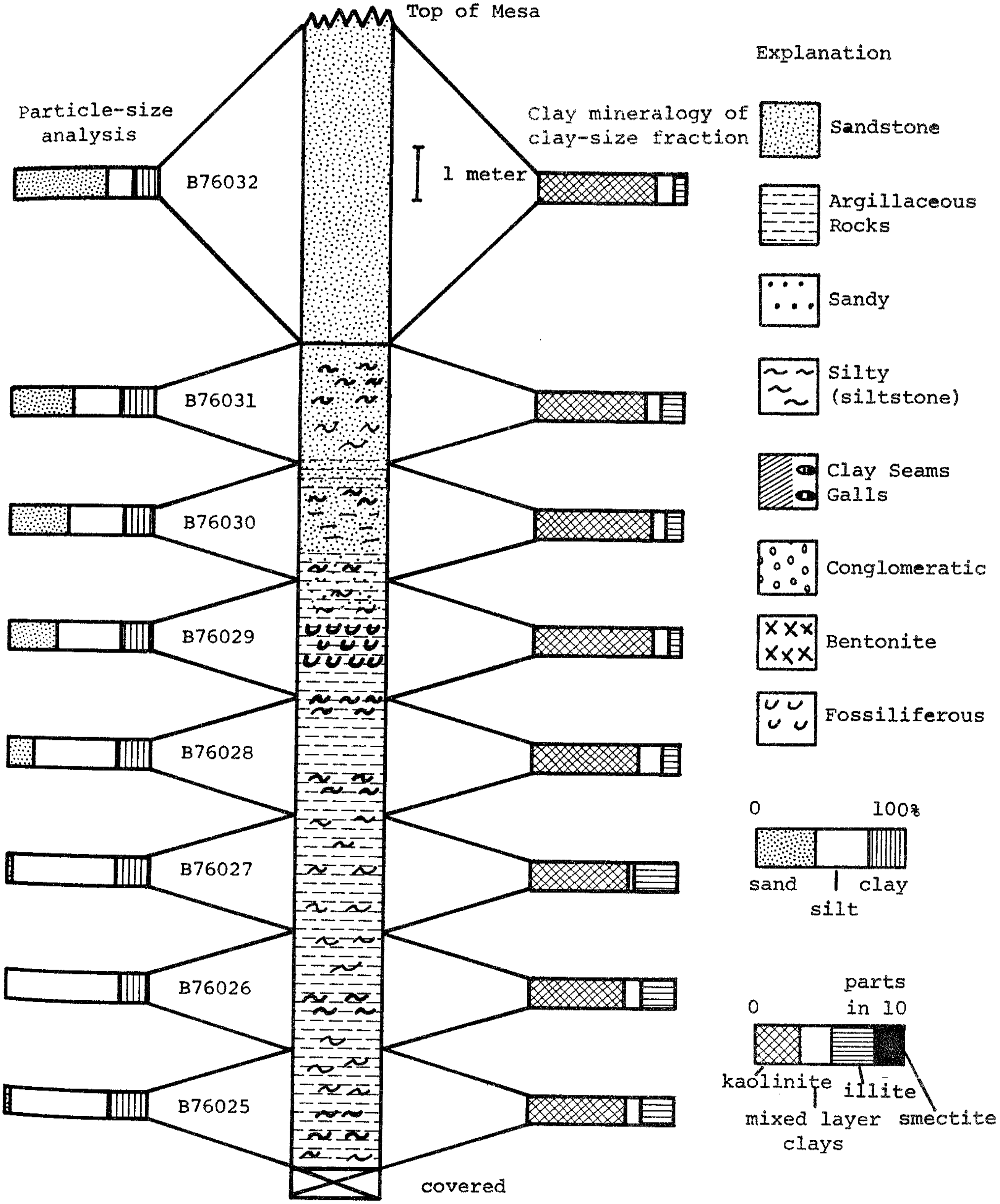


Figure 14--Measured Section

CAÑADA DE LAS MILPAS SECTION - CLAY MESA SHALE(2)
SEC. 32ac T. 15 N., R. 1 E.
SKY VILLAGE NE QUADRANGLE

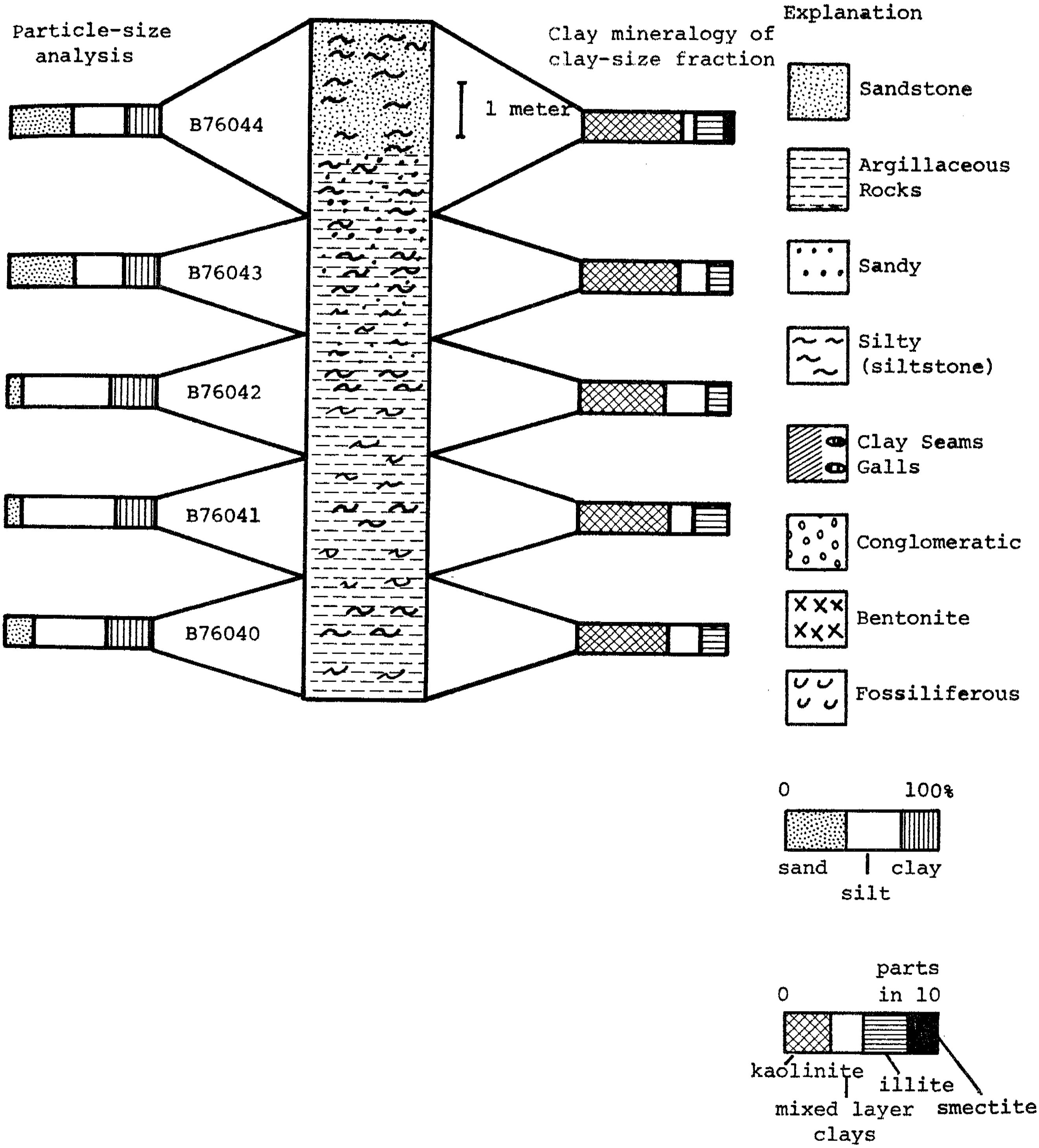


Figure 15--Measured Section

MESA GOLONDRINA SECTION - DAKOTA - BURRO CANYON(?) (7)

SEC. 5ba T. 25 N., R. 2 E.

LLAVES QUADRANGLE

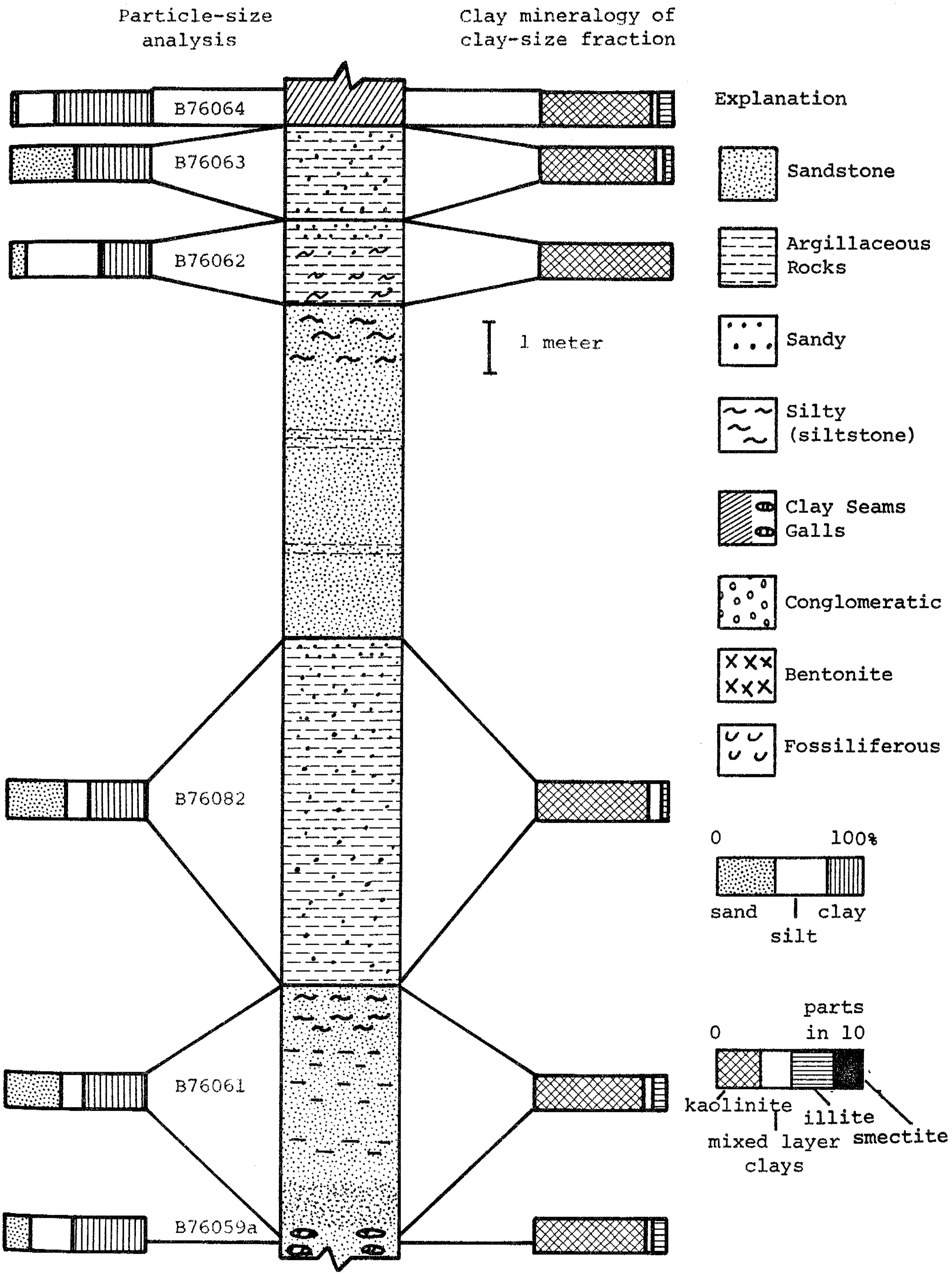


Figure 16--Measured Section

SEÑORITA CANYON SECTION - DAKOTA(5)
SEC. 33d T. 21 N., R. 1 W.
CUBA QUADRANGLE

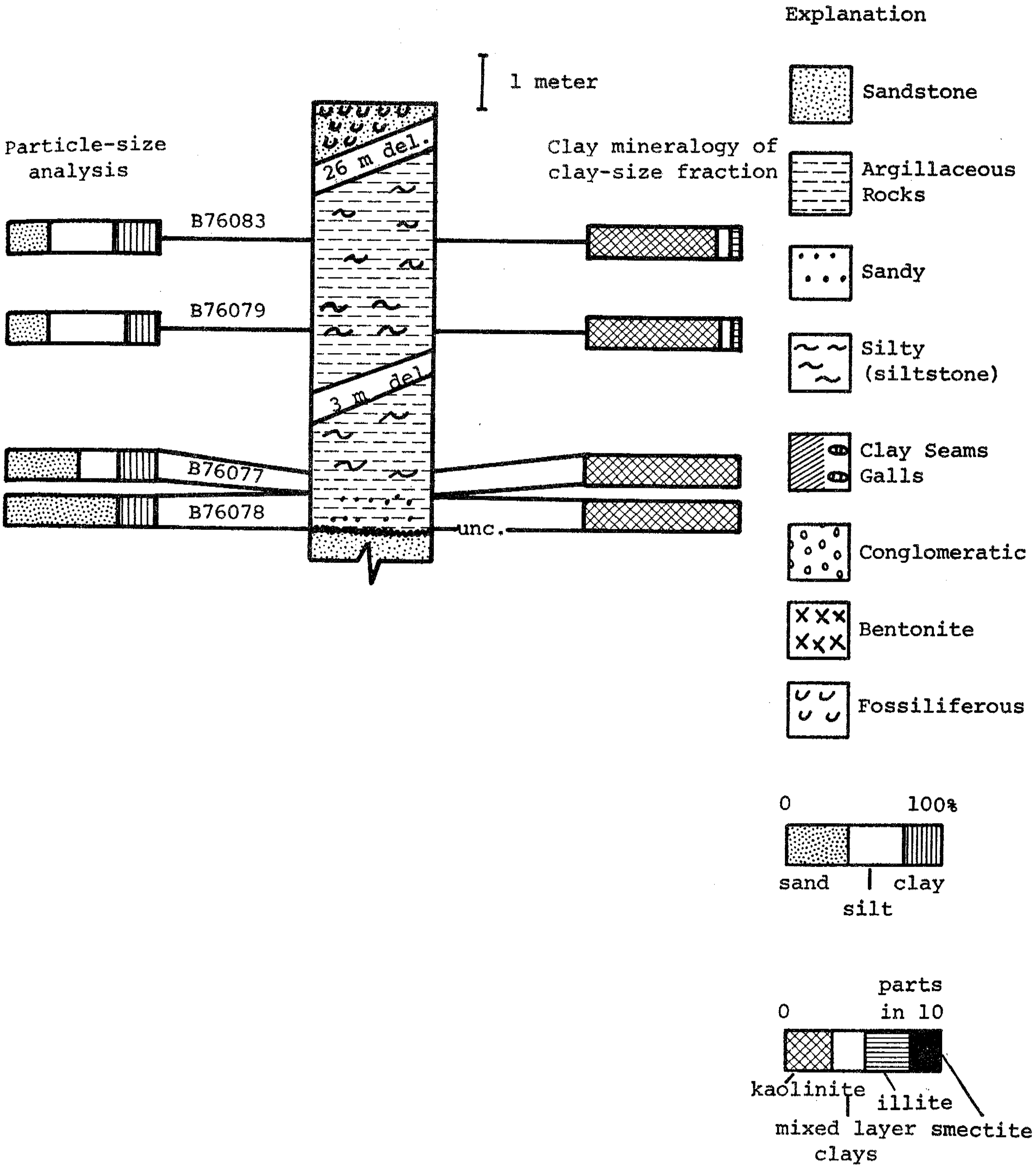


Figure 17--Measured Section

MESA CORRAL SECTION - DAKOTA - BURRO CANYON(?) (6)
(Myers Kaolinite Deposit)

SECS. 2&11 T. 23 N., R. 2 E.

ARROYO DEL AQUA QUADRANGLE

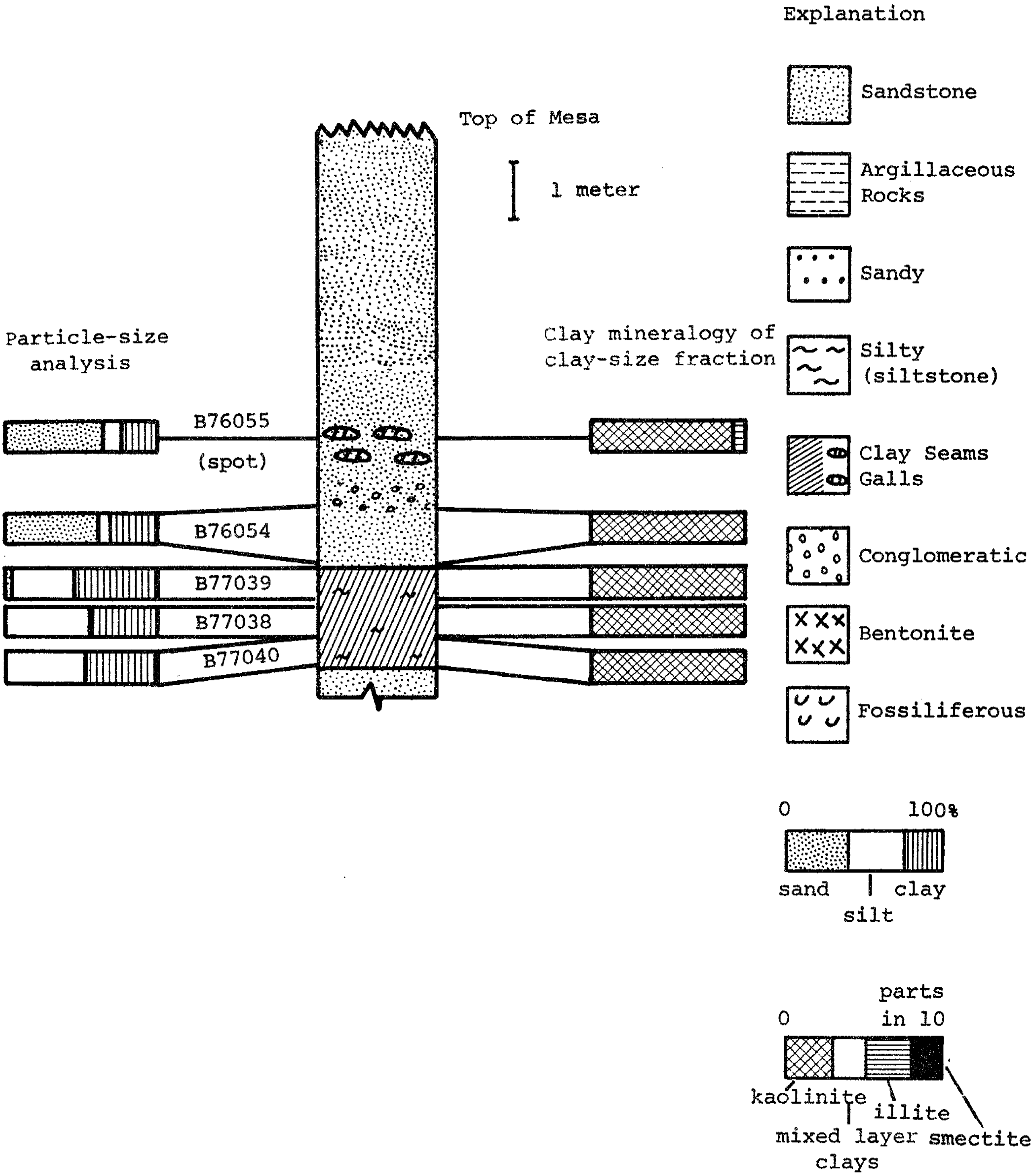
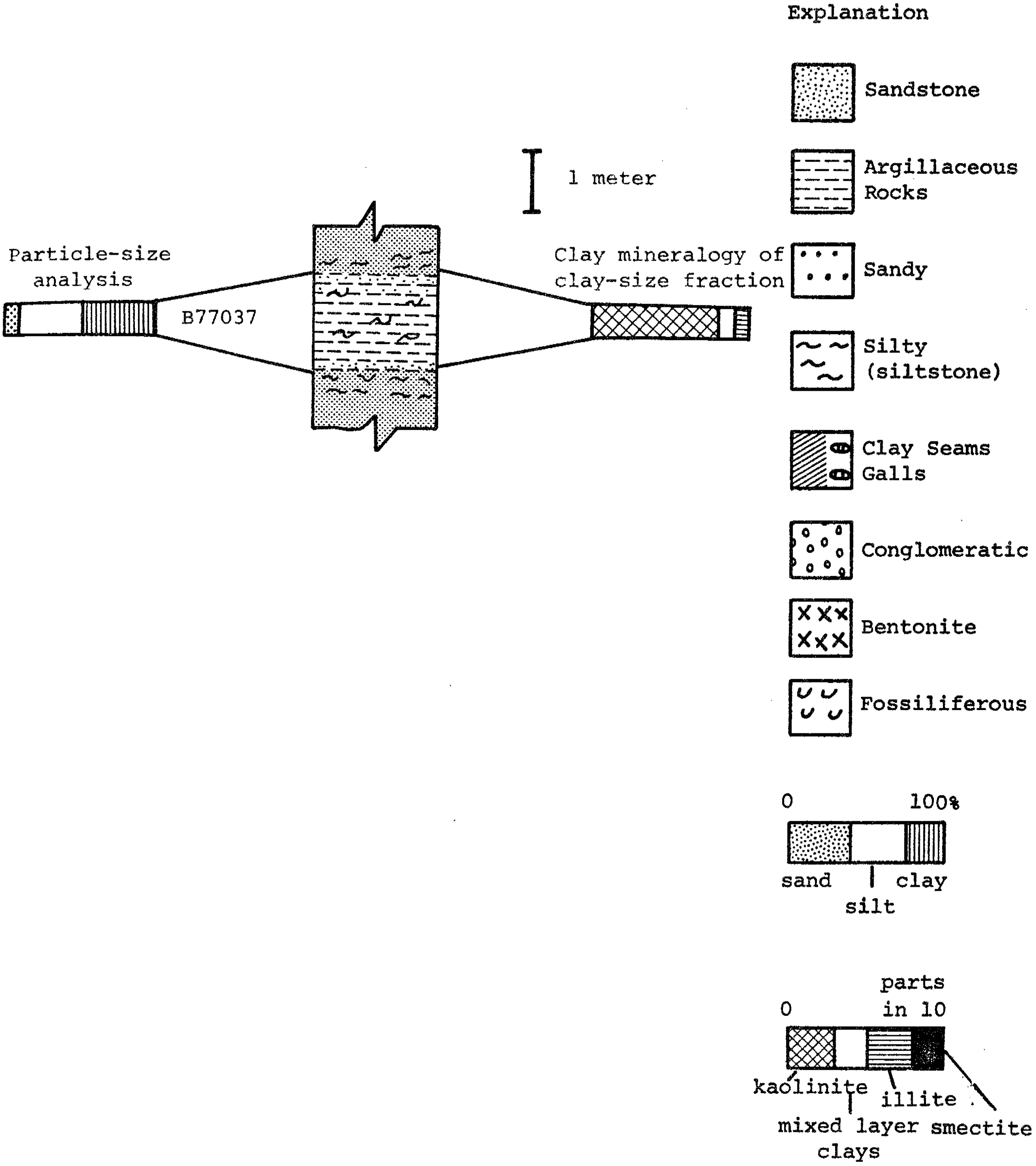


Figure 18--Measured Section

TOWER MESA SECTION - DAKOTA FORMATION (BASE) (8)
SEC. 13 b T. 23 N., R. 2 E.
YOUNGSVILLE QUADRANGLE



(locality 6), a colloidal origin is postulated, with the samples being deposited in a marsh, lagoon, or swamp, because of their extremely fine-grained, flint-like appearance (figure 19) and because they are composed of only kaolinite. Other samples (such as B77037; figure 18) were probably brought in as kaolinite or illite particles that settled out in quiet waters (such as a lagoonal or marsh environment). The Burro Canyon(?) Formation is described as being deposited under braided stream conditions while the lower Dakota Sandstone is deposited in meandering streams.

Discussion of trends--Commonly continental deposits containing clay minerals reflect the environment of the source area and later diagenesis. Nonmarine units include Jackpile sandstone, Burro Canyon(?) Formation, and basal Dakota Sandstone (figures 15-18; Mesa Golondrina section, Mesa Corral section, and Señorita Canyon section). Since these units are predominantly sandstones or silty sandstones, the permeability is high, allowing clays to either be physically transported by the percolating water or to develop authigentically. In general the kaolin group, especially kaolinite, is associated with fluvial and nearshore environment (Grim, 1968, p. 55); kaolins are stable in freshwater environments and unstable in marine environments. When present in marine environments, this commonly indicates a nearby kaolin source area and rapid accumulation of the sediments.

Generally in the units described in this study the basal (nonmarine) sandstones are coarser grained and contain very high percentages of kaolinite. Other studies in similar units that have indicated similar results are: Brown and others, 1977; Krumm, 1969; Lee and Chaudhuri, 1976; Pryor and Glass, 1961; and Smoot, 1960.

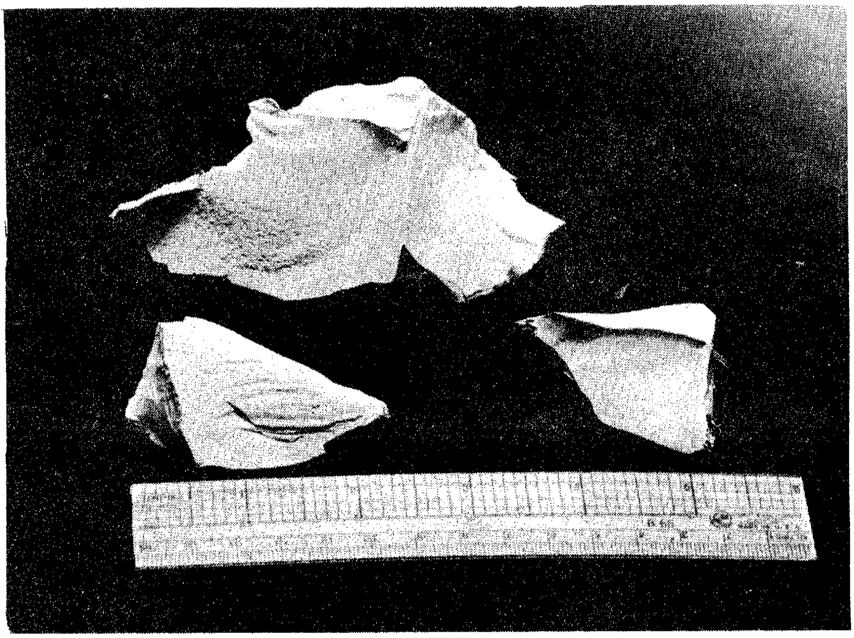


Figure 19--Photograph of sample B77038 from Myers kaolinite pit (Mesa Corral), showing conchoidal fracturing typical of a flint clay.

Rocks with high permeabilities can have water circulating through them which may alter existing clay minerals or produce authigenic types; therefore examining the clay mineralogy in sandstones and using only the clay-mineral trends for inferring depositional environments is probably not justified. Clay-mineral trends can be used in addition to other sedimentological tools to infer post-depositional environments.

Transition from nonmarine to marine often involves diagenetic changes in sediments. The marine environment is alkaline, with little leaching and the water contains a good deal of dissolved calcium, potassium and magnesium. These conditions favor the formation of smectite, illite, or chlorite rather than kaolinite (Grim, 1968; Millot, 1970). Clay-mineral particles, transported by freshwater streams and stable in that environment, may undergo differential flocculation due to varying particle size (Whitehouse and others, 1960) and also chemical alterations when reaching a marine environment (Brown and others, 1977; Gibbs, 1977). To give a range of sizes for various clay minerals (Whitehouse and others, 1960): Smectite--0.9 μm to 0.1 μm (mean 0.4 μm); kaolinite--10 μm to 0.4 μm (mean between 1-2 μm); illite--sand size to 0.4 μm (mean between 2-4 μm).

The presence of a kaolinitic marine sediment (such as the samples of the Oak Canyon and Clay Mesa Shales) indicates a nearby and terrestrial source of the kaolinite and a relatively rapid accumulation of kaolinite in an unfavorable environment. Several studies have indicated trends in clay-mineral suites for nearshore to basinward deposition (Burst, 1958; Brown and others, 1977; Gibbs, 1977; Lee and Chaudhuri, 1976; Parham, 1966; Pryor and Glass, 1961; Postma, 1967; Smoot, 1960; Weaver, 1967b). One study by Pryor and Glass (1961) on the Cretaceous-Tertiary of the upper Mississippi embayment indicated clay minerals of regressive-transgressive cycles. Basically the clay minerals of regressive (fluvial and upper delta) deposits are dominantly kaolinite while transgressive (inner neritic) are nearly equal amounts of kaolinite, illite, and smectite, and transgressive (outer neritic) are dominantly smectite.

The four sections of marine shales (two of Oak Canyon Member and two of Clay Mesa Shale) are predominantly from nearshore (marginal marine--lagoonal, littoral, or shallow marine), with deeper marine in the middle portions, and some grading into shoreward sandstone deposits (figure 10). These units were produced by dominantly transgressive cycles (as indicated by the equal amounts of kaolinite, illite, and smectite). The basal contact of the shale of the Oak Canyon Member with the sandstone of this member is fairly sharp although the upper contact with the Cubero Sandstone is gradational. The clay mineralogy (see figures 11, 12) of these basal portions indicate approximately proportional amounts of kaolinite (4-5 parts in 10), smectite (2-3 parts in 10), and illite (2-3 parts in 10) in the < 2 μm fraction based on x-ray peak heights. At the upper contact there is a definite increase in kaolinite (6-7 parts in 10). The Burro Canyon(?)-lower Dakota is dominantly kaolinite which may indicate a regressive cycle. The clay-mineral data basically supports the dominantly marine to nonmarine nature determined by previous workers and discussed in the section on Stratigraphic Nomenclature.

The Clay Mesa Shale is also marine with the top and basal parts deposited in nearshore shallow water and the middle part deposited in deeper and quieter waters; the former coarser grained and more kaolinitic than the later (figures 13, 14). Also, there are calcareous concretions in the middle part of the Clay Mesa. Again the clay-mineral trends add support to the other tools in inferring depositional environments.

The most promising clay-bearing zone in the study area (figure 17) is over five feet thick, contains a relatively pure kaolinite, is very fine grained, and resembles flint clay (figure 19) with conchoidal fracturing (sample B77038).

Figure 20 is a SEM photomicrograph of sample B77038. The texture of flint clay is fine-grained usually requiring magnification of 5000x or higher to resolve individual grains or crystals. The matrix is tightly compacted of fine flakes, sheaves, and interspersed tight, thin books of kaolinite, all closely intergrown and interlocked, and this produces the high bulk density (Keller, 1976a,b; 1977). This sample fractures conchoidally, has high bulk density, and does not slake in water; it is described as flint-like and is sedimentary in origin. Figures 21 and 22 are SEM photomicrographs of other sedimentary kaolin group clays (B76062) and (B77037) for which depositional conditions were slightly different, thus the extremely dense flint clay did not develop. The environment of deposition for flint clays is commonly low-lying paludal (marsh); often the clays are deposited in basins, in either clastic silicate rocks or in karstic carbonates (Keller, 1968). The source is probably weathered clay residue from pre-existing argillaceous carbonate and other sedimentary rocks (such as the Morrison Formation). A colloidal suspension is logical since the samples (B77038-40) are monomineralic with respect to clay minerals and have very little sand-size particles (< 3%). The other kaolinitic lenses of sedimentary origin and of refractory quality usually have other clay minerals present and contain more sand-size particles. Keller (1968) suggests that dissolved mineral matter is carried into a paludal (marsh) environment where a colloidal suspension may be formed by dialysis. After crystallization to illite, subsequent leaching can convert this material <u>in situ</u> into a dense homogeneous kaolin. Other kaolinite zones

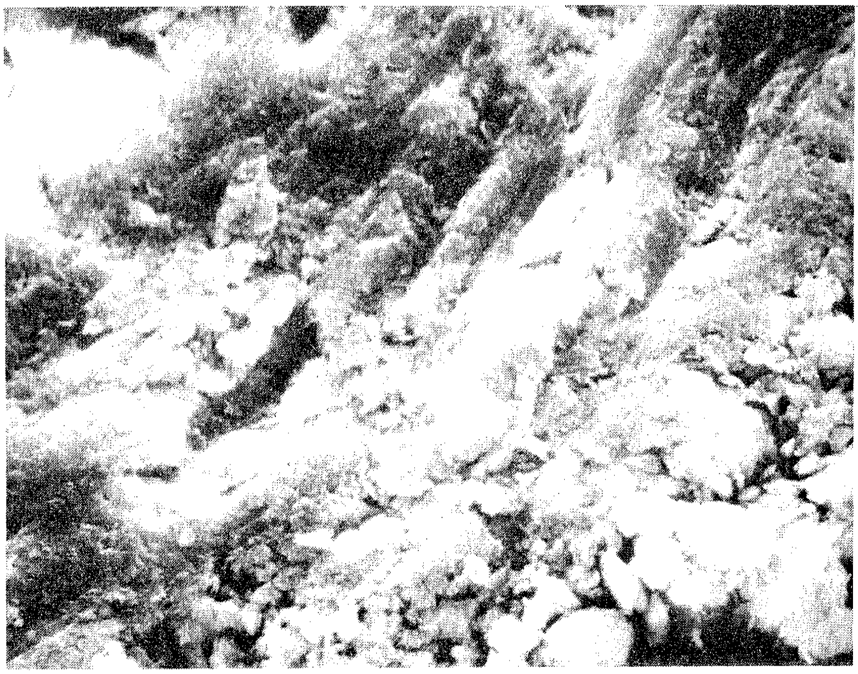


Figure 20--SEM photomicrograph of a flint-like clay (sample B77038). Magnification is 2,500x.

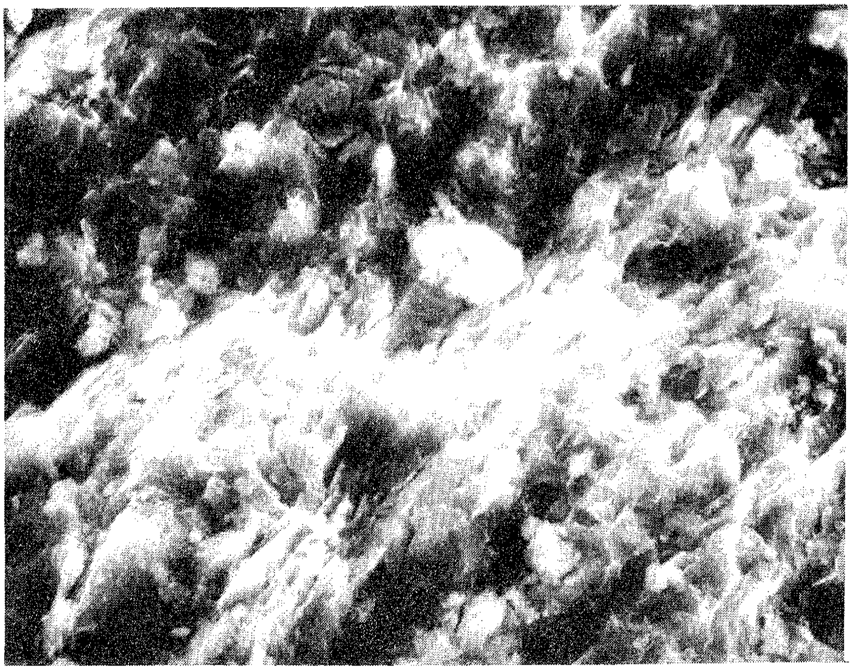


Figure 21--SEM photomicrograph of a sedimentary high-kaolin clay (sample B76062). Note coarser grain size and more porous nature as compared to figure 20. Magnification is 2,500x.

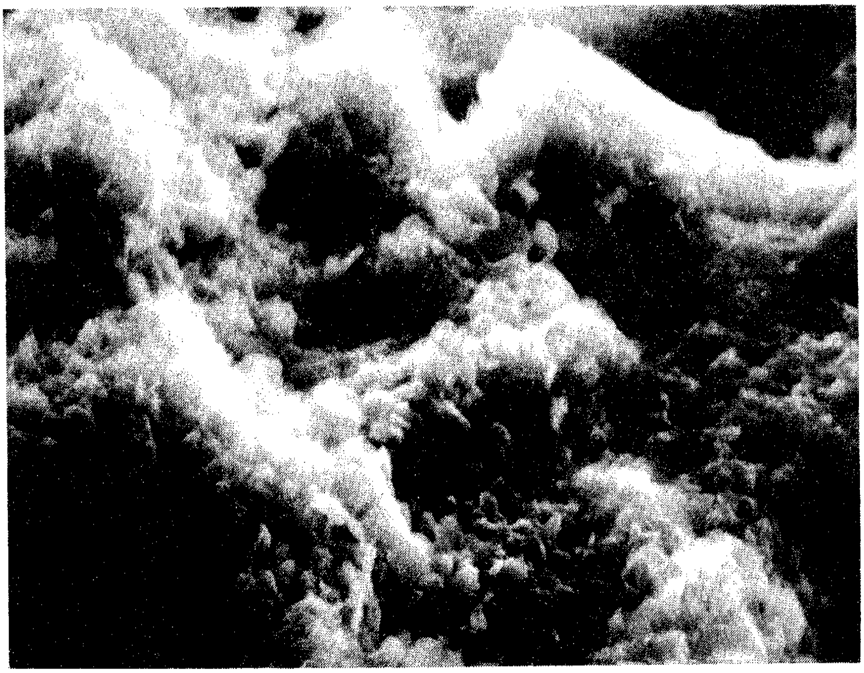


Figure 22--SEM photomicrograph of a sedimentary high-kaolin clay (sample B77037) under high magnification (5,000x).

were probably deposited by streams carrying individual kaolinite or illite particles that settled out nearshore and were compacted and dewatered to form the zones.

This flint-clay zone was suggested to be a climatic indicator by Leopold (1943). This is true to a point because, as shown in previous discussion, the Burro Canyon(?) is a braided-stream deposit, while the lower portion of the Dakota is a meandering-stream deposit. Braided streams have steeper gradients and more fluctuating, higher discharge than do meandering streams. The climatic conditions are semi-arid to arid or periglacial. These conditions prevent abundant vegetation and therefore high sediment availability (Doeglas, 1963; Selley, 1970). In contrast meandering streams form in areas of gentler gradient and lower discharge, but where seasonal discharge is fairly steady. The sediment availability is low because of extensive vegetation produced in the more humid climates (Selley, 1970).

Shale lenses occur in both meandering and braided-stream deposits. In braided-stream deposits there are pebbly sandstones with a few thin lenses of green and red shale. These deposits grade upward and laterally into a meandering-stream complex of channel sandstones and overbank carbonaceous shales.

The overbank shales in the Burro Canyon(?) and Dakota have three types of lithologies. The lowest is a gray-green shale similar to the shale lenses of braided-streams; it is commonly associated with the coarser grained, noncarbonaceous channel sandstone. The overlying shale is silty, dark gray to black, carbonaceous and contains thin siltstone beds. This type of shale is the most common. The third type of shale is similar to the second, but is dark gray to black, carbonaceous clayey shale rather than silty (Owen, 1973). The clay mineralogy of the three are similar (Appendix II) dominantly kaolinite with some illite and mixed-layer (illite-smectite) clay minerals. This supports a nonmarine origin (possibly a regressive cycle).

The sections described from Mesa Golondrina, Mesa Alta, and Mesa Corral (containing the API reference clay) probably occur in the transition from braided to meandering stream deposits (Burro Canyon(?)-Dakota transition) and, in that sense, may show the effect of climatic change. With increasing amounts of vegetation and lower stream gradients, low-lying swamps formed. Some of the floodplain and overbank shales contain coaly fragments. The formation of lagoonal or paludal areas favored intense plant growth therefore an acidic environment. Much of the claystones and shales were deposited during this time. The acidic conditions leached out many soluble ions, and kaolinite was produced (from the Al, O, Fe^{+3}, Si, and H ions).

DISCUSSION OF DEPOSITIONAL ENVIRONMENTS FOR CLAY SAMPLES

Concentrations of high kaolinitic clay, and therefore of more ceramic value (see section on Ceramic Testing), were found in nonmarine deposits (Mesa Golondrina, Mesa Corral, and Mesa Alta; figures 15-18). Although the clay minerals in marine shales may consist dominantly of kaolinite, more illite, mixed-layer clay (illite-smectite) minerals, and smectites are present than in nonmarine types. The nonmarine environments favored the kaolins at the expense of the smectites and mixed-layer illite-smectite clay minerals. The dominant method of deposition occurred as individual clay particles that were transported (detrital) via a braided or meandering stream. Meandering streams favored deposition because of lower gradients carrying finer grained particles and more vegetation to trap and alter (via a leaching process) these particles. Some of the clay lenses in the nonmarine environments are simply sedimentary kaolinite brought in as particles and settling out in quiet waters (Tower Mesa--B77037, figure 18). Other deposits are alterations of the feldspars in conglomeratic zones found in the braided-stream environments (clays replace feldspar in the conglomerate). Mesa Corral locality contains an example of what I believe is a flint clay (figure 19; sample B77038, figure 17). This type of clay usually suggests deposition from colloidal suspension. Generally the clay particles of sedimentary-type deposits in the study area were carried in the streams and may have been the result of reworking of the Morrison Formation as suggested by Saucier (1974). The clays minerals of the Morrison consist of smectite, smectite-illite, and some kaolinite. With reworking and leaching these clays minerals were altered to kaolinite.

In summary, the shales of the Burro Canyon(?) are nonmarine and consist dominantly of kaolinite with minor amounts of illite and expandable clays. The shales of the Dakota are nonmarine at the base grading upward to marine (upper Oak Canyon and Clay Mesa Shale). Their clay mineralogy consist dominantly of kaolinite plus some illite with the outer shelf marine shales having a greater amount of expandable clays (smectites and mixed-layer clays). The presence of kaolinite also indicates a terrestrial source area and rapid accumulation.

REFRACTORY STUDIES

Definition of Terms

The American Ceramic Society defines clay as "A fine-grained rock which, when suitably crushed and pulverized, becomes plastic when wet, leather-hard when dried and on firing is converted to a permanent rock-like mass." In this study a clay-bearing unit contains an abundance of clay minerals (shales, claystones, siltstones). The primary purpose of the study was to find economical refractories, and thus a high kaolinite content is needed (table 4a, 4b, 5a) in the unit. Kaolin has been defined as a fine-grained, earthy rock which contains a significant amount of kaolin minerals (Committee on Correlation of Age and Genesis of Kaolins, 1972; Ross and Kerr, 1930). However kaolin minerals, of which kaolinite is one, may form in many different ways: 1) crystallation in cavities with other rock, 2) replacements, 3) alteration of water-laid clastic silicate parent material, 4) in situ alteration of 'primary' silicate crystalline rock, 5) kaolinization at an unconformity, as below an artesian aquifer, 6) hydrothermal argillation (water heated by subsurface sources), 7) in situ alteration of clay parent rock, 8) sedimentary deposition of kaolin minerals, 9) diagensis, 10) those under controversial geologic interpretation (Keller, 1976a, p. 107).

The kaolins in this study were probably deposited from marine or nonmarine water and then altered slightly by diagenetic processes. A minor amount of kaolin was formed by crystallization in cavities, and replacement of previously existing silicates.

General definitions of refractory clays according to use by Grimshaw (1971) are as follows:

Table 4a--Physical Properties of Clay Minerals
(After Austin, unpublished data collected from several sources.)

Property	Clay Mineral			
	Kaolinite	Illite	Mixed-Layer	Chlorite
Refractoriness (resistance to heat)	High	Intermed.	Low	Intermed.
Water Absorption (after firing)	High	Low	Intermed.	--
Drying Shrinkage (before firing)	Intermed.	Low	High	--
Firing Shrinkage	Low	High	Intermed.	--
Fired Strength	Low	High	Intermed.	--

Table 4b--Uses of Clay Minerals
(After Austin, unpublished data collected from several sources.)

High Kaolinite	High Illite	High Mixed-Layer
Refractories	Structural clay products	Lightweight aggregate
Pottery	Lightweight aggregate	Structural clay products
Chinaware		
Chemical stoneware		
Sanitary ware		
High-grade tile		
Porcelain		
Paper clay		
Cement		
Fillers and extenders		
Structural clay products		

Table 5a--Description of Principal Types of Refractory Clays According To Mineral Composition (from Van Sant, 1957)

Clay types	Principal mineral and general description
Semiplastic clays	Large quantities of kaolinite; smaller quantities of halloysite, quartz, and other impurities.
Plastic clays	Mostly kaolinite with some halloysite and illite, and variable quantities of quartz and other impurities.
Semiflint clays	Halloysite and kaolinite with appreciable quartz.
Flint clays	Halloysite, kaolinite, and some quartz.
Burley flint clays	Halloysite; contains small oolites of halloysite and kaolinite. Some diaspore may be present.
Burley clays	Oolites and nodular varieties of diaspore clay with some halloysite and kaolinite.
Diaspore clays	These clays vary in texture, color, and composition but are primarily composed of diaspore and have an alumina content exceeding 60 percent; they often contain titania in doubtful mineral form and high concentrations of iron oxide.

Table 5b--Classification of Refractory Clays According To Alumina and Silica Content (from Van Sant, 1957)

Type clay	Al_2O_3 percent	SiO_2 percent
Plastic and semiplastic	22-23	50-65
Semiflint	33-36	45-49
Flint	30-40	42-55
Burley flint	38-45	30-35
Weak burley	45-53	30-35
Burley	52-60	16-30
Diaspore	60-85	-----

Ball clays--A very plastic, fine-grained refractory clay firing usually to a white or ivory, but sometimes light buff. Its function is chiefly that of a bonding or suspending agent. The high plasticity is the result of fine-grain size. They contain illite and sometimes smectites as well as kaolinite. Ball clays are sedimentary clays, freshwater deposits at least fluvial in part. Often ball clays are found in small pockets associated with lignites and coarse gravels.

China clay (and kaolins)--China clays are white-burning and composed largely of kaolinite. They are used for the manufacture of whitewares, special refractories, and insulators. These clays are mainly residual clays formed *in situ*.

Refractory clays--These are clays that have high resistance to heat without loss of shape. There are many clays in this group (tables 5a, 5b)--the most important are fire-clays which include flint clays, plastic clays, shales, and any variations (semiflint, semiplastic). Flint clays have a dense structure, moderate hardness, and conchoidal fracture. These clays are difficult to slake in water and very low in plasticity. Plastic clays are much softer than flint clays and are readily broken down by water into moldable highly plastic mass. Shales contain refractory clays that have been compacted by pressure so that the unit cleaves along well-defined planes (has fissility). All gradations may be found between these three types of clays.

SIGNIFICANCE OF TESTS

Physical

Physical properties dependent on particle size are texture, homogeneity, porosity, specific gravity, bulk density, permeability, and penetrability. Texture influences shrinkage, porosity, fusibility, and plasticity. Homogeneity is usually important in manufactured articles (pottery and bricks), and any segregation or lamination has to be destroyed in processing to prevent uneven firing. Porosity influences absorption, spalling resistance, conductivity, mechanical and chemical erosion, refractoriness, and strength. Specific gravity of raw materials used in the preparation of basic refractory materials are relatively high and characteristic. Bulk density is important in calculating stress factors in structural ceramic materials. High density is commonly desired because this imparts high physical strength and high PCE (Baumann and Keller, 1975). Permeability is important in paving bricks and tiles, porcelain and stoneware. Penetrability describes the behavior of an object to the passage of liquid--the manner in which a liquid may be drawn into the pores of an object by capillary action. Hence a coarse-grained brick is more penetrable to water than a fine-grained brick.

Chemical

The x-ray diffraction and bulk chemical analyses determine various components of the clay-bearing rocks. These components are useful in evaluating the characteristics of the clays since nonclay materials will influence the properties of the clays. The result of the chemical analyses are reported in table 6. Figure 2 shows x-ray traces of a sample (B76082) indicating the treatment used to determine the clay

Table 6 -- Chemical Analyses of Samples
(analyses done at the New Mexico Bureau Chem Lab)

Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	MnO	S	TiO_2	LOI[1]
B76062	48.50	32.36	1.89	0.04	0.63	1.08	0.17	tr.	tr.	0.65	14.19
B76063	71.75	14.91	1.00	0.24	1.50	0.50	1.18	tr.	tr.	0.65	8.00
B76082	67.58	18.16	2.86	0.29	0.32	0.55	1.17	tr.	tr.	0.45	8.79
B77037	66.22	18.52	2.02	0.33	0.29	0.88	3.13	tr.	tr.	0.45	8.32
B77038	49.93	34.03	0.74	tr.	0.08	0.91	0.07	tr.	tr.	0.36	14.04
B77039	62.19	24.21	1.76	tr.	0.10	0.84	0.12	tr.	tr.	0.65	10.27
B77040	52.12	31.55	1.77	tr.	0.11	1.02	0.07	tr.	tr.	0.42	13.64
Theoretical composition based on $Al_2O_32SiO_22H_2O$											
	46.5	39.5									14.0
Range for fire clays				MgO + CaO		Na_2O + K_2O					
	40-80	10-40	1-5	less than 5		less than 3					5-14
Typical brick-making clays											
	63.2	18.2	4.1	0.8	0.7	1.1	3.3			0.7	6.4
Typical Georgia kaolins											
	45.30	39.14	0.27	0.04	0.13	0.1	0.15			1.54	13.7
Typical Florida kaolins											
	46.30	37.7	0.8	--	0.5	--	0.2			0.5	13.7
Flint clays from											
Missouri	43.0	40.1	0.3	0.1		0.2				1.5	14.2
Israel	36.0	47.0	1.2	0.2		0.3				3.0	13.9
S. Africa	45.0	32.0	0.5	0.1		0.3				3.0	14.0

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[1] Loss on ignition

minerals (see Appendix II for x-ray traces of other samples). The various components that influence the properties and were determined and reported as the oxides are: silicon, aluminum, iron, calcium, magnesium, manganese, titanium, and alkalies (potash and soda), plus sulfur. The effects and occurrences of these components on the clays are:

Silicon--Silica occurs as hydrous aluminum silicate in the clay minerals, as uncombined silica in the form of quartz or amorphous silica, and in small amounts in other silicates such as mica. The effects of free silica in clay are: 1) reduces the plasticity, 2) lessens the shrinkage on drying and firing, 3) reduces the tensile and crushing strengths, unless the silica is of small particle size, and 4) in many cases, it reduces the refractoriness.

Aluminum--Most of the aluminum in the clays of the basal formations of the Cretaceous (Dakota and Burro Canyon(?)) occur in the clay mineral kaolinite. Illite and smectite are also aluminum silicates (containing 20-25% aluminum) and are common constituents of clay-bearing units. Besides occurring in clay minerals, aluminum also is part of feldspars, mica, hornblende, tourmaline (all moderately fusible). Aluminum is the most refractory substance in clay. In general the refractoriness of a clay increases in proportion to the increase in the alumina-silica ratio. In terms of mineralogy, as kaolinite (high aluminum) increases, refractoriness increases. Although this is modified by the amount of fluxing materials that are present.

Iron--Iron is present as: ferric oxide (Fe_2O_3), ferrous oxide (FeO), magnetic iron oxide (Fe_3O_4), iron sulfides, (FeS and FeS_2), and iron carbonates. The principal effects are: 1) alteration in color, 2) reduce refractoriness, 3) soluble iron compounds may form a scum, and 4) may form iron spots which are clearly visible in the burned clay.

Calcium--The main calcium minerals in clays are: calcite ($CaCO_3$), gypsum ($CaSO_4 \cdot 2H_2O$), anhydrite ($CaSO_3$). The chief effects of calcium minerals are: 1) they act as fluxes, combining with Al and Si to form low melting-point liquids, thus reducing vitrification temperature and refractoriness of the clay, 2) they produce a liquid of great corrosive power, 3) may reduce shrinkage and facilitate the clay drying, 4) may combine with iron to bleach red color, 5) $CaCO_3$ may convert to lime with heating (900° C) and may absorb moisture and cause cracking. Clays containing more than 5% calcium are usually considered unusable.

Magnesium--These minerals occur to a small extent in most clays chiefly as magnesite ($MgCO_3$), and dolomite ($MgCa(CO_3)_2$), and magnesium sulfate (epsom salts). Magnesium oxides have a fluxing action similar to lime and when the sulfate is present it produces an objectionable white scum or film on the fired ware.

Alkalies--The alkalies commonly present in clays are potash (K_2O) and soda (Na_2O). The chief effect is to reduce the refractoriness or vitrification temperature and are called fluxes. Alkalies do impart imperviousness and strength to the fired clay. Also most alkalies are nonplastic and will reduce the green and dry strengths of the clays.

Manganese--These minerals occasionally occur in clays as a thin film of oxides. They act as fluxes, but their amount is usually too small to be significant.

Sulfur--Sulfur is present in clays and are chiefly pyrites, and various sulfates, particularly calcium, magnesium, and sodium. Sulfur gases will produce a vesicular structure and bloat the clay.

Titanium--Small amounts of titanium minerals (chiefly rutile, anatase, and brookite) are fairly common in most clays. They are persistent and are not altered to temperatures up to 1300° C; above 1500° C they act as feeble fluxes.

Refractoriness of Clay Samples

Based on preliminary x-ray tests and outcrop exposure, twenty-seven samples were sent to the U.S. Bureau of Mines for refractory tests. These samples were: B76025 - 76031 (Clay Mesa Shale); B76033 - 76039 (Oak Canyon Member); B76047 - 76053 (Oak Canyon Member); B76059a, 76062 - 76064 (76076), and 76082 (Burro Canyon(?) - Dakota); B77038 - 77040 (Burro Canyon(?) - Dakota). One sample (B77037) from Mesa Alta-Radio Tower (figure 23 and figure 18) received similar tests at the New Mexico Bureau of Mines and Mineral Resources. From the preliminary ceramic evaluation, samples from Mesa Golondrina, Mesa Corral, and Mesa Alta had extensive ceramic testing performed. A summary of the preliminary tests is:

B76025 - 76031 (figure 13)--These samples had short firing ranges and were limy. The lower 4 m (2 samples) were marginal as lightweight aggregates (probably not economic for the study area). The remaining five samples had abrupt vitrification. Particle size of the samples is very silty with small amounts of sand-size particles at the bottom of the section. Also the amount of kaolinite increased with increasing grain size. The expandable mixed-layer clays and smectites varied from a trace to 2 parts in 10. This, plus the ceramic properties, indicate the clay-bearing shale to have no ceramic or refractory uses.

B76033 - 76039 (figure 11)--The lower 4 m and upper 2 m (3 samples) were marginal for lightweight aggregate and structural products (building brick). There was little or no carbonates present, but the samples developed dryer scum and were too soft for structural products. The particle sizes of these shales were predominantly silt. The amount of kaolinite increased up the section with the lower two units having

Figure 23--Clay zone (sample B77037) from Mesa Alta--Radio Tower. Hammer is 0.36 m long.

approximately equal amounts of kaolinite, illite, and mixed layers. Smectites were present in varying amounts. These samples have no economical ceramic or refractory uses.

B76047 - 76053 (figure 12)--The lower 6 m (3 samples) were marginal for lightweight aggregate and structural clay products. All had short firing ranges and the upper four samples had abrupt vitrification, developed dryer scum, and were too soft. These shales have no ceramic or refractory uses.

B76059a, 76062 - 76064, 76076, and 76082 (figure 15)--These samples proved to have good refractory properties except 76059a which was too soft and developed dryer scum. The other samples had good firing ranges and would be good as structural clay products (building brick, structural tile, sanitary ware). They fired to a light color (white to yellowish-gray) and had a hardness of 3-6 (Moh's scale). The samples varied from 30-50% clay-size, 20-60% silt-size and trace to 40% sand-size particles. Kaolinite was the dominant clay mineral (8-10 parts in 10).

B77037 (figure 18)--Based on preliminary firing, the sample appeared to be usable as structural products. PCE tests were done and indicated the clay to be low refractory (cone 20-23). Because of the high amount of alkalies (see table 6-chemical analyses) and sand-size particles, the fired sample was too soft and did not have a pleasant fired color (yellowish-gray). The particle-size analysis indicated: sand, 10%; silt, 45%; clay, 45%. The clay mineralogy is dominantly kaolinite (8 parts in 10) with minor amounts of mixed-layer illite-smectite clays and illite. The PCE and chemical tests indicate the sample to be marginal for structural products.

B77038 - 77040 (figure 17)--These samples, from the API reference location, are of relatively pure kaolinite and are very fine grained (< 3% sand; 45-50% silt; 50-60% clay). Sample 77038 is possibly a flint clay. No preliminary refractory tests were done on these samples, but rather they were mixed in equal proportions with a sample from Mesa Golondrina and had extrusion tests done. On the basis of this test these samples meet the ASTM specification (C62-75a) for Grade NW building brick. Chemical analysis indicate 24-34% alumina; 50-62% silica; approximately 1-2% iron oxide, and traces of other fluxes.

SUMMARY AND RECOMMENDATIONS

In summary the southern and southwestern portions of the Chama Basin contain structural- and refractory-quality clay minerals in discontinuous tabular lenses associated with channel sandstones predominantly in nonmarine environments (braided or meandering stream). The thickness of the clay zones ranges from two to seven feet (see Appendix II). At Tierra Amarilla there is a four-foot earthy greenish soft sandstone at the top of the Burro Canyon(?) (Landis and others, 1974). Southwest of Mesa Golondrina a similar clay zone (samples B76061 and B76082). Southeast of Mesa Golondrina at Mesa Corral is a five-foot thick flint-like clay zone (samples B77038 - B77040). At Mesa Alta near the contact of the Dakota with the Burro Canyon(?) is a two- to three-foot zone (sample B77037). Finally, south of Youngsville a similar zone was described by Leopold (1943). South of Cuba, where the Jackpile sandstone (Morrison Formation) occurs, this zone is absent. The Jackpile is a kaolinite-bearing sandstone. The clays of the younger formations (Burro Canyon(?) and Dakota) may be the result of reworking of the older Jackpile and other Morrison units. The zone occurring in the Burro Canyon(?) in the Chama Basin may be all that is left of this unit because of pre-Dakota erosion represented by the 30-40 m.y. unconformity. North into Colorado and east into Kansas (Plummer and Romary, 1947; Van Sant, 1957; Waage, 1953) there are economic units of refractory clays in similar Lower Cretaceous units.

Since these lenses appear to be fairly extensive, only drilling with careful stratigraphic control could locate enough of these clays to allow economical mining. To date the only method to delineate deposits is by pattern drilling (Patterson and Murray, 1975). Drilling involves using a grid with 400- to 800-feet centers (to depths of 200 feet). Various kinds of kaolin minerals involve different drilling equipment. Refractory clays ordinarily require diamond bits and core barrels of the type used for hard-rock mining. This is because the clay and overburden are hard. The economic limits of the ratio of overburden to clay range between 6 and 8 to 1 depending on the type of overburden and the reclamation laws (Patterson and Murray, 1975). A high percentage of fire clay in the past has been mined underground. This is because the deposits are at great depths and the overburden is too hard to strip profitably (Patterson and Murray, 1975).

Refractory clay output in the United States peaked in 1957. Production has decreased since then and has probably bottomed out. Demands forecast for refractory clay in the year 2000 are expected to be 12 to 17 million short tons and, for kaolins of other uses, five to six times the amount now being sold (Cooper, 1970).

Currently one of the problems faced by the refractories industry is the availability of high-grade refractory clays at competitive costs. Underground mining is expensive, and alternative sites and clay deposits are needed. One answer is the benefication of poorer quality kaolin to improve the purity and to recover a co-product such as glass sand.

Other problems encountered by the clay industries in general include the cost of shipping both raw and finished products, increase fuel costs, and ecological pressures. This has forced substitutes for many of the clay products. These include using cement, wood, glass, plastics, scoria, and aluminum and other metals. These factors have to be considered before any mining could be economically attempted.

Most of the clay-bearing units in this study were located on public domain land (National Forest) and are under the jurisdiction of the U.S. Department of Interior. Information on staking and patenting mineral claims would also have to be obtained.

Reeves (1963) has reported drilling for refractory clays only in the Mesa Alta-Mesa Corral area. This region and the mesas to the north and east are all capped by the Dakota Sandstone. The clay-bearing zone appears to be only in the Burro Canyon(?) - Dakota and not in the Morrison or Dakota-Mancos. The shales in the Dakota-Mancos are marine shales that are unsuitable for refractory or structural products because of their physical and chemical properties.

The terrain is rugged in this region. Roads are poor, and most are unpaved; there is no rail service near. The quality and quantity of the clay is such that these clay-bearing zones could not economically be mined. This will remain to be the case until costs can be kept to a minimum and more extensive mapping to locate the lenses of clay are done.

APPENDIX I--TESTS

Sampling Techniques

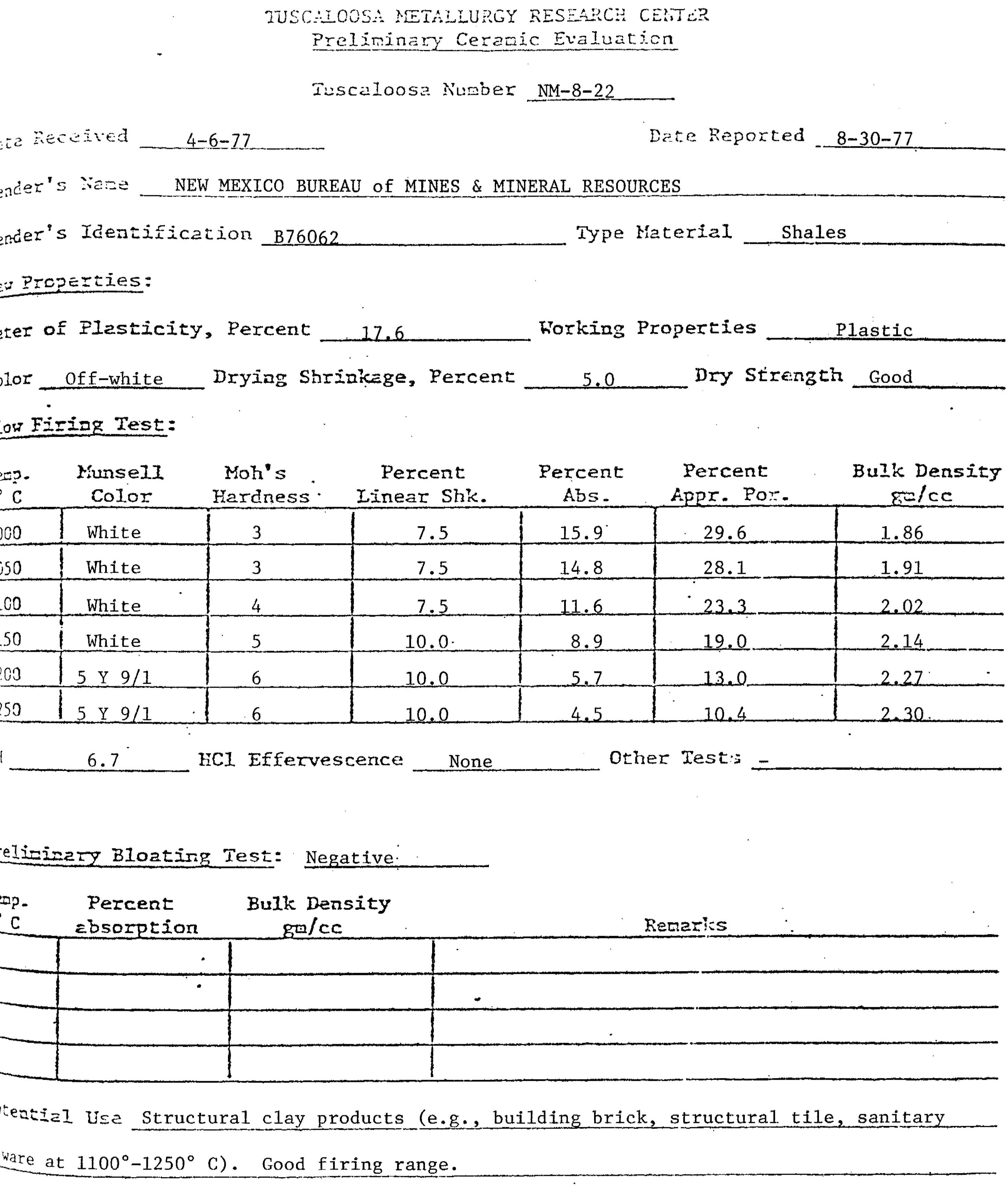
A representative sample needs to be collected, therefore channel samples approximately 2-m thick were taken. The size of the sampled interval varied according to changes in lithology and sometimes with surficial features (color, texture). The samples were dried, crushed, and a representative sample chosen. Various tests were then done. The procedure for each test follows.

REFRACTORY TESTS

Preliminary Ceramic Testing

The 27 samples sent to the U.S. Bureau of Mines for ceramic testing had preliminary tests run to determine if the clays deemed further testing. These tests determined the general properties of the sample and include: water of plasticity, color, hardness, pH, linear shrinkage, percent absorption, percent apparent porosity, bulk density, and bloating properties. The procedures for these tests are those of the U.S. Bureau of Mines (Liles and Heystek, 1977). A copy of a sample report form for one sample is shown in figure 24.

The sample is dried at 105° C, then crushed by a roll crusher to pass 3/4-inch (2-cm) mesh. Pieces of this material are then picked at random for quick-firing (to determine the bloating properties; this test was not done by me). The remaining material is then split by riffling to obtain a representative 2-lb (1 kg) sample, which is crushed to pass 20 mesh. About 1 lb (0.5 kg) of the crushed material is blended with incremental additions of water. From the mixed material, six individual 1- by 2- by 3/8-inch (2.5- by 5- by 1-cm) briquets are extruded in a laboratory-size hydraulic ram press. The amount of water required to form the sample is recorded as the "water of plasticity." Shrinkage marks (always a standard distance apart) are applied to the briquets, which are then air-dried for 24 hours, and oven-dried at 110° C for an additional 24 hours. Linear shrinkage is determined by measuring the reduction in the space between the shrinkage marks, and dry strength is determined by visual inspection as "good," "fair," or "poor." One of the six briquets is then fired, using a 24-hour cycle, to a temperature of 1,000° C, which is maintained for 1 hour. The briquet is allowed to



TUSCALOOSA METALLURGY RESEARCH CENTER

Preliminary Ceramic Evaluation

Tuscaloosa Number NM-8-22

ate Received 4-6-77 Date Reported 8-30-77

ender's Name NEW MEXICO BUREAU of MINES & MINERAL RESOURCES

ender's Identification B76062 Type Material Shales

w Properties:

ater of Plasticity, Percent 17.6 Working Properties Plastic

olor Off-white Drying Shrinkage, Percent 5.0 Dry Strength Good

ow Firing Test:

mp. °C	Munsell Color	Moh's Hardness	Percent Linear Shk.	Percent Abs.	Percent Appr. Por.	Bulk Density gm/cc
00	White	3	7.5	15.9	29.6	1.86
50	White	3	7.5	14.8	28.1	1.91
00	White	4	7.5	11.6	23.3	2.02
50	White	5	10.0	8.9	19.0	2.14
00	5 Y 9/1	6	10.0	5.7	13.0	2.27
50	5 Y 9/1	6	10.0	4.5	10.4	2.30

6.7 HCl Effervescence None Other Tests -

eliminary Bloating Test: Negative

mp. °C	Percent absorption	Bulk Density gm/cc	Remarks

tential Use Structural clay products (e.g., building brick, structural tile, sanitary ware at 1100°-1250° C). Good firing range.

Figure 24--Sample sheet of test form from U.S. Bureau of Mines.

cool in the kiln. The procedure is repeated for the five remaining briquets, each at one of the following temperatures: 1,050°, 1,100°, 1,150°, 1,200°, or 1,250° C. After cooling, the linear shrinkages are determined for each firing temperature. The briquets are weighed, then covered with water and boiled for 5 hours. The soaked briquets are reweighed first in air and then immersed in water. From the three weights obtained on each briquet, the percent absorption, percent apparent porosity, and bulk density are calculated (the calculations are shown in the section on the procedures that I followed for these tests).

Each briquet is redried at 105° C, and Mohs' hardness is determined. Next, the color of each briquet is classified using the Munsell System. Finally, the briquets are mounted on a display card (figure 25 shows one of my samples displayed).

During the preliminary testing, an additional sample of the minus 20-mesh material is processed to determine pH and degree of effervescence. In this test 10 g of the sample are mixed with 100 ml of distilled water and the pH of the slurry is determined. Subsequently, 10 ml of concentrated reagent-grade hydrochloric acid is added to the slurry to visually assess the degree of effervescence as "none," "slight," or "high."

A quick-fire test to determine the bloating characteristics of each sample for its possible use as a lightweight aggregate was done by the U.S.B.M. This test was not done as part of my thesis since bloating of shales for lightweight aggregate is not economical in this region.

I used similar procedures with modifications for our laboratory setup for the preliminary tests. The modifications followed the American Society for Testing Materials, annual book of standards (1963).

Calculations for apparent porosity, water absorption, and bulk density are:

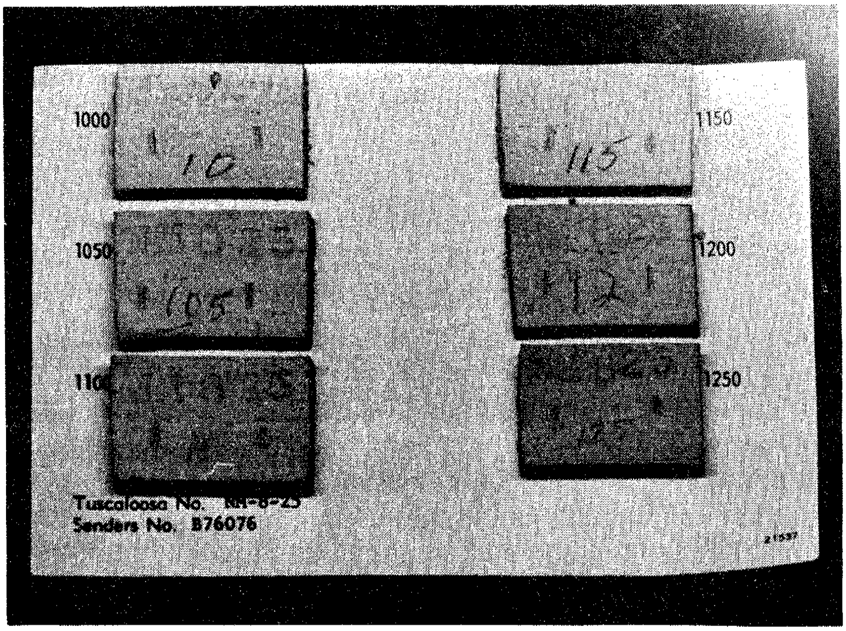


Figure 25--Display card of briquets that had preliminary refractory tests done by the U.S. Bureau of Mines.

D = the dry weight of the sample after heating to 110° C.

The sample is placed in water and boiled for 2 hours. After boiling the sample is allowed to cool to room temperature. The suspended weight, S, is determined after cooling while the sample is suspended in water. This weighing is usually accomplished by suspending the sample in a loop of 22-gage copper wire hung from one arm of the balance. The balance was previously counter-balanced with the wire in place and immersed in water to the same depth as used when the refractory sample is in place.

The sample is then blotted lightly with a moistened cotton cloth to remove all drops of water from the surface and the saturated weight, W, is determined. All weights are determined to 0.1 g.

The exterior volume, V, is calculated using:

$$V=W-S$$

Apparent porosity, P, is calculated using:

$$P=(W-D)/V \times 100$$

Water absorption, A, is calculated using:

$$A=(W-D)/D \times 100$$

Bulk density, B, is calculated using:

$$B=D/V$$

From the results of the preliminary tests, further testing (PCE) may be warranted.

Pyrometric Cone Equivalent (PCE)

Principle--This test is used to evaluate the refractoriness of samples (Klinefelter and Hamlin, 1957 ; Liles and Heystek, 1977). Generally samples that show low shrinkage, high absorption, and a light color at the highest firing temperatures in the preliminary tests will have PCE tests run on them. There are standard manufactured cones consisting of a series that deform under heat treatment beginning about 600° C and ending about 2000° C. The temperature intervals between cones vary, but the average interval is about 20° C. Deformation of the cone depends both on the time and temperature. The cone itself is a three-sided pyramid, and as the proper temperature is approached the tip slowly bends until it touches the holding plaques (figure 26). Deformation temperature is reached when the tip of the cone makes contact.

Procedure--Test cones are molded to shape in a small metal mold. Cornstarch can be added to aid in forming the cones and to prevent the clay from sticking to the mold. Clays for molding into cones should be ground to pass a 65- or 100-mesh sieve. Usually 5-6 grams are enough to make 6 or more of the small cones. Several cones should be made since they are fragile, and several trials may be run before correct temperature is reached.

The test cones are compared with standard cones in accordance with ASTM test method C24-72 (American Society for Testing and Materials, 1974). A sample is generally classified as a low-duty fire clay if it has a PCE of 15 to 28; medium duty if PCE is between 29 and 31; high duty if PCE is 31-1/2 to 32. With a PCE of 33 or higher, the clay is classified as a super-duty fire clay (tables 4a, 4b, 5a, 5b).

Results--The U.S. Bureau of Mines did preliminary refractory tests on 27 of the samples taken as a part of this study. An example of the preliminary tests report form is shown in figure 24. Liles and Heystek (1977) explain the procedures used by the U.S. Bureau of Mines for these tests. Five of the 27 samples had more extensive testing (PCE). One sample (B77037) from Mesa Alta was kept at New Mexico Tech so that I could do the refractory tests to become familiar with the testing procedures.

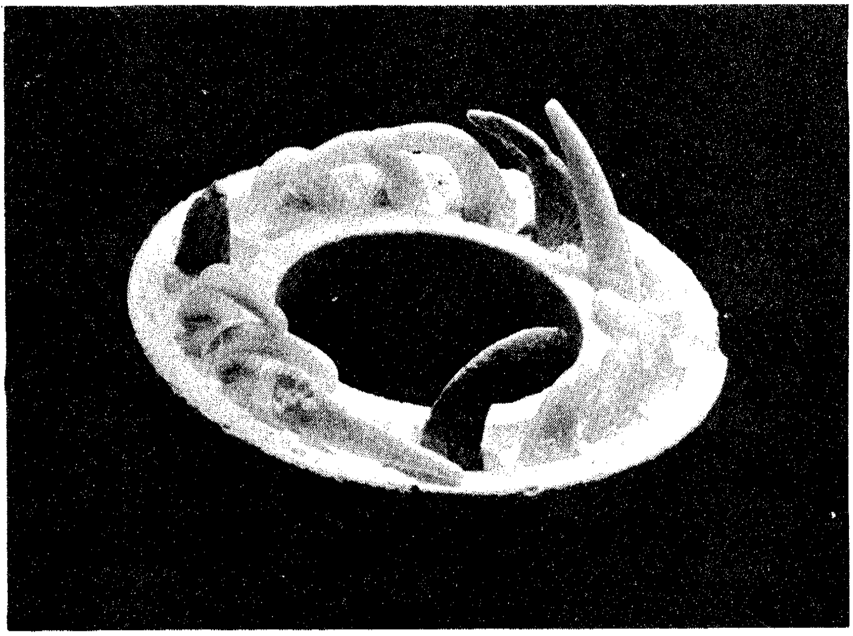


Figure 26--Example of pyrometric cone equivalent (PCE) test (sample B77037 from Radio Tower section).

Figure 26 shows the PCE test of this clay. The sample (B77037) deformed between cone 20 and 21 (about 1564° C) and is classified as a low-duty refractory.

PARTICLE SIZE

Procedure

A sample is dried at 105° C for 24 hours and then crushed in a chipmunk crusher. If needed, larger particles are further crushed in a mortar and pestle. About 40 g are placed in an oven at 105° C overnight. The samples are removed one at a time to prevent cooling and water absorption. The sample is weighed out to 20 g on a Metler balance. Duplicates of each sample are made. The 20 g of sample is put in a 1000-ml beaker with 20 ml of a dispersant (Calgon) and about 400 ml of distilled water. The solution is thoroughly mixed and allowed to settle overnight. If unflocculated, the sample is then wet sieved through a 230-mesh screen to remove all the sand-plus size material. The sand-plus material is dried and weighed. The remaining material is mixed with distilled water to bring the total to 1000 ml. The sample is agitated, to uniformly mix the water and sample, and is allowed to settle for 30 minutes. Using a pipette, 20 ml of the suspension in the container is removed from above the clay-silt interface.

Depths of the clay-silt interface after 30 minutes (for particles of specific gravity of 2.65 and assuming the particles possess spherical shapes).

C°	CM
16	2.20
20	2.44
24	2.69
28	2.94
32	3.18

The extracted mixture is placed in a crucible, dried, and weighed. The clay, silt, and sand-plus fractions are calculated using the formulas:

[Weight of sand-plus/20 g] + [weight of clay - .001 g
(weight of Calgon)/20 g] + [weight of remainder (silt/20 g] = 100%.

SCANNING ELECTRON MICROGRAPHS

Sample Preparation

For micrography, four clay samples were broken from hand-specimens exposing the natural texture or fabric of the rock. These broken pieces were then lightly plated with a thin film of gold (since the clay is nonconductive). ". . . the micrographs are simply photographic views of their lithologic textures observed on the fractured surface of a hand specimen of kaolin under a '1000x-10000x hand lens'. The rationale for the SEM study of kaolin is that eventually the petrology of the clay may be interpreted in part from its texture, or fabric, magnified to visual recognition, after adequate experience is gained from sufficient observations..." (Keller, 1977), p. 311). Figures 20-22 are scanning electron micrographs (SEM) of three samples (B76062, B77037, B77038).

Apparatus

A Hitachi Perkin-Elmer (Model HHS-2R) scanning electron microscope operated at 25 KV in secondary electron emission mode was used. The photographs were taken by a Polaroid camera using Polaroid 545 film.

X-RAY DIFFRACTION TESTING

Procedure

This test involves making a random mount-smear (oriented) slide (Gibbs, 1965, 1968; Theisen and Harward, 1962). An oriented slide is used to enhance the basal (00ℓ) reflections. This slide is made by placing approximately 50 g of the sample in a 250-ml beaker. Distilled water is added, and the sample is stirred. After 10 minutes, 2 centrifuge tubes are filled by pipetting the liquid from the top of the beaker. The tubes are then placed in a centrifuge for 30 minutes. The liquid above the slurry in the bottom of the centrifuge tubes is poured out. The slurry is removed from the bottom of the tube with a glass stirring rod and placed on a glass slide with tape along the edges. Another glass slide is used to smear the slurry (Theisen and Harward, 1962). This method avoids size segregation, but care is required to assure an uniform cover and thickness of clay on the irradiated area of the slide.

For a few samples an unoriented mount (randomly oriented) is used to observe the (hkℓ) reflections. The procedure here was to grind the sample to pass through 200-mesh sieve. A glass slide is smeared with vaseline, and the sample is sprinkled on, covering the slide (like flouring a cake pan). The excess is removed by lightly tapping the slide.

All diffraction traces were made on a Norelco wide-range x-ray diffractometer using monochromatic Cu radiation at 40 KV and 20 ma. Divergence, anti-scatter, and receiving slits were 1°, 4°, 1°, respectively. For the preliminary study of the mineralogy four x-ray traces were run: untreated sample from 2° to 40° 2θ at a speed of 2° 2θ per minute; if chlorite was present, an untreated sample was run from 24° to 26° 2θ at a speed of $1/4^\circ$ 2θ per minute; a sample treated by suspending for 1 hour over ethylene glycol heated to 60^0 C (Brunton, 1955) from 2^0 to 14^0 2θ at a speed of 2^0 2θ per minute; and a sample heated for 30 minutes at 375^0 C (Austin and Leninger, 1975) from 8^0 to 9^0 2θ and then 2^0 to 14^0 also at a speed of 2^0 2θ per minute (figure 2).

Semi-Quantitative Analysis

Most semi-quantitative analysis of clay minerals determine only the relative amounts of the different clay-mineral groups in the samples. There are three methods available to determine absolute quantities of clays (Schoen, Foord, Wagner, 1973). The first method involves separating the 2 µm fraction (clay-size) from the total sample, and determining the relative percentages of the clay-mineral groups in this size fraction, and then calculating absolute percent in the whole sample. The second method involves analyzing the total sample using an external standard. Absolute percent of clay-mineral groups in the total sample is determined directly by x-ray diffraction; corrections for variations in preferred orientation are made (Quakernaat, 1970). The third method uses x-ray diffraction to determine the total percentage of clay-mineral groups in the whole sample, followed by the determination of relative percentages of each clay-mineral group in the 2 µm fraction and then calculating the absolute percent (as in method 1) (Schultz, 1964).

The basic concept of quantitative analysis was first discussed by Johns, Grim, and Bradley (1954). Since then, Gibbs (1967) and Schultz (1955, 1960, 1964) have modified and developed new quantification techniques. The method of Johns, Grim, and Bradley was based on the fact that the equation for intensity of an x-ray peak can be reduced to the simple form $I = I = F^2$ (L.P.), where I = the integrated intensity of the diffraction line, F = the structure factor, and (L.P.) = the combined Lorentz and polarization constant for each diffraction angle. By assuming that the composition (hence structure factor) of an illite is nearly the same as a smectite, one can relate the intensity of the 17 Å glycolated smectite peak, to the intensity of the 10 Å illite peak, for an equal volume of both minerals, by using the (L.P.) alone. Various investigators have used different multiplication (L.P.) factors (from 2 to 7). Since chlorite and kaolinite have large compositional and structural differences, the use of the (L.P.) factor alone will not work. So other factors relating the intensity of the 7 Å kaolinite or chlorite peak to the 10 Å illite are used. This method is fast and has good precision, but there is difficulty in comparing studies by different investigators.

Schultz's method (1955, 1960, 1964) involved using pure standard clays with compositions and crystallinities similar to the unknowns. The samples are compared by x-ray diffraction to determine empirical factors relating peak intensity to volume or weight percent. These multiplication factors are more accurate than those determined on the basis of Lorentz-polarization relations. The method takes longer, and some idea of the proper standards are needed.

Gibbs (1967) used a similar approach to Schultz, but he obtained his standards by separation from his samples. He added an internal standard and plotted the weight percent clay against the ratio of peak intensities from the clay and internal standard. The separation takes time and adding an internal standard results in dilution of the sample and may produce changes in orientation of the clay minerals.

In general, precisions of ±5-10% (note: these methods are not necessarily accurate to 2 decimals, in fact, probably only accurate to parts in 10) are reported for natural samples using any of the described methods (Johns, Grim, and Bradley, 1954; Schultz, 1964; Gibbs, 1967). Table 7 (from Carroll, 1970) lists clay minerals and the minimum amount needed to determine the presence of the clay. The measurement of x-ray peak intensity can introduce errors. Intensity (total number of counts in a peak above background) is proportional to peak area. Areas have been measured by polar planimeters, counting chart boxes, and graphical integration. For peaks of constant width, peak height is proportional to area and is more easily measured. Carroll (1962); Brindley (1961); Mackenzie and Mitchell (1966); and Schoen, Foord, and Wagner (1973) have reviewed studies done on quantitative analysis of clays.

TABLE 7-- QUANTITATIVE IDENTIFICATION BY X-RAY DIFFRACTION OF CLAY MINERALS AND CERTAIN OTHERS IN THE CLAY FRACTION (<2 MICRONS) OF SEDIMENTARY MATERALS (Cu $K\alpha$; kv 50, ma 20, 1° SCATTER SLIT, 006″ RECEIVING SLIT, CPS. 10^3, MULTIPLIER 1, RATEMETER 4; ORIENTED MOUNT ON TILE) 1° 2θ PER MINUTE; CHART SPEED 30″ PER HOUR

Mineral	Lowest percentage identifiable	*hkl*	Principal *d* spacing used for identification, Å	2θ°, (approx.)
Kaolinite	5	001	7.13-7.16	12.36-12.4
Kaolinite, disordered	1-5	001 (broad)	7.15	12.38
Halloysite, $4H_2O$	10	001	10.1	8.75
Halloysite, $2H_2O$	10	001	7.21	12.26
Mica, $2M_1$	1	002	9.99-10.4	8.85-8.80
Illite[a]	5	001 (broad)	10.16	8.70
Glauconite[b]	?	001	10.06-10.19	8.79-8.67
Chamosite[c], Fe^{+2}	?	001	7.10	12.46
Chamosite[c], Fe^{+3}	?	001	7.04	12.56
Biotite	1	002	10.1	8.77
Vermiculite[d]	5	001	14.2	6.22
Montmorillonite Group[e]	10	001	15.4 (variable)	5.7
Chlorite, Mg	1	001	14.1-14.2	6.27-6.22
Chlorite, Fe	10	001	14.1-14.2	6.27-6.22
Mixed-layer clays[f]				
Palygorskite	5	110	10.2-10.48	8.66-8.46
Sepiolite	?5	110	12.05-13.3	7.33-7.18
Quartz	1	101	3.34	26.66
Quartz	5	100	4.26	30.85
Cristobalite, α	5	101	4.04	22.0
Feldspar, orthoclase	5	040,202	3.25-3.28	27.4-27.16
Feldspar, plagioclase	5	002,040	3.17-3.18	28.14-28.0
Calcite	5	104	3.03	29.47
Dolomite	1	104	2.88-2.89	30.05
Ferric oxide[g]	<1			
Halite[h]	5	200	2.83-2.84	31.72-31.61

[a] mixed-layer 1b mica polytype.

[b] varies from mixed-layer type (authigenic) to recrystallized mica-type (consolidated sediments).

[c] poorly crystalline and may be oxidized to disordered kaolin-like mineral; not identifiable by X-ray diffraction alone.

[d] may be interstratified with biotite; heating and glycolation (negative) necessary for identification.

[e] (001) spacing dependent on hydration and exchangeable cation present.

[f] *d* spacings variable due to nature of minerals interstratified.

[g] finely crystalline or amorphous coatings on mineral particles.

[h] dry clay not dispersed in water.

Compiled by Dorothy Carroll (1970)

CHEMICAL ANALYSIS

Seven samples had chemical analyses done on them (table 6). These analyses determined: SiO_2, Al_2O_3, Fe_2O_3, MgO, Na_2O, K_2O, CaO, MnO, ZnO, S, FeO, TiO_2, and loss of ignition. The procedures were:

Duplicates for each analysis were made. Silica was determined by gravimetric procedure; the remainder were determined by atomic absorption except titanium which was determined by colorimetric method.

Silica--Fuse 0.5000 g in a platinum crucible with Na_2CO_3 and digest the fusion in a porcelain casserole with an excess of dilute HCl. Remove the crucible from the solution and wash thoroughly. Evaporate the solution to dryness and dehydrate at a temperature of about 130° C. Warm a few minutes with 20 ml 1:1 HCl, then boil with 120 ml of water. Filter, removing all adhering silicic acid from the casserole with the aid of a rubber-tipped glass rod, save filtrate. Wash thoroughly with hot water. Transfer the paper and the residue to a platinum crucible and ignite, finally heating over a blast lamp while the crucible is covered. Cool and weigh the crucible and contents. Add about two drops H_2SO_4 and 3 ml HF and evaporate to dryness. Ignite at the full heat of a Bunsen burner, cool and weigh. The difference in weight represents the bulk of the silica to which is to be added a small portion recovered from the filtrate. Fuse with $K_2S_2O_7$, the residue left in the platinum crucible after the expulsion of SiO_2. Dissolve the fusion in hot water and wash into the filtrate. Add about 1 g of $(NH_4)_2S_2O_8$ and a slight excess of NH_4OH to filtrate and bring to a boil. Filter, washing thoroughly with 10% NH_4OH containing NH_4Cl. Do not save filtrate. Transfer the paper and the precipitate to the original beaker and add about 20 ml of HNO_3 and 10 ml $HClO_4$. Evaporate to fumes of $HClO_4$. Add 100 ml water, boil and filter. Ignite and weigh the residue which consists of silica to the bulk recovered above. Using another portion of sample follow the general digestion procedures described below to do the remaining analyses. General digestion procedure--add approximately 500 mg of sample to a nalgene beaker. Wet with water and HNO_3 and evaporate to dryness twice with 10 ml of HF. Add 20 ml of aqua regia and let stand 1 hour under no heat. Quantitatively transfer with water to a glass beaker and evaporate to dryness. Add 10 ml $HClO_4$ and evaporate to dryness. Add 10 ml HCl and bring up to 100 ml in a volumetric. Determine Al, Ca, Fe, K, Mg, Mn, Na, Zn, and S, by atomic absorption using approximate standard conditions and standard concentrations (report as oxides). For Ti, evaporate 50 ml of the solution to dryness and add 25 ml of 10% H_2SO_4. Determine Ti by standard colorimetric procedure. Use 40 ml of sample solution and add 10 ml of reagent solution (10% H_2SO_4, 10% H_3PO_4, 6% H_2O_2). Read absorbance at 400 mμ. Compare with 1000 ppm of Ti standard.

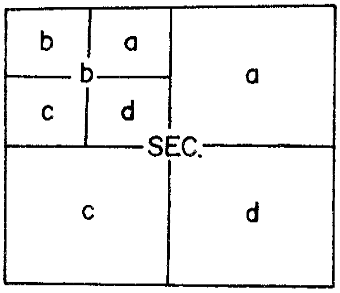
APPENDIX II--MEASURED SECTIONS

Only the portion(s) of the unit that was sampled is measured and described. Location within the section is shown at right. All sections were sampled in the Spring and Summer of 1976 and 1977. Petrology terminology is from Folk (p. 147, 1974). Numbers in parenthesis following section name indicates the location of samples as shown in figure 1.

Petrology of Mudrocks

(Folk, 1974)

Grain size of mud fraction	Soft	Indurated non-fissile	Indurated fissile
over 2/3 silt	silt	siltstone	silt-shale
subequal silt and clay	mud	mudstone	mud-shale
over 2/3 clay	clay	claystone	clay-shale



System of sample location

Cañada de las Milpas Section — Sky Village NE quadrangle (3)

Fig.11 — Dakota Sandstone — Oak Canyon Member
Sec. 32ac, T. 15 N., R. 1 E.

Measured: July, 1976, Munsell rock color chart (Geol. Soc. America)

Cubero Sandstone Tongue of the Dakota Sandstone above

Oak Canyon Member of the Dakota Sandstone:

Sample	Description	Thickness (m)
B76039	Silt-shale, grades to siltstone, medium-gray (N5) to brownish-gray (5YR 4/1); jarosite coatings; selenite crystals	2.5
B76038	Sandy mud-shale, dark-gray (N3) to brownish-gray (5YR 4/1), less fissility than lower samples; abundant selenite crystals; jarosite and hematite staining; carbonaceous fragments	2
B76037	Same as B76038	2
B76036	Same as B76038	2
B76035	Silt-shale, medium-gray (N5); fissile; jarosite; selenite crystals; 1-2 bentonite beds (15-18 cm each)	2
B76034	Silt-shale, medium-gray (N5); fissile; jarosite and hematite present; selenite crystals; bentonite bed (10 cm)	2
B76033	Silt-shale, medium-light-gray (N6); fissile; jarosite and hematite; selenite crystals	2
——	Conglomeratic sandstone, dark-yellowish-orange (10YR 6/6); abundant carbonaceous fragments	0.5
	Total Oak Canyon	15 m (49.8 ft)

Unconformable contact with Jackpile

Bernalillito Mesa Section — Sky Village NW quadrangle (1)

Fig. 12 — Dakota Sandstone — Oak Canyon Member
Sec. 27 line ab, T. 15 N., R. 1 W.

Measured: June, 1976, Munsell rock color chart (Geol. Soc. America)

Cubero Sandstone Tongue of the Dakota Sandstone above

Oak Canyon Member of the Dakota Sandstone:

Sample	Description	Thickness (m)
B76053	Silt-shale, grades to siltstone, medium-gray (N5) to brownish-gray (5YR 4/1); jarosite coatings; selenite crystals	1.5
B76052	Sandy, mud-shale, dark-gray (N3) to brownish-gray (5YR 4/1), less fissility than lower samples, abundant selenite crystals, jarosite and hematite coatings, carbonaceous fragments	2
B76051	Same as B76052	2
B76050	Same as B76052	2
B76049	Sandy, mud-shale, dark-gray (N3) to medium-gray (N5), fissile, bentonite bed (15-18 cm), similar to B76052	2
B76048	Same as B76049, also has bentonite bed	2
B76047	Silt-shale, to siltstone medium-gray (N5); fissile; jarosite coatings, carbonaceous fragments, selenite crystals, unconformable contact with Jackpile	2
B77025	Mudstone lens composed of kaolinite, expandible mixed—layer clays and illite, in Jackpile, grayish-yellow-green (5GY 7/2)	0.3
	Total Oak Canyon	13.5 (44.9 ft)

Clay Pit Section — San Ysidro quadrangle (4)

Fig. 13 — Clay Mesa Shale Tongue of Mancos Shale
Sec. 26bd, T. 15 N., R. 1 E.

Measured: July, 1976, Munsell rock color chart (Geol. Soc. America)

Top of Mesa

Paguate Sandstone Tongue of Dakota Sandstone:

Sample	Description		Thickness (m)
B76032	Sandstone, pale-yellowish brown (10 YR 6/2) caps ridge, massive bedded		5.5
		Total	5.5

Clay Mesa Shale Tongue of Mancos Shale:

Sample	Description		Thickness (m)
B76031	Sandy siltstone grading into a silty sandstone; medium-gray (N5) to brownish-gray (N5), less friable than lower units; selenite crystals; jarosite coatings		2
B76030	Similar to B76031		2
B76029	Silt-shale, medium-gray (N5), carbonaceous fragments; fossiliferous; abundant selenite crystals; jarosite and hexahydrite coatings		2
B76028	Similar to B76029		2
B76027	Similar to B76029		2
B76026	Similar to B76029		2
B76025	Similar to B76029		2
		Total	14 (45.9 ft)

Bottom covered

Cañada de las Milpas Shale Section — Sky Village NE quadrangle (2)

Fig. 14 — Clay Mesa Shale Tongue of Mancos Shale
Sec. 32ac, T. 15 N., R. 1 E.

Measured: July, 1976, Munsell rock color chart (Geol. Soc. America)

Paguate Sandstone Tongue of Dakota Sandstone above

Clay Mesa Shale Tongue of Mancos Shale:

Sample	Description	Thickness (m)
B76044	Sandy siltstone - grading into a silty sandstone, medium-gray (N5) to brownish-gray (5YR 4/1); massive, less fissility than lower units	3.2
B76043	Similar to B76044	2
B76042	Silt-shale, medium-gray (N5), carbonaceous fragments; fossiliferous; abundant selenite crystals; jarosite and hexahydrite coatings	2
B76041	Similar to B76042	2
B76040	Similar to B76042	2
	Total Clay Mesa	11.2 (36.7 ft)

Cubero Sandstone Tongue of Dakota Sandstone below

Mesa Golondrina Section — Llaves quadrangle (7)

Fig. 15 — Dakota-Burro Canyon(?)
Sec. 5ba, T. 25 N., R. 2 E.

Measured: June, 1976, Munsell rock color chart (Geol. Soc. America)

Dakota Sandstone above

Dakota Sandstone — Burro Canyon(?) Formation:

Sample	Description	Thickness (m)
B76064	Clay-shale, light-gray (N7) grades into a silty sandstone	0.7
B76063	Mud-shale, medium-light-gray (N6) grades into a clay-shale	1.8
B76062	Carbonaceous mud-shale, dark-gray (N3) grades into light-gray (N7) mud-shale	1.5
——	Silty sandstone and shale; no sample; alternating in sequence of sandstone and shale	6.5
B76082	Carbonaceous sandy shale, medium-dark-gray (N4) includes some grayish-red-purple (5RP 4/2) and greenish-gray (5G 6/1) claystone, grades into a silty shale and thins into a silty sandstone	6.5
B76061	Conglomeratic sandstone, white (N9) to yellowish-gray (5Y 8/1), contains clay lenses and pockets (B76059), with conglomerate bed at base; medium-bedded, crossbedding in lower third of unit; some limonite staining, thin laminations; medium- to coarse-grained, moderately sorted; subangular to subrounded quartz; poorly cemented with kaolinite and silica; friable; good porosity	4.8
B76059a	Clay pockets and lenses, very light gray (N8), in conglomeratic sandstone (fig. 27), over 90% kaolinite. Up to 1/3 m (≈1') thick. Included in unit B76061	—
	Total section measured	21.8 (72.5 ft)

Burro Canyon(?) below

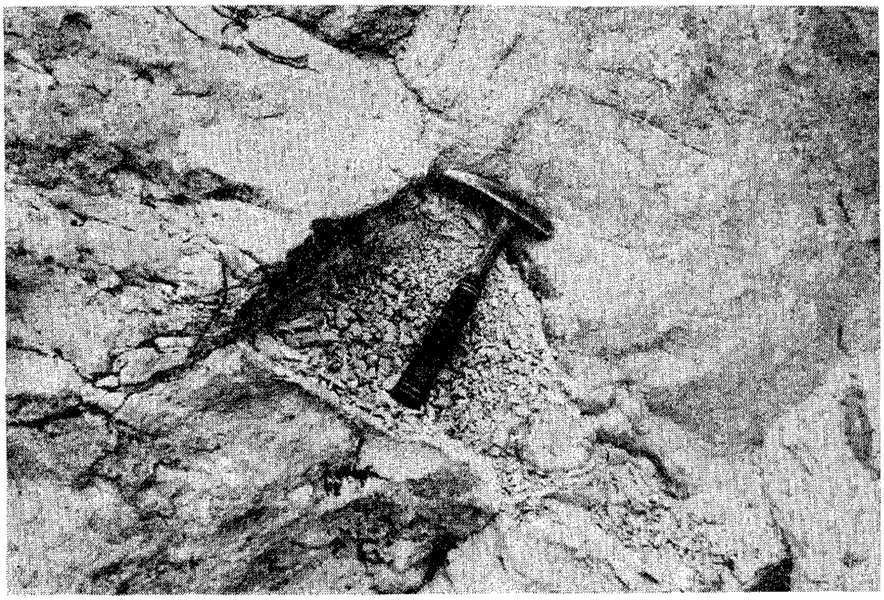


Figure 27--Clay pocket (sample B76059a) in Dakota-Burro Canyon(?), Mesa Golondrina.

Señorita Canyon Section — Cuba quadrangle (5)

Fig. 16 — Dakota Sandstone — Oak Canyon Member
Sec. 33d, T. 21 N., R. 1 W.

Measured: August, 1976, Munsell rock color chart (Geol. Soc. America)

Cubero Sandstone Tongue - highly bioturbated with *Ophiomorpha* burrows (approximately 15m)

Oak Canyon Member:

Sample	Description	Thickness (m)
B76083 and B76079	Silt-shale, grades through siltstone to sandstone, medium-gray (N5) to brownish-gray (5YR 4/1)	31
——	Sandstone, light-brown (5YR 6/4) with shale interbedding	4.2
B76077	Siltstone, medium-light-gray (N6); grades into unit above	0.26
B76078	Sandstone, kaolinitic, very light gray (N8)	0.54
	Total	36
		(118.8 ft)

Unconformable contact with Jackpile sandstone(?) or Burro Canyon(?) Formation

Mesa Corral (Myers Kaolinite Deposit) — Arroyo del Agua quadrangle (6)

Fig. 17 — Dakota Sandstone — Burro Canyon(?) Formation
Secs. 2 & 11, T. 23 N., R. 2 E.

Measured: June, 1977, Munsell rock color chart (Geol. Soc. America)

Top of ledge

Dakota Sandstone — Burro Canyon(?) Formation

Sample	Description	Thickness (m)
B76055	Sandstone, pale-yellowish-brown (10YR 6/2); crossbedded with conglomeratic units containing kaolinite concretions up to 2 cm in diameter	6.1
B76054	Sandstone, very light-gray, kaolinitic cement	1
B77039	Claystone; medium-light gray (N6), mottled; fine-grained	0.5
B77038	Claystone, very pale orange (10YR 8/2) to very light gray (N8) grading to light-bluish-gray (5B 7/1); very fine grained; conchoidal fracturing (fig. 19); moderate-red (5R 4/6) banding	0.6
B77040	Claystone, light-green-gray (5B 7/1), softer than B77038	0.5
	Total unit	8.7 (28.5 ft)

White conglomeratic sandstone below
(Burro Canyon(?))

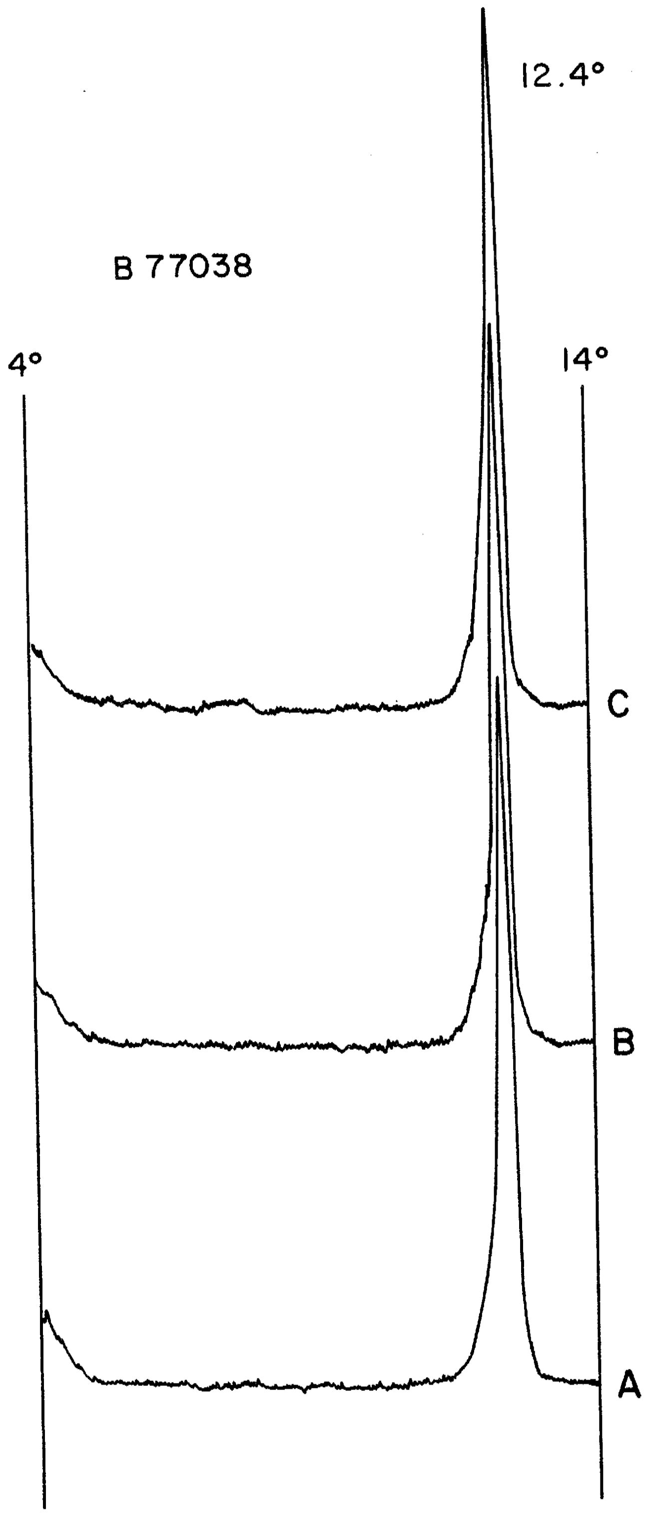


Figure 28a--X-ray traces of sample B77038 showing three runs: A) untreated sample (NH_4OH) used as a dispersant), B) slide placed over ethylene glycol and heated 1 hour at 60°C, and C) slide heated for 30 minutes at 375°C.

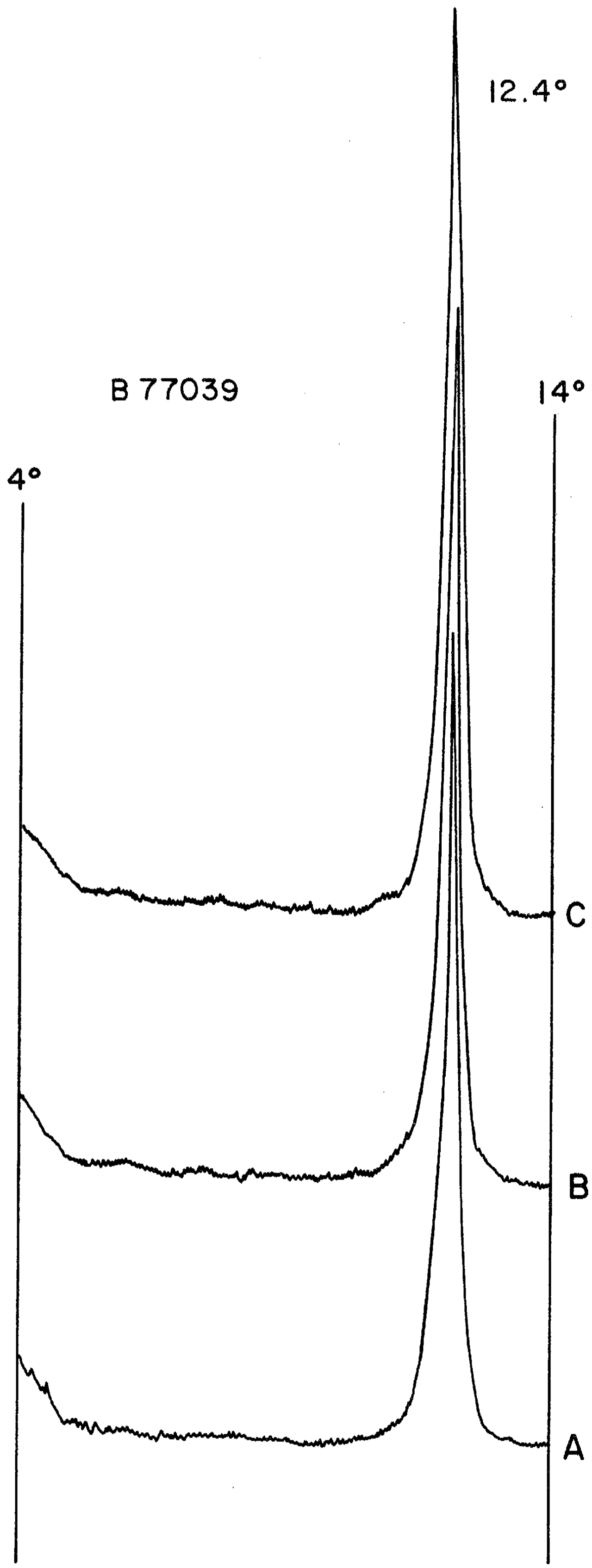


Figure 28b--X-ray traces of sample B77039 showing three runs: A) untreated sample (NH_4OH used as a dispersant), B) slide placed over ethylene glycol and heated 1 hour at 60°C, and C) slide heated for 30 minutes at 375°C.

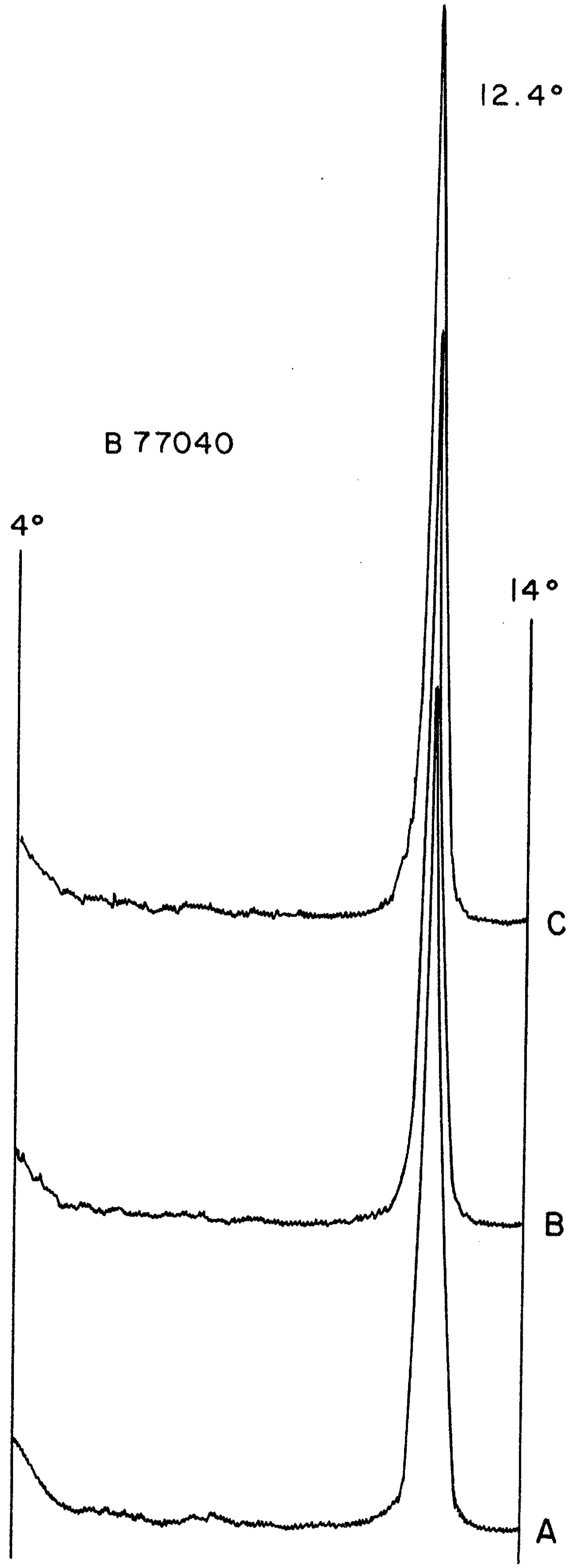


Figure 28c--X-ray traces of sample B77040 showing three runs: A) untreated sample (NH_4OH used as a dispersant), B) slide placed over ethylene glycol and heated 1 hour at 60°C, and C) slide heated for 30 minutes at 375°C.

Figure 29a--Myers kaolinite pit at Mesa Corral (samples B77038-040). Hammer is 0.36 m long.

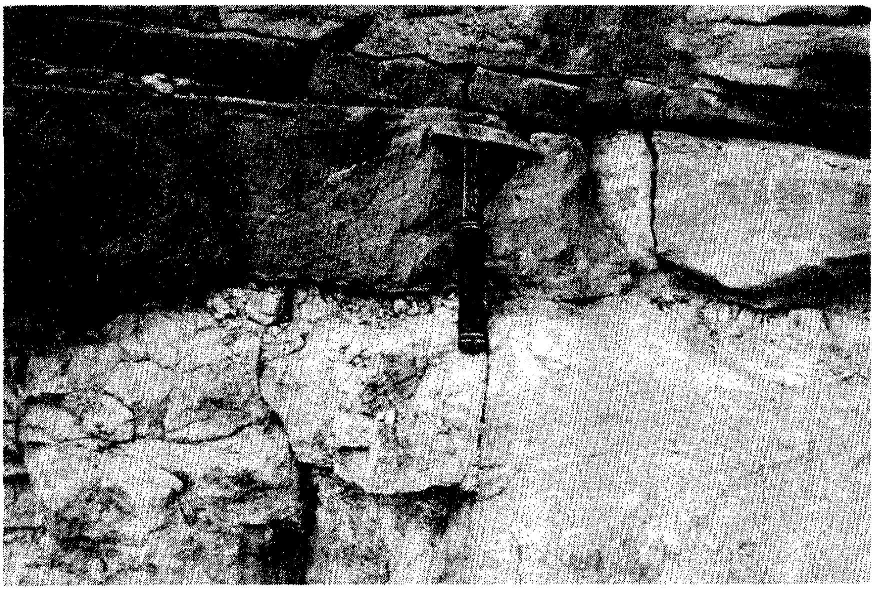


Figure 29b--Upper contact of clay zone (Myers kaolinite pit) with sandstone of the Dakota Sandstone.

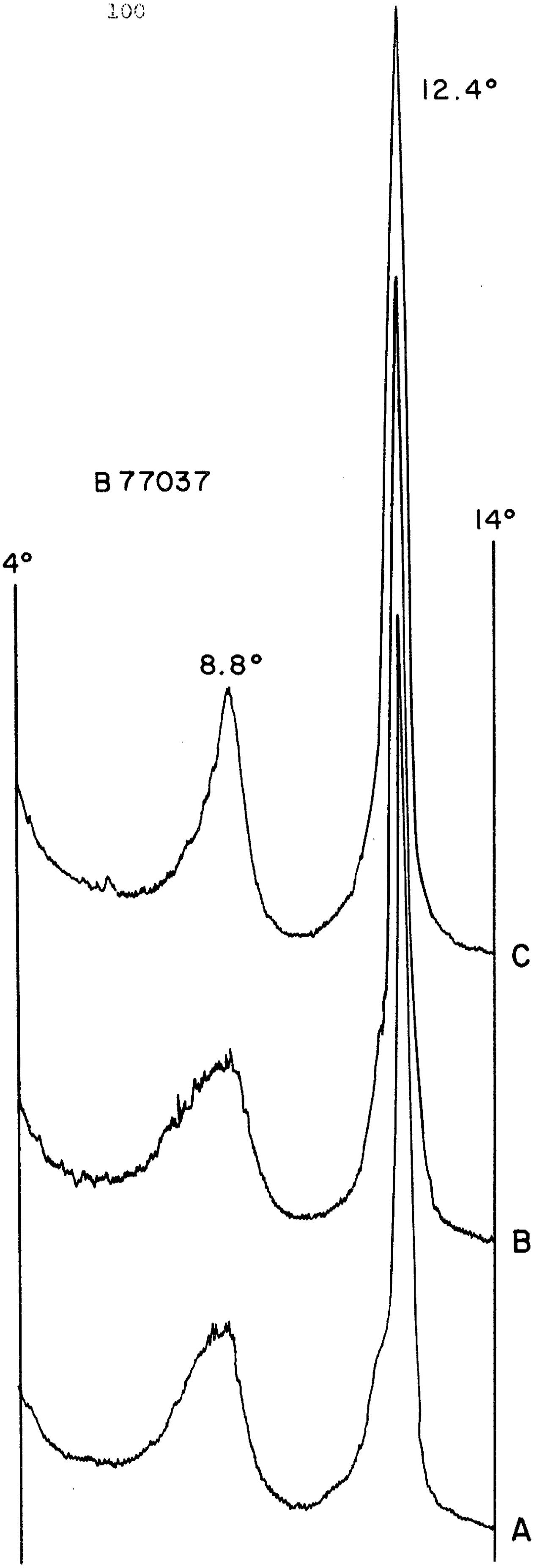


Figure 30--X-ray traces of sample B77037 showing three runs: A) untreated sample (calgon used as a dispersant), B) slide placed over ethylene glycol and heated 1 hour at 60°C, and C) slide heated for 30 minutes at 375°C.

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