Geology of the La Vida Mission Quadrangle, San Juan and McKinley Counties, New Mexico

U.S. GEOLOGICAL SURVEY BULLETIN 1940

In cooperation with the
Bureau of Indian Affairs,
U.S. Department of the Interior

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By RALPH L. MILLER, MARY ALICE CAREY, and
CAROLYN L. THOMPSON-RIZER

In cooperation with the
Bureau of Indian Affairs,
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A study of a quadrangle in the
southwestern part of the San Juan
Basin, including coal beds in the
upper part of the Upper
Cretaceous Menefee Formation

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Geology of the La Vida Mission Quadrangle, San Juan and McKinley Counties, New Mexico

By Ralph L. Miller, Mary Alice Carey, *and* Carolyn L. Thompson-Rizer

Abstract

The La Vida Mission 7½-minute quadrangle is located in the southwestern part of the San Juan Basin, an area that in recent years has attracted much attention because of its coal, oil and gas, and uranium resources. In this part of the basin, thick coal beds in the Fruitland Formation of Late Cretaceous age have been the object of numerous quadrangle geologic maps and of commercial exploitation. Another coal-bearing zone has long been known in the upper part of the Menefee Formation about 500 feet (ft) (152 meters (m)) below the Fruitland, but has been little studied. This report not only provides an appraisal of the Upper Menefee coal beds in a quadrangle where they are well exposed, but also presents the comprehensive geology of this particularly interesting area, including physiography, stratigraphy, environments of deposition, and structure.

The quadrangle is in the drainage basin of the Chaco River. Several topographic, geologic, and archeologic features lend special interest to the quadrangle. Among these are dry washes tributary to the Chaco in the northwestern part of the quadrangle that have eaten into the soft rocks of an upland area to produce a spectacular example of badlands erosion. This badlands area is made colorful by the reds and oranges resulting from burned coal beds. Also of special interest is Juans Lake, the largest body of water in the southern San Juan Basin. This ephemeral lake has had an unusual history since it was formed in the 1930's by the damming of Kim-me-ni-oli Wash.

Chaco Culture National Historical Park, formerly named Chaco Canyon National Monument, includes ruins of several Anasazi pueblos in areas remote from the large community on Chaco Wash. One of these, Kin Bineola, is located in the southeastern corner of the La Vida Mission quadrangle. On the topographic map (in pocket) it is labeled Kim-me-ni-oli Ruins. The confluence of favorable factors—geologic for building materials, hydrologic for water supply, and topographic for dam sites and for large, nearly flat areas for cultivation—made this an ideal site for the home of some 300 Anasazi, who built and occupied the pueblo for about two centuries.

The subsurface sedimentary rocks of the La Vida Mission quadrangle make up formations of Paleozoic and Mesozoic age. The pre-Cretaceous rocks are known principally from the log of a well drilled to basement by Sinclair Oil and Gas Co. just west of the quadrangle, and the Jurassic and Cretaceous formations are known from the logs of a series of drill holes south of the quadrangle. Basement rocks penetrated by the deep well are quartzite and may be correlative with the thick Uncompahgre Formation of southwestern Colorado. Rocks of Cambrian through Silurian age are believed to be absent from northwestern New Mexico. The oldest sedimentary rocks, directly overlying the basement, may be a few feet up to 20 ft (6 m) of dolomite of the Upper Devonian Elbert Formation. A limestone formation, 30 to 50 ft (9 to 15 m) thick, of Mississippian age is probably next above the Elbert. Rocks of Pennsylvanian age in the Sinclair well total about 525 ft (160 m), of which approximately the lower third is largely shale and the upper two-thirds limestone. Permian rocks, predominantly continental eolian and water-laid clastics, total about 1,900 ft (579 m). Almost 1,100 ft (335 m) of shale and siltstone, including red beds, are assigned to the Triassic, and nearly 1,200 ft (366 m) of sandstone, siltstone, mudstone, and a little limestone to the Jurassic.

The La Vida Mission quadrangle is located near the western edge of the interior Upper Cretaceous seaway, where numerous advances and retreats of the sea caused intertonguing of continental and marine deposits, including coaly zones in several formations. In the subsurface beneath the quadrangle, about 3,250 ft (991 m) of this complex are present, from the base of the Dakota Sandstone to about the middle of the Menefee Formation. Outcropping rocks of the quadrangle are restricted to two formations, the upper half of the Menefee Formation, which is composed of sandstone and mudstone, and almost all of the Cliff House Sandstone. The former is deltaic, and the latter nearshore marine. In the uppermost 200 ft (61 m) of the Menefee, numerous thin and a few moderately thick coal beds are present.

Terrace gravels deposited by the Chaco River within the quadrangle are present at five levels, the highest 330 ft (101 m) above the river, the lowest 20 ft (6 m) above the river. The

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source of most of the gravel is outside the quadrangle. South of the river, gravel on numerous high places has been preserved on remnants of a pedimentlike surface and is composed of locally derived rock. Mapped Holocene deposits consist of alluvium, stabilized eolian sand, sand dunes, and slope wash. Extensive areas of residual soil concealing the bedrock also have been mapped.

Within the quadrangle, the bedrock dips very gently and uniformly to the north to north-northeast, the only deviation being one very small anticline. Sandstone dikes are also present in and near the quadrangle.

Coal beds are located in four separate areas, all in the northern part of the quadrangle. One area is in the northwestern corner, two are north of the Chaco River, and one is on the slopes of three closely spaced small mesas near the eastern border. Four coal beds were mapped in the western area, two in the area north of the Chaco River, and two in the eastern area. The thickest coal bed locality is at the north edge of the quadrangle. Here, a coal bed is 61 inches (in) (155 centimeters (cm)) thick, but where measured elsewhere, it is only 45 in (114 cm) or less thick. Other coal beds are present within the coaly zone, but they were not mapped because they are of very small extent laterally or are thin. Coal resources are calculated to be 790,000 short tons in the western area, 1,365,000 short tons north of the Chaco River, and 2,870,000 short tons in the eastern area, for a total of 5,025,000 short tons. Because of the lenticularity of the coal beds, their small areal extent within the quadrangle, and other considerations, the coal resources are considered uneconomic. No unweathered samples of coal were available from within the quadrangle. Samples from drill holes penetrating coal beds in the upper part of the Menefee elsewhere show that the coal is high-volatile bituminous or low-volatile subbituminous, and that the quality varies from low ash to high ash. In all the samples, sulfur content is low.

Two wells drilled for oil in the quadrangle were dry holes. However, a small oil field on an anticlinal structure 1½ miles (2.4 km) west of the quadrangle has produced 8,000 barrels of oil from the Dakota Sandstone. Possibilities for structural traps for oil or gas within the quadrangle are poor, and possibilities for stratigraphic traps for oil or gas in the quadrangle are unknown. Hard red clinker from baked shale overlying a burned coal bed was used for fill in construction of part of new State Highway 371. Dusky-brown, organic-rich mudstone (humate), which is abundant in the quadrangle, elsewhere has been mined and used as a soil conditioner.

INTRODUCTION

Geologic Interest

The La Vida Mission quadrangle is in the southern part of the San Juan Basin, an area that in recent years has attracted much attention because of its coal, and oil and gas resources. In addition, large uranium deposits have been developed in the Morrison Formation in the Grants area near the southern margin of the basin. However, the Morrison lies at depths in excess of 3,500 feet (ft) (1,067 meters (m)) in the vicinity of the La Vida Mission quadrangle.

Because of the keen economic interest in the San Juan Basin as a result of these known, and possible additional, sources of energy, considerable geologic mapping has been done in the basin during the past 50 years, beginning with maps at a scale of 1:62,500 and 1:63,360 without topographic base (Sears, 1934; Dane, 1936; Hunt, 1956). More recently, geologic maps of the basin at 1:250,000 scale have been published (O'Sullivan and Beikman, 1963; Hackman and Olson, 1977). Preliminary or reconnaissance geologic maps at 1:24,000 scale for coal resources or environmental analysis of quadrangles near the La Vida Mission quadrangle have also been published or placed in open-file reports by the U.S. Geological Survey (USGS).

In the middle of the San Juan Basin, the coal-bearing Fruitland Formation of Late Cretaceous age has drawn interest recently because of thick coal beds, some of considerable lateral extent, and because of the potential for coal bed methane. Coal beds in the upper part of the Menefee Formation, some 500 ft (152 m) lower in the section, have been considered less promising and have not been mapped. In order to assess the Menefee coal beds in an area of reasonably good exposures, and to provide a more detailed and comprehensive geologic report on a quadrangle in the southern part of the inner San Juan Basin, the La Vida Mission quadrangle was selected for this study.

The fieldwork and most of the office work for this project were financed by the Bureau of Indian Affairs on behalf of the Navajo Nation. Additional office work, and preparation and printing of the final report, were financed by the USGS.

Location and Extent of Quadrangle

The La Vida Mission quadrangle is located in San Juan and McKinley Counties in the southwestern part of the San Juan Basin in northwestern New Mexico (fig. 1), between 36°00′ and 36°07′30″ latitude and 108°07′30″ and 108°15′ longitude. It incorporates parts of six townships, lying within Townships 20, 21, and 22 N. and Ranges 12 and 13 W. The quadrangle takes its name from the La Vida Mission School for Navajo Indians located on the south side of the Chaco River in the northernmost part of the quadrangle. The west border of the quadrangle lies 1⅓ miles (mi) (2.1 kilometers (km)) east of the east border of the Navajo Indian Reservation. The quadrangle is approximately 8.6 mi (13.8 km) north-south and 7.0 mi (11.3 km) east-west, with a total area of 60 square miles (mi^2) (156 square kilometers (km^2)).

Figure 1. Location of La Vida Mission quadrangle.

Accessibility

The La Vida Mission quadrangle is traversed in a north-south direction by State Highway 371 (geologic map, pl. 1, in pocket), which was partly rerouted and paved in the early 1980's. Southward from the quadrangle, State Highway 371 merges with State Highway 57 about 3 mi (4.8 km) north of Crownpoint, and State Highway 57 continues south to join Interstate 40 (old U.S. 66) at Thoreau. The distance from Thoreau to the south border of the quadrangle is 40 mi (64 km). Access from the north, from Farmington, is via State Highway 371 to the north border of the quadrangle, a distance of about 55 mi (88 km).

Within the quadrangle, an all-weather gravel road extends from the north-central part of the quadrangle westward from new State Highway 371 at Tsaya trading post (topographic map) to Whiterock Chapter House just west of the quadrangle; another gravel road runs eastward from new State Highway 371 nearly to Lake Valley Navajo School (labeled Lake Valley Boarding School on topographic map), then swings northward past La Vida Mission School to rejoin new State Highway 371 at the Chaco River Bridge. Another all-weather road branches off from Lake Valley Navajo School and continues southward near the east border of the quadrangle past Lake Valley Chapter House to and beyond the south border of the quadrangle. Old State Highway 371, lying between the west edge of the quadrangle and the new highway, serves the western part of the quadrangle south of the Whiterock road. It is also an all-weather road except at one spot where, during very hard wind storms, a large sand dune may move across the road and block it until reopened by a bulldozer.

Field Investigations

Field investigations of the quadrangle started in 1979, when the authors, Miller, Carey, and Thompson-Rizer, initiated the mapping and stratigraphic studies. K.K. Krohn, S.S. Crowley, and M.A. Kirschbaum each assisted Miller for periods of a week or 10 days. Mapping by Miller, Carey, and Thompson-Rizer continued in 1980, with assistance briefly by N.K. Gardner. Miller and Carey returned to the field in 1981 and 1982 for additional mapping and for reconnaissance of adjacent areas. Miller spent a week in the field in 1984 making additions and corrections to the earlier work. A total of 29 man-weeks were spent in the field, or about 14 weeks for the two-man teams and one solo week.

Geologic mapping was done directly on scale-stable sheets of the topographic map of the quadrangle at 1:24,000. Almost all the mapping was done on foot after driving each morning to a convenient starting point. Most section corner and quarter corner markers are in place in the area, and this facilitated accurate locations, particularly in areas where topography is subdued. Geologic sections were measured principally with a hand level and a 6-ft (1.8-m) tape on slopes, and with a 100-ft (30.5-m) tape across gentle topography. Coal beds were measured with a 6-ft (1.8-m) tape. In most places, the coal beds could be exposed from top to base with the tools at hand, so the full thickness could be measured. The coal beds were not sampled for chemical analysis because all outcrops of coal are weathered and the only underground mine near the quadrangle is abandoned and unsafe to enter.

Acknowledgments

The authors are deeply indebted to David Atanasoff, principal of the Lake Valley Navajo School, for permission to use the school dormitory and kitchenette facilities throughout the course of the fieldwork. Members of the school staff and students were unfailingly helpful and friendly, contributing to the ease and pleasure of the hours not in the field. We are also indebted to Joy Atanasoff for information on the region.

In addition to his coauthors, the senior author was accompanied in the field at various times by K.K. Krohn, S.S. Crowley, N.K. Gardner, and M.A. Kirschbaum, all of

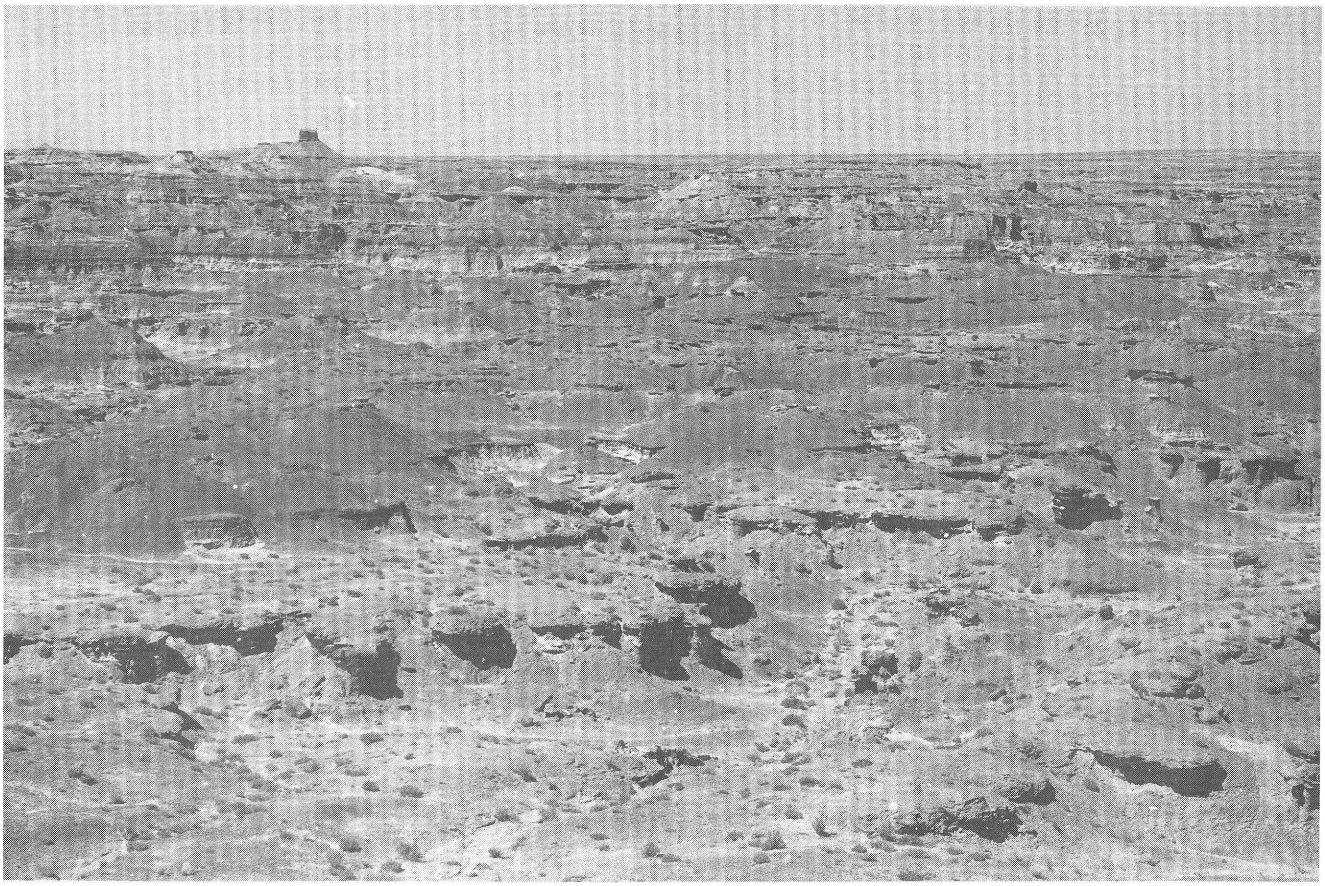


Figure 2. "Menefee badlands" viewed from a point on the rim in the southwest corner of sec. 4, T. 22 N., R. 13 W.

the USGS. Their keen interest and unflagging support greatly assisted and enlivened the progress of the fieldwork. Many of the photographs in this report were taken by N.K. Gardner.

Consultations and advice during fieldwork and report preparation were provided by R.B. O'Sullivan, J.W. Mytton, J.E. Fassett, A.R. Kirk, and A.B. Olson of the USGS, and D.W. Love of the New Mexico Bureau of Mines and Mineral Resources. Their help is gratefully acknowledged. The project benefited throughout its duration from the strong support of Jack Medlin, then chief of the Branch of Coal Resources, USGS.

GEOGRAPHY

Topography

Most of the La Vida Mission quadrangle is a gently undulatory sandy plateau which developed on thick units of mudstone and thinner units of sandstone of the Menefee Formation. Above these surfaces rise small mesas, buttes, pinnacles, and ledges. These prominences are capped by one or another of the sandstone units. Local relief ranges from as little as 10 ft (3 m) to as much as 150 ft (46 m).

In the northwestern part of the quadrangle, tributaries of the Chaco River, which is close by to the east, have eroded back into the Menefee Upland, forming a spectacular badlands area of intricately dissected topography (topgraphic map and fig. 2). Steep slopes rise above dry gullies. Numerous buttes, towers, and pinnacles dot the landscape. In places, thin sandstone beds cap pedestals of mudstone, forming mushroom-shaped pillars and spires, small and large (figs. 3 and 4). This style of badlands topography has aptly been termed "hoodoo landscape." Local relief in this maze is as much as 300 ft (91 m). The gullied mudstone slopes are predominantly gray, with sandstone units forming light-colored bands and organic-rich mudstone units (humates) forming dark-brown bands. In the higher parts of the badlands, coal beds are included in the rock sequence. Where thicker beds of coal have burned, bright-orange and reddish-orange clinker has formed above the coal, and reddish talus mantles the slopes below. In these areas, the scenic aspect of the topography deserves the word "spectacular." Several other areas of badlands erosion are present in the quadrangle, but all are much smaller and less spectacular than the northwestern badlands.

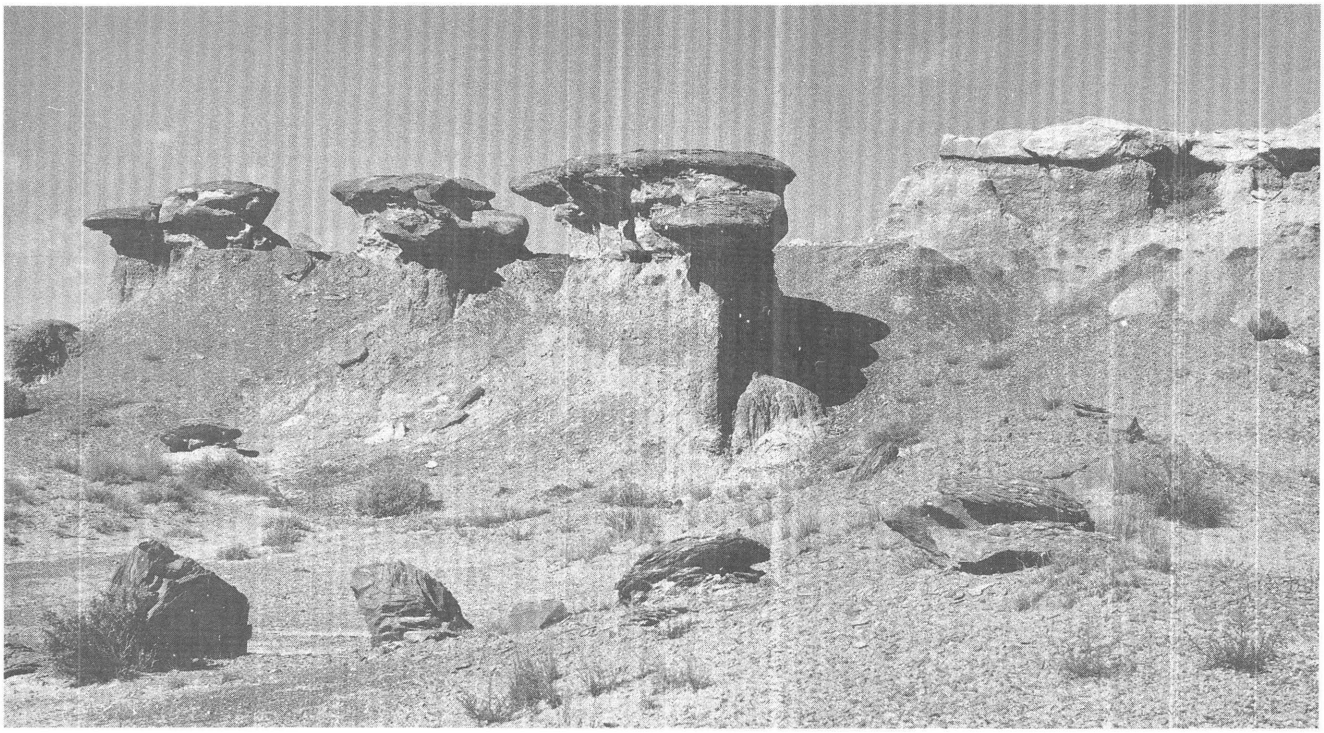


Figure 3. Hoodoos in the eastern part of the "Menefee badlands" (sec. 33, T. 22 N., R. 13 W.).

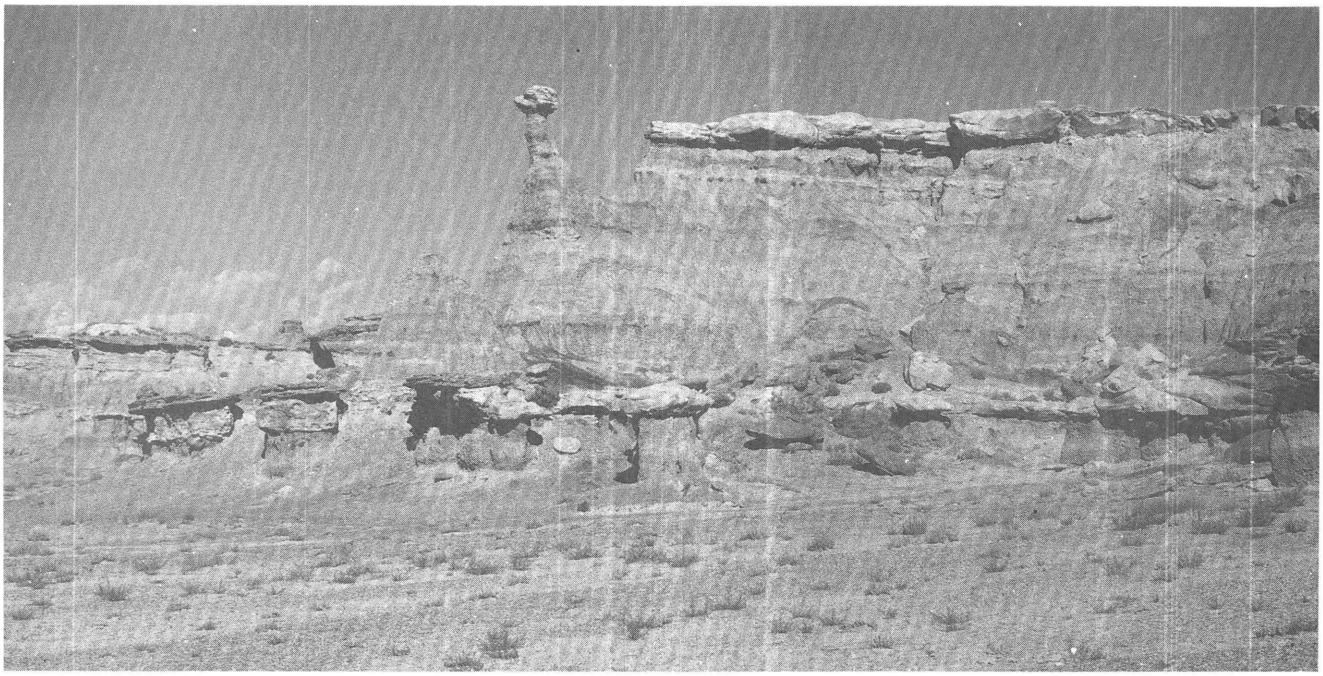


Figure 4. Tall pillar ("big bird") in the eastern part of the "Menefee badlands" (north-central part of sec. 33, T. 22 N., R. 13 W.).

In the northern and northeastern parts of the quadrangle, the Cliff House Sandstone, which overlies the Menefee Formation, crops out on the valley wall north of the Chaco River. In the northeast corner of the quadrangle, a nearly vertical cliff of Cliff House Sandstone, more than 200 ft (61 m) high, overlooks the river. Elsewhere, the sandstone shelves back from the river in a series of small cliffs and ledgy outcrops. The highest elevation, 6,370± ft (1,942± m), is the top of a prominent butte near the northwest corner of the quadrangle, and the lowest elevation, 5,810± ft (1,771± m), 2 mi (3 km) to the northeast is where the Chaco River leaves the quadrangle.

Seven mesas and numerous buttes, mounds, and pillars rise above the broad, gently sloping landscape and lend topographic and geologic interest to the whole area. All these features are unnamed (topographic map), but we informally named the three mesas in the northeastern part of the quadrangle the north, middle, and south mesas, respectively, and so labeled them on plate 1 (in pocket) to facilitate discussion of the coal beds that crop out on their slopes. These three mesas are capped by massive-bedded, resistant basal sandstone of the Cliff House Sandstone, as is the small but prominent butte mentioned above in the northwestern part of the quadrangle; all other mesas and buttes are capped by one or another of the sandstone units of the Menefee Formation.

Drainage

The Chaco River is the master stream not only for the La Vida Mission quadrangle, but also for most of the southern San Juan Basin. It crisscrosses the northern border of the quadrangle from east to west in two southward-extending loops (fig. 1 and topographic map).

The river channel ranges from 500 ft (152 m) to 1,800 ft (549 m) wide and averages about 700 ft (213 m). The alluviated valley floor bordering the channel is about 2,500 ft (762 m) wide at its widest spot. Throughout most of its course across the quadrangle, gentle slopes border the river, but in the northeast corner, where it swings up against an upland area underlain by massive Cliff House Sandstone, the vertical cliff, previously mentioned, and steep talus slopes overlook the river. The flat-floored channel of the river is dry at most times, except when snow is melting in the spring. After a hard rain, floods fill the channel from bank to bank, and a small flow may persist for several days after the storm. In the La Vida Mission quadrangle there is not a drop of flowing surface water for probably more than 300 days a year.

A north-flowing tributary of the Chaco, Kim-me-ni-oli Wash (topographic map and fig. 12), accounts for most of the integrated drainage of the quadrangle. It parallels the east border for most of its course, then turns northwest to enter the Chaco in the north-central part of the quadrangle. Like the Chaco River, it is dry except after the infrequent storms. The wash, which has its headwaters at the Continental Divide about 30 mi (48 km) south of the La Vida Mission quadrangle, has a total drainage basin of about 1,200 km^2 (463 mi^2) (Bullard, 1983, p. 79). It drains almost all of the eastern half and much of the southwestern part of the quadrangle.

The west-central and southwestern parts of the La Vida Mission quadrangle are drained westward by tributaries of Indian Creek, which flows northward across adjacent The Pillar 3 SE quadrangle in a course roughly parallel to Kim-me-ni-oli Wash and enters the Chaco River farther downstream. Between Kim-me-ni-oli Wash and Indian Creek, the drainage divide trends almost due north and then northwest. The old road from Crownpoint to Farmington follows the north-trending section of this divide so exactly that not a single drainage culvert was needed for more than 4 mi (6.4 km); nor was the road susceptible to inundation or washouts, which plague many of the other dirt roads in the region.

Earthen dams have been built across many washes in the quadrangle to catch and retain storm water for the sheep, goats, cattle, and few horses that live on the range. Some of these dams across the broader washes are as long as 0.4 mi (0.6 km). During the summer and fall months, however, when fieldwork on this project was in progress, none of the dams in the quadrangle was retaining any water. Many of the shorter dams do occasionally channel storm water into scooped-out ponds, which provide some water for stock. A few scooped-out hollows are fed by water from nearby wells pumped by windmills.

On gently sloping surfaces, the runoff may spread out over small or large areas as a sheet of water that sweeps away vegetation and carries along small- to medium-sized pebbles. This phenomenon has been called sheet-flood erosion or sheet wash. Numerous large and small sheet-flood areas in the La Vida Mission quadrangle have been mapped because they are distinctive features of the landscape. They are described further in the section on "Quaternary deposits." In nearly flat or gently undulatory sandy areas near drainage divides, rainwater, no matter how torrential, does not collect in channels or sheet floods but seeps underground as fast as it falls. Thus it helps to replenish the ground-water supply.

The prominent exception to the prevailing aridity of most of the landscape is Juans Lake, which, when inundated (see topographic map), is by far the largest body of water in the Chaco River drainage basin. It is about 1.25 mi (2.0 km) long and 0.5 mi (0.8 km) wide. During the course of our fieldwork (1979–82) the lake was filled. The margins of the lake were marshy, with thick vegetation. This provided excellent cover for waterfowl, a few of which could often be seen on the open water during the warmer months. There was no more favorable site for migratory waterfowl for many miles in any direction.

Alice Juan (1981, p. 23) described the formation of Juans Lake as follows:

> A long time ago there was no lake in this area, which is now called Lake Valley. Then in the 1930's a dam was built, and the lake was formed. Some of the

people who started working on the ditches and building the dam were: Old man Succo, Henry Succo, Sam Henry, Juan Etcitty, and Bit'ahnii Yazhi.

These men worked on the dam for many days. They brought their own bedrolls, food, wagons, scrapers, plows, and seeds to be planted. They started off with ten to fifteen teams of horses in order to build the ditch about half a mile or a mile on the south [sic, read east] side of what is now Lake Valley. The ditch ran all the way down onto the west side of the Lake Valley Chapter House. After the dam was built, the passage of water led into a lake. This is how the place was named Lake Valley.

Alice Juan's account requires elaboration to understand the drainage system. Two dams were needed to make the lake, a long one to cut off the intermittent flow of Kim-me-ni-oli Wash located just east of Lake Valley Navajo School and an adjacent, shorter one to block any drainage, probably rare, of the dry wash west of the school. The extensive, nearly flat area in the lower reaches of the dry wash was scoured out with scrapers, to make a shallow basin and to provide earth for construction of the dams. A short ditch was dug to lead Kim-me-ni-oli water westward into this basin, thus forming the lake. To supplement the supply of storm water entering the wash from inside the La Vida Mission quadrangle, a complex system of low dams was built for 3 mi (1.8 km) upstream from the main dam at Lake Valley Navajo School in order to block the tributaries coming from the high area to the east. Storm water, thus impounded, was fed into the ditch mentioned by Mrs. Juan and was carried quickly down to the main dam before it could seep underground or evaporate. The rearrangement of the drainage accomplished by all these dams results in the peculiar situation that a main drainage has been diverted into the lower reaches of one of its tributaries. Also, both the outlet and the principal inlet are at the northeast end of the lake and but 700 ft (213 m) apart, whereas the secondary and apparent inlet is 1.5 mi (2.4 km) to the southwest.

The purpose of all this work was to provide water for irrigation, but it also provided an attractive site for the Lake Valley Navajo School, which was founded in 1935. It is not clear from scanty records whether the dam building was finished and Juans Lake formed before the first school building was completed, or vice versa. Regardless, unpaved but passable roads across the tops of both dams provide all-weather access not only to the school but also to the northeastern part of the La Vida Mission quadrangle south of the Chaco River.

Juans Lake has had a checkered history. After completion of the dams, some farming ensued using water from the lake for irrigation. Juan Etcitty (1981, p. 9) records that peach trees, corn, watermelon, and alfalfa were grown on farms just north of Lake Valley Navajo School. These farms were probably located in the west half of sec. 31, T. 22 N., R. 12 W. and the northeastern part of adjacent sec. 36, T. 22 N., R. 13 W. The agricultural experiment seems to have lasted only a few years, however, and was probably terminated by a prolonged dry spell that depleted the lake waters. Mrs. David Atanasoff (oral commun., 1984) believes that enthusiasm for the project was also tempered by one or more drownings in the lake and by swampy conditions created in some areas. Be that as it may, the dam at the lower end of the lake was breached and the lake drained. Mrs. Atanasoff (oral commun., 1982) stated that in her 10-year residence at the school, before 1978 the lake was always dry. In that year, however, contractors for new State Highway 371 repaired the breached dam in order to restore the lake and use the water for road building. The lake filled rapidly, partly from storm waters but also from a constant supply of water pumped from a deep uranium mine into Kim-me-ni-oli Wash at a location about 19 mi (31 km) south of Juans Lake. Mrs. Atanasoff (oral commun., 1982) stated that from the time dewatering of the mine began in late 1977, the lake never went dry, although many thousands of gallons were pumped from the lake by the road builders. In 1983, however, the mine was closed and mine dewatering ceased. When Miller visited the area in 1984, Juans Lake again was nearly dry, with but a few puddles at the lower end of the lake. An abundance of intense storms within the drainage basin, a fortuitous circumstance, seems necessary to replenish Juans Lake even temporarily, now that no water from the mine enters Kim-me-ni-oli Wash.

In 1984, Miller visited one of the five previously inaccessible islands in the southwestern part of the lake. This island, which is directly northeast of a low-lying point, is one of the two rising above the 5,900-ft contour on the topographic map. It proved to be a knob composed of a jumble of hewn, angular blocks of fine-grained sandstone apparently dumped at that place during excavation of the lake basin. The other four islands, not visited, may also be manmade.

The effects on the erosional pattern of Kim-me-ni-oli Wash of the influx of abundant water from the mine dewatering have been described by Alison H. Mills and Thomas W. Gardner (1983). Type and rates of erosion before dewatering were established by study of air photos taken on four different dates. Changes resulting from the dewatering were demonstrated by observations and measurements at 20 sites along the wash, including 5 within the La Vida Mission quadrangle. Mills and Gardner also show air photos of the relocation of the main channel of the wash between 1935 and 1965 as a result of construction of the previously mentioned diversion dams on the east side of the wash above the main dam at Lake Valley Navajo School.

Drainage History

The erosional history of Chaco River and its tributaries is only partly understood. Although the sequence of events seems quite clear, the timing of those events, the structural, stratigraphic, and climatic factors controlling them, and the correlation with other drainage systems are still nebulous.

Charles B. Hunt assayed an interpretation of the geomorphic history of the entire Colorado Plateau in a USGS Professional Paper entitled "Cenozoic Geology of the Colorado Plateau" (1956). In his rather tentative hypothesis, the Colorado Plateau was uplifted and tilted to the northeast during late Tertiary time. He wrote (p. 85):

> Sediments deposited when the Plateau was tilted could have produced the younger set of superposed drainage features, such as the curious manner in which Chinle Creek and Chaco River turn out of strike valleys and into canyons to join the San Juan River. These features could readily be the product of superposition from late Tertiary deposits.... Under this interpretation, the late Pliocene to Recent history of the Colorado Plateau has witnessed no great changes in the pattern or position of the drainage.

Earlier, the broad outlines of the drainage history of the southern part of the San Juan Basin had been elucidated by the late Kirk Bryan (published posthumously, 1954, p. 8–10). In describing the geomorphology of the region in the vicinity of Chaco Culture National Historical Park, Bryan wrote:

> To the north...lies a plain...[that] occurs generally on the more elevated parts of the San Juan Basin and is more or less independent of the hardness of the underlying rock. Canyons divide this plain into several parts that are obviously remnants of a once continuous erosion surface that formerly extended over the entire region.... Whether a single peneplain or a more complex series of erosion cycles will be demonstrated by further work in the area, Chaco River and the adjacent streams gained their courses in a region of such moderate relief that the direction of flow was more or less independent of the distribution of hard and soft rocks. After a general uplift of the Plateau country, the "Canyon Cycle of Erosion" was initiated and the great canyons of the Colorado River system were cut.
>
> Chaco River, a distant and rather feeble tributary of the Colorado, also lowered its bed.

The plain Bryan described lies at elevations of 6,200 to 6,300 ft (1,890 to 1,920 m). It extends westward and northwestward from the Chaco Canyon region across Kin Klizhin Ruins, Pretty Rock, and Tanner Lake quadrangles, which touch the La Vida Mission quadrangle on its east side, northeast corner, and north side, respectively (fig. 9). A small part of this plain is preserved in the extreme northeast corner of the La Vida Mission quadrangle north of the Chaco River (topographic map), and the surfaces of the prominent mesas in the northeastern part of the quadrangle south of the river probably are slightly lowered remnants of this plain.

The inception of downcutting of the major drainages below the plain has not been dated. Canyon cutting presumably began along the lower Colorado River in northern Arizona during late Tertiary time; Hunt (1956, fig. 62) suggested late Pliocene time for this event. With continuing uplift of the plateau, the wave of canyon cutting must have proceeded up the Colorado River and thence up its major tributaries, including the San Juan River, and its tributary, Chaco River. No accurate dating of the inception of canyon cutting of Chaco River has yet been possible, but the consensus is that it occurred during Pleistocene time. In the vicinity of the La Vida Mission quadrangle, downcutting amounted to about 400 ft (122 m). Assuming that it began early in late Pleistocene time, about 500,000 years ago, the average rate of downcutting would be about 1/20 inch (in), or a bit more than 1 millimeter (mm) per year. A later start would, of course, require a faster rate.

Lowering of the floor of Chaco River, however, did not proceed at a steady rate. There were numerous pauses, perhaps dictated by climatic changes, during which lateral cutting was dominant and terraces were formed. These terraces are veneered with gravels largely carried in from sources to the east outside the La Vida Mission quadrangle-Chaco Canyon region, as described later in the section on terraces. In the Chaco River Valley, seven levels of terrace formation have been recognized (Weide and others, 1979). In the La Vida Mission quadrangle, only five are present. Correlation or lack of correlation of these with terraces in other parts of the valley has not been established.

Downcutting of the Chaco River continued below the present valley floor. Seismic profiles by Ross (M.S. thesis, 1978, cited by Love, 1983) in the Chaco Canyon area indicate that the river incised as much as 30 m (98 ft) below the valley floor. At another location in Chaco Canyon, Love (1983, p. 188) indicated a depth to bedrock of "at least 38 m (125 ft)." In light of these determinations, depth to bedrock below the streambed of the Chaco in the La Vida Mission quadrangle may well be as much as 100 ft (30 m). Seismic studies also have been made by Mahrer and Bullard (1983) in the middle and upper reaches of Kim-me-ni-oli Wash south of the La Vida Mission quadrangle. The two seismic profiles nearest the quadrangle are close together and 15 km (9.3 mi) upstream. In these profiles, the depth to bedrock is 10.5 m (34.5 ft) in the shallowest part of the profiles and 18.2 m (59.7 ft) in the deepest part.

The period of downcutting was succeeded by a period of alluviation, during which the channel to bedrock of the Chaco was filled to its present level. Kim-me-ni-oli Wash, concurrently with its master stream, filled its own deep channel. The upper 19 ft (5.8 m) of this fill is exposed in a vertical-walled arroyo at the outlet of Juans Lake just west of Lake Valley School. At the base of the wall the alluvium consists of 9.5 ft (2.9 m) of coarse gravel made up of subrounded flat pebbles of fine-grained sandstone up to 6 in (15 centimeters (cm)) in size and subrounded chips and fragments of siderite. The overlying unit is an interbedded fine-grained sand, silt, and mud, with lenses of gravel. At the top are 4.5 ft (1.4 m) of gravel similar to the basal gravel

Table 1. Weather data from stations near La Vida Mission quadrangle[1]
[Dashes indicate measurements not taken]

Station	Distance and direction from La Vida Mission quad. (miles)	Altitude (feet)	Mean annual rainfall (inches)	Mean annual snow (inches)	Mean annual temperature (°F)
Chaco Culture National Historical Park	14 east	6,125	8.53	18.4	50.7
Crownpoint	28 south	6,978	10.24	26.1	51.2
Farmington	44 north	5,494	7.96	—	—
Shiprock	56 northwest	4,974	7.35	9.1	53.3
Tohatchi	37 southwest	6,800	10.22	22.4	52.0
La Vida Mission quadrangle	—	6,000±			

[1] Source: Cooley and others, 1969, Regional hydrology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: U.S. Geological Survey Professional Paper 521–A, table 4.

but made up of sandstone pebbles less than 1 in (2.5 cm) in size. All this material is locally derived from the sandstone, and mudstone with siderite concretions of the Menefee Formation. The gravel was deposited during flooding in the Wash and the sand, silt, and mud during more quiet intervals. Together they indicate rapid filling of the bedrock channel.

A recent episode of renewed downcutting has affected some parts of the Chaco River. In Chaco Canyon, 8 mi (13 km) upstream from the La Vida Mission quadrangle, Bryan (1954, p. 23) reported that the river had incised as much as 30 ft (9.1 m) to form a steep-walled arroyo in the alluvial valley fill. This new wave of downcutting has not affected the Chaco in the La Vida Mission quadrangle. Along Kim-me-ni-oli Wash, however, the alluvial fill has been trenched as much as 19 ft (5.8 m) in the arroyo just west of Lake Valley Navajo School. The arroyo becomes shallower downstream but persists almost to the mouth of the wash. Upstream from the dam at the school, stretches of shallow arroyo are interspersed with alluvial flats above the check dams that have ponded the streamflow. The topographic map shows the stretches of arroyo along the wash by the contours that hug both sides of the main drainage for distances of as much as 0.5 mi (0.8 km) downstream from the contour crossings. This manifestation of the topographer's skill is well shown in secs. 5, 8, and 17, T. 21 N., R. 12 W. (topographic map).

Climate

The central part of the San Juan Basin is characterized by low precipitation and extremes of temperature. Weather stations have not been established for the immediate area of the La Vida Mission quadrangle, but records are available from stations in all directions from the quadrangle. Cooley and others (1969) have recorded weather data from stations in northwest New Mexico in the vicinity of La Vida Mission quadrangle, as shown in table 1.

It is apparent from table 1 that Tohatchi, which is near Newcomb (fig. 9) and close to the high Chuska Mountains, and Crownpoint, which is just north of the Hosta Butte Upland, get the most rainfall, because of the influence of these highlands, and that Shiprock, in a lowland area and highest mean annual temperature, gets the least rainfall and snowfall. The Chaco region most closely resembles the La Vida Mission quadrangle topographically, and it is also closest in distance and altitude. Its average annual weather regime probably approximates that of the La Vida Mission quadrangle.

Most of the precipitation in summer falls in the form of sudden, violent but short-lived thunderstorms, at times accompanied by hail. Any given place may, however, miss most of the storms, and another nearby place may get more than its share. In the hot summer months, dark clouds commonly are seen in the afternoon somewhere in the distance. Rain may fall from some of these, but often the raindrops evaporate before reaching the ground. Persistent rains are more common in the fall. Snowfalls are quite violent and short lived. The temperature frequently soars above 100 °F (38 °C) in summer, but evenings and nights are cool and pleasant. In winter, temperatures below 0 °F are not uncommon.

A pervasive aspect of the weather of the region is wind, which on many days picks up about 10 a.m. and is likely to blow hard the rest of the day. Work on maps and notes becomes difficult unless some type of windbreak is nearby. The direction from which persistent hard winds blow was measured several times, and was consistently between S. 30° W. and S. 80° W. Live sand dunes developed in open country are likewise elongated in this general direction. Hack (1941), in a regional study of sand dunes in Arizona and adjacent parts of northwestern New Mexico, recorded a similar directional trend for longitudinal dunes, which in the region near the La Vida Mission quadrangle averaged N. 60° E. Particularly strong winds pick up silt and fine sand from nonvegetated areas and result in "sand" storms, which can be quite violent.

Vegetation

No systematic study of the plants of the quadrangle was made. In general, vegetation is sparse, particularly in the areas underlain by mudstone of the Menefee Formation. Hicks (in Cooley and others, 1969, p. A33) indicated that the flora for desert areas on shaly rocks of Cretaceous age in the western San Juan Basin include such common types as chamiso, salt grass, shadscale, sacaton, galleta, and Indian rice grass. To these may be added, for sandy areas, sagebrush, broom weed, Russian thistle (tumble weed), snakeweed, Mormon tea, prickly pear cactus, and rare barrel cactus. Tufted grasses are widespread, mostly on relatively flat surfaces. They furnish most of the fodder for the flocks of sheep that are herded across the region by the Navajos. Brush grows along the Chaco River and in a few other moist areas.

Trees are extremely rare in this part of the San Juan Basin. A few cottonwood grow in Kim-me-ni-oli Valley. One lone tree (piñón) on top of an elongate butte in the northeast corner of sec. 28, T. 21 N., R. 13 W. is visible from all directions. It is such an unusual sight that it attracts the attention of all travelers and has been used as a station for resection by geologic mappers.

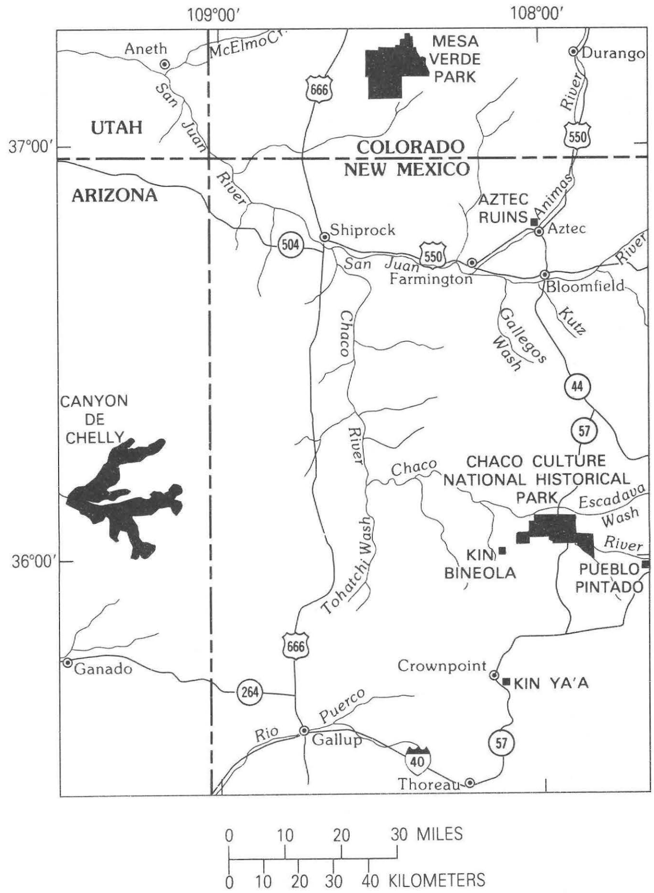


Figure 5. Chaco Culture National Historical Park, Kin Bineola, and other Anasazi ruins in and near the San Juan Basin. (After Lyons and others, 1977, fig. 1.)

Population

Ancient inhabitants of the La Vida Mission region belonged to the Anasazi peoples. They occupied a large part of the San Juan Basin from about the middle of the 9th century to about the middle of the 12th century A.D. The large pueblo-type towns built by the Anasazi in Chaco Canyon are well known to the thousands of visitors annually to the Chaco Culture National Historical Park, formerly named Chaco Canyon National Monument. Less well known is the fact that the Anasazi built other numerous structures outside of Chaco canyon, as shown in figure 5 (Lyons and others, 1977). The largest of the ruins of these outlying communities in the San Juan Basin have been made part of the historical park, including one within the La Vida Mission quadrangle named Kin Bineola (fig. 5). On the topographic map (in pocket), Kin Bineola is labeled Kim-me-ni-oli Ruins from the nearby wash of that name.

Kin Bineola, a Navajo term meaning "a house in which the wind blows [swirls]" (Mrs. David Atanasoff, oral commun.), is a spectacular ruins. A photograph of the ruins taken by a member of the Hyde Expedition in 1899 appears in figure 6. Two members of the expedition, one mounted, are visible in the middle foreground. The prominent butte in the distance has been called "Teardrop Mesa" after its shape, which is shown on the topographic map (northeast corner of sec. 6, T. 20 N., R. 12 W.).

Four topographic and geologic features combined to make this a favorable site for the community. Probably most important was the low-lying area south and west of the building site, which provided fertile ground for agriculture, by irrigation on the nearly flat areas and by floodwater farming on the adjacent, very gently sloping areas. The northernmost part of this lowland area lies within the La Vida Mission quadrangle, as shown on the topographic map (T. 21 N., R. 12 W., southeastern part of sec. 31 and southwestern corner of sec. 32, and in adjacent parts of T. 20 N., R. 12 W., secs. 5 and 6). On the geologic map (pl. 1), the lowland is shown as alluvium along the drainages and as slope wash (Qsw) or as sedentary soil (sl) on the gently sloping areas. Hewett (1936, p. 124) described the irrigation system at Kin Bineola (which he spelled Biniola) as follows:

> The best example of irrigation works in the entire Chaco system is that at Kin Biniola.... The ruin is in the basin of a wash [now named Kim-me-ni-oli Wash] which is tributary to Chaco Canyon [River]. The valley is here quite broad and on the eastern side is limited by a low mesa, at the base of which stand the ruins of the pueblo. The wash is about a third of a mile to the west. South of the ruins is a large natural depression, which was made to serve as a reservoir for the flood

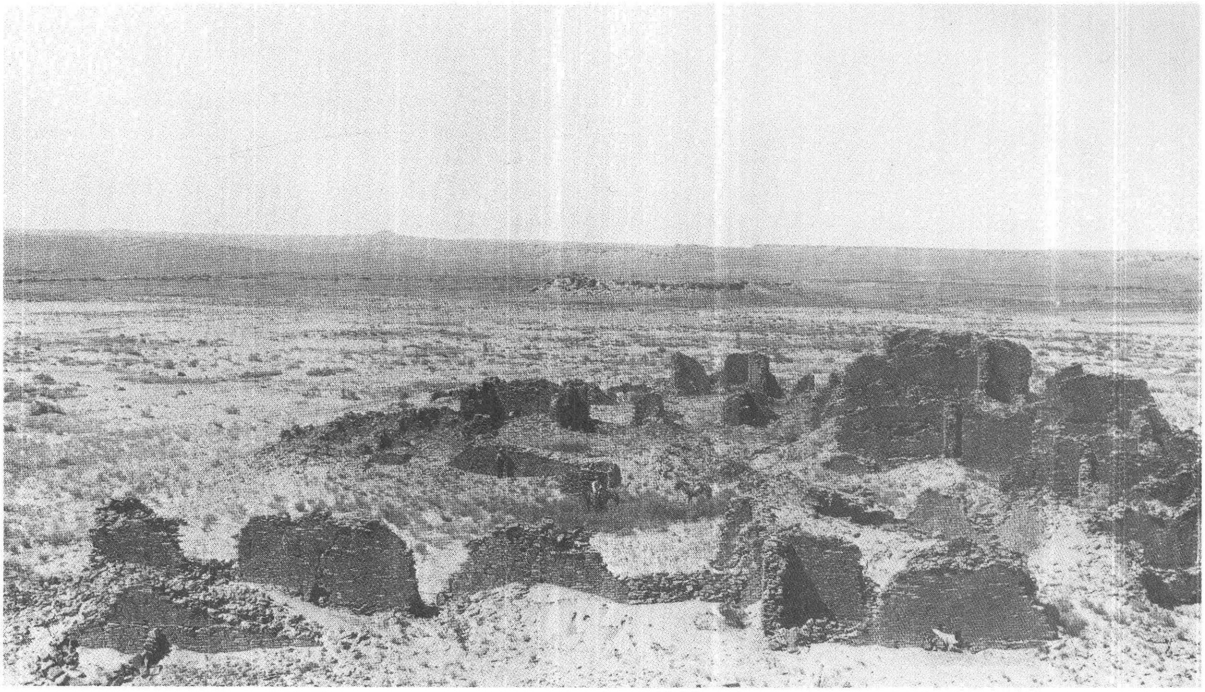


Figure 6. Kin Bineola Ruins (Anasazi), photographed in 1899 by a member of the Hyde Expedition (U.S. Department of the Interior, 1968, Master Plan, Chaco Canyon National Monument, p. 15). Note man on horseback in the lower center. "Teardrop Mesa" is in the middle distance.

> waters diverted from the wash. A ditch fully two miles long conducted the water from this lake to the fields, which were quite extensive. The ditch is carried around the mesa and along a series of sand hills on a fairly uniform grade. It was mainly earth work, but whenever necessary the lower border was reinforced with retaining walls of stone, portions of which still remain in place.

More comprehensive studies with maps of this elaborate irrigation system have not been published.

The second feature making this a favorable site for a community is the site's proximity to Kim-me-ni-oli Wash, which after Chaco River itself is the stream with the largest drainage basin of the region and hence carries water that could be used for irrigation and other purposes more frequently and in greater quantity than other drainages. A third feature favoring the building site is the presence of a low-lying, nearly flat bedrock spur extending westward into the lowland from the cliffed upland. This bedrock provided a stable foundation on which to build. A fourth feature that recommended this site to the Anasazi was the presence of abundant stone for building material. The low cliff close to the site and the higher cliff behind are made up of sandstone in the Menefee Formation. Some of this sandstone is thin bedded, and these beds provided abundant nearly flat pieces of rock on the talus slopes below the cliffs. Figure 7 shows how these rocks were used in constructing the walls of the building. To the foregoing favorable attributes of the Kin Bineola site it might be added that the high area above the upper cliff at about 6,130 ft (1,868 m) provides an excellent lookout in all directions.

Kin Bineola has about 100 ground-floor rooms and may have been three or even four stories high, with as many as 400 rooms. Ten small ceremonial kivas (roofed circular rooms entered by descending a ladder) have been identified, and one grand kiva is close by outside the ruin. Fisher (quoted in Hewett, 1936, p. 159) estimated that as many as 800 people may have lived in the pueblo, but a more recent population study by Drager (1977, p. 167) reduced the estimate to about 300. Lyons and Hitchcock (1977, p. 125 and fig. 37) indicated that an Anasazi road apparently ran westward from the communities in Chaco Canyon toward Kin Klizhin Ruins east of Kin Bineola and possibly on to Kin Bineola. The authors of this report did not recognize any traces of prehistoric roads within the La Vida Mission quadrangle, but more intensive study of specialized aerial images and more experienced eyes may eventually substantiate the presence of an Anasazi route of travel into the quadrangle from the east, and may lead to recognition of additional roads leading away from Kin Bineola.

The total population currently living within the boundaries of La Vida Mission quadrangle is difficult to appraise. There are no villages as such, though some of the staff at Lake Valley Navajo School and at La Vida Mission School live on the school grounds throughout the year. During most semesters, the student body approaches 100 at the Lake Valley Navajo School and about 60 at La Vida

Figure 7. A section of the walls of Kin Bineola Ruins (Anasazi) showing the style of construction. (Photograph by Nancy T. Gardner.)

Mission School. In order to arrive at an approximation of the population, the number of houses shown on the topographic map, not including the schools, was counted. Not all the houses are shown, however, and some that are shown have been abandoned. Perhaps these two factors more or less balance each other. Figures from the 1980 census indicate that for rural areas the average number of occupants of a Navajo home is 4.5 to 5 (Andrew Abata, Bureau of Indian Affairs, Crownpoint, oral commun., 1985). How many Navajo were missed by the census is indeterminate. If one uses the larger average number above, the population of the La Vida Mission quadrangle may approximate or somewhat exceed 300. Except for a few of the staff at each of the two schools, and a family at the Tsaya Trading Post, all residents are Navajo Indians. The principal occupations for the men are raising sheep, goats, and a few cattle, and for the women weaving and making jewelry. Because of the current high cost of silver, however, the last of these occupations has practically ceased. No agriculture, not even gardens, was noted anywhere in the area. All the water generated by the active windmills is used for watering stock. Water for home use is hauled in from outside because pumped ground water is too saline for household use. The Tsaya Trading Post, along State Highway 371 near the center of the quadrangle (topographic map), is one of the most active trading posts in the San Juan Basin.

Numerous circular houses (hogans) in the region attest to the former lifestyle of the Navajos. Almost all these hogans have been abandoned, and the former occupants live in small, one-story homes, many of them of substantial construction. A typical hogan of the past (fig. 8) has an inside diameter of 15 to 16 ft (4.6 to 4.9 m), with walls of stone blocks about 1 ft (0.3 m) thick. The walls themselves, pierced by one door and one small window, are about 5½ ft (1.7 m) high and are capped by a gently sloping, timbered roof caulked with mud. The rock for construction came from sandstone units in the Menefee Formation. Comparison of the hogan shown in figure 8 with the walls of Kin Bineola shown in figure 7 illustrates the contrast in building styles of the Anasazi and the Navajos.

HISTORY

Early Exploration

The central and southern parts of the San Juan Basin were largely avoided or ignored by early explorers of the

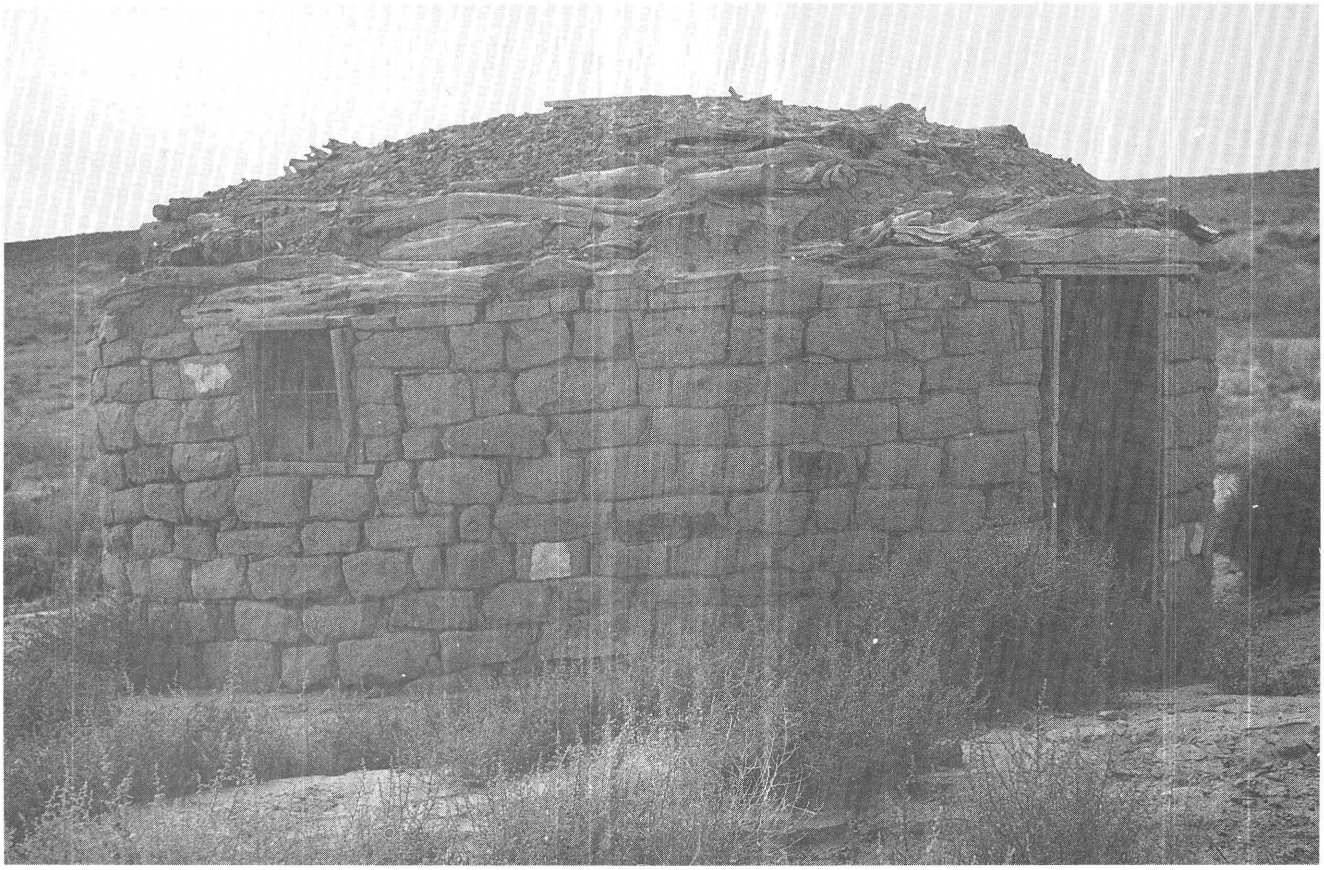


Figure 8. Abandoned Navajo hogan in the north-central part of sec. 26, T. 22 N., R. 13 W. Note the contrast in style of wall construction between the Anasazi and the Navajos by comparing this photograph with figure 7. Construction rocks in both cases come from sandstone units of the Menefee Formation.

Southwest, the Spaniards and their successors. This was partly because of the harshness and aridity of the landscape, but also because routes of travel passed to the north or south to avoid the barrier of the high Chuska Mountains, which are near the western margin of the basin but are not shown on Kelley's structural map (fig. 11) in this report. Geologists of the George M. Wheeler survey (geographical and geological surveys west of the 100th meridian) and the John Wesley Power survey (geographical and geological survey of the Rocky Mountain region), following the early explorers in the mid-19th century, likewise saw little of geologic or economic benefit to be gained by investigating the geography, geology, and resources of the basin. The uplifts and mountain ranges bordering the basin exposed older rocks and did attract geologic attention well before the turn of the century.

The first mention of possible energy resources in the basin seems to have been a report entitled "Report of the Exploring Expedition from Santa Fe, New Mexico, to the Junction of the Grand and Green Rivers of the Great Colorado of the West in 1859, Under the Command of Capt. J.N. Macomb, Corps of Topographic Engineers with Geological Report by Prof. J.S. Newberry" (Newberry, 1876). The Macomb expedition made its way from Santa Fe, N. Mex., to the junction of the Green and Grand (Colorado) Rivers in southeastern Utah by way of southern Colorado. It returned, however, by a more southern route, past Shiprock in the northwest corner of New Mexico and of the San Juan Basin. Newberry wrote that the party proceeded up the San Juan River, passing through a hogback ridge "called by the Mexicans the Creston—through which we worked our way with great difficulty." In this vicinity Newberry observed "several beds of lignite, of which one, six feet thick, visible for many miles along the river, is unusually compact and pure" (p. 108). This appears to be the earliest record of any possible energy resources in the San Juan Basin. The bed Newberry noted is probably the 5.4-ft-thick (1.6-m-thick) bed, with 0.2-ft (0.06-m) parting, described by Hayes and Zapp (1955) in their lower coal-bearing member of the Menefee Formation. Later, Holmes (1877), in an annual report of the Hayden Survey of the Territories for 1875, noted coal beds in his Upper Coal-Bearing Series (now the Fruitland Formation) and in his Lower Coal-Bearing Series (now the Menefee Formation) at the north edge of the San Juan Basin in the La Plata Valley, Colo. Whitman Cross, in 1899 in USGS Geologic Atlas Folio 60 of the La Plata (1:62,500) quadrangle, also mentioned the coal beds in the Mesaverde Formation in the

Table 2. Geologic quadrangle maps (1:24,000) of coal-bearing areas near La Vida Mission quadrangle
[Location of quadrangles shown in fig. 9]

Name of quadrangle	Date of map	Coal-bearing formation(s)	Authors
Bisti Trading Post	1979	Fruitland	O'Sullivan, Scott, and Heller
Burnham Trading Post	1979	Fruitland	Scott, O'Sullivan, and Heller
Pueblo Bonito NW	1979	Fruitland	Weide, Schneider, Mytton, and Scott
Pueblo Bonito	1979	Fruitland-Menefee	Schneider, Weide, Mytton, and Scott
Kin Klizhin Ruins	1979	Menefee	O'Sullivan, Scott, and Weide
Pretty Rock	1985	Fruitland	Strobell, O'Sullivan, Mytton, and Erpenbeck
Tanner Lake	1986	Fruitland-Menefee	O'Sullivan, Mytton, Strobell, Scott, and Erpenbeck

same region but did not consider them sufficiently important to describe them in the section of his report devoted to economic geology.

Within and near the south edge of the San Juan Basin near Gallup, N. Mex., coal beds were reported, and coal was mined as early as 1882 (Sears, 1925). The proximity of the main line of the Santa Fe Railroad facilitated development of coal mining in this part of the basin, and several underground coal mines resulted. All these are now abandoned. Interest in the coal potential of this area led to a series of geologic investigations in the 1920's and 1930's (Sears, 1925, 1934; Dane, 1936; Sears and others, 1941; Hunt, 1956). All these publications dealt with coal-bearing sequences near the base of the 2,000-ft-thick (610-m-thick) Menefee Formation and (or) in older formations below. In these reports, complex intertonguing relations of marine and coal-bearing continental deposits were delineated. The nomenclatorial problems of this complex sequence later were largely resolved by Beaumont, Dane, and Sears (1956).

Recent Coal Investigations

As underground mining activity in the southern part of the San Juan Basin slackened in the 1950's and 1960's, attention focused on the thick coal beds in the Fruitland Formation near the San Juan River (Shomaker and others, 1971). This interest was sparked by the development of technology and equipment for large-scale strip mining, and by the concept of generating electricity at the site rather than transporting the coal long distances to fuel power plants. The first such mine and power plant began operations in the Fruitland Formation near Shiprock in 1963. The Fruitland Formation lies about 500 ft (152 m) above the top of the Menefee in the La Vida Mission region. It has been traced from the Shiprock area southward near the west edge of the basin and then southeastward across quadrangles north and east of the La Vida Mission quadrangle. A series of preliminary and reconnaissance maps containing the Fruitland belt of outcrop has been released. Maps of quadrangles near the La Vida Mission quadrangle are listed in table 2. The relations of these quadrangles to the La Vida Mission quadrangle are shown in figure 9. In addition, geologic maps at smaller scales covering areas that include or are contiguous to La Vida Mission quadrangle are listed in table 3 and shown in figure 10. All the maps listed in the tables are helpful in understanding the regional geology of the southern San Juan Basin and the more detailed geology of areas near or including the La Vida Mission quadrangle.

Table 3. Small-scale geologic maps of areas near or including La Vida Mission quadrangle
[Location of maps shown in fig. 10]

Name of map	Date of map	Scale	Relation to La Vida Mission quadrangle	Authors
Geology, structure, and uranium deposits of the Shiprock quad., New Mexico and Arizona	1963	1:250,000	Includes La Vida Mission quadrangle	R.B. O'Sullivan and H.M. Beikman
Geology, structure, and uranium deposits of the Gallup 1° × 2° quad., New Mexico and Arizona	1977	1:250,000	Adjacent on south	R.J. Hackman and A.B. Olson
Map showing geologic structure of the southern part of the San Juan Basin, N. Mex.	1954	1:126,720	Includes La Vida Mission quadrangle	C.B. Hunt and C.H. Dane
Preliminary geologic map of western San Juan Basin, San Juan and McKinley Counties, N. Mex.	1957	1:125,000	Adjacent on west	R.B. O'Sullivan and E.C. Beaumont
Geologic map of Chaco Canyon 30′ × 60′ quadrangle, showing coal zones of Fruitland Formation, San Juan, Rio Arriba, and Sandoval Counties, N. Mex.	1983	1:100,000	See figure 10	J.W. Mytton

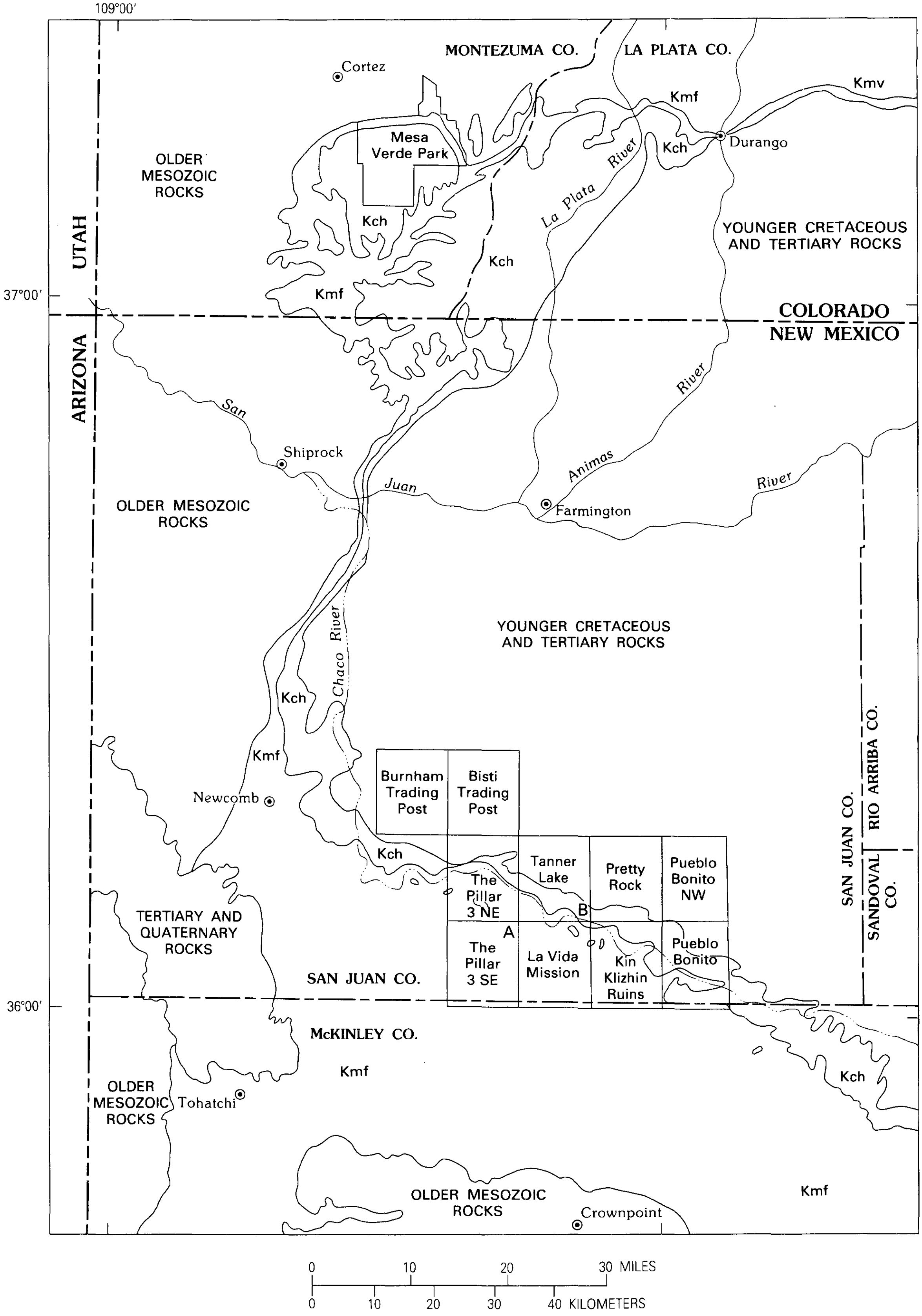


Figure 9. Generalized geologic map of part of the San Juan Basin, showing location of La Vida Mission quadrangle and nearby quadrangles for some of which geologic maps have been published (Kch, Cliff House Sandstone; Kmf, Menefee Formation; Kmv, Mesaverde Formation east of Durango); also shows locations of published measured sections of upper half of Menefee Formation (A) in The Pillar 3 SE quadrangle and of Cliff House Sandstone (B) in Tanner Lake quadrangle (Miller, 1984). The Pillar 3 NE quadrangle has been mapped, but not yet published. The Pillar 3 SE quadrangle has not been mapped.

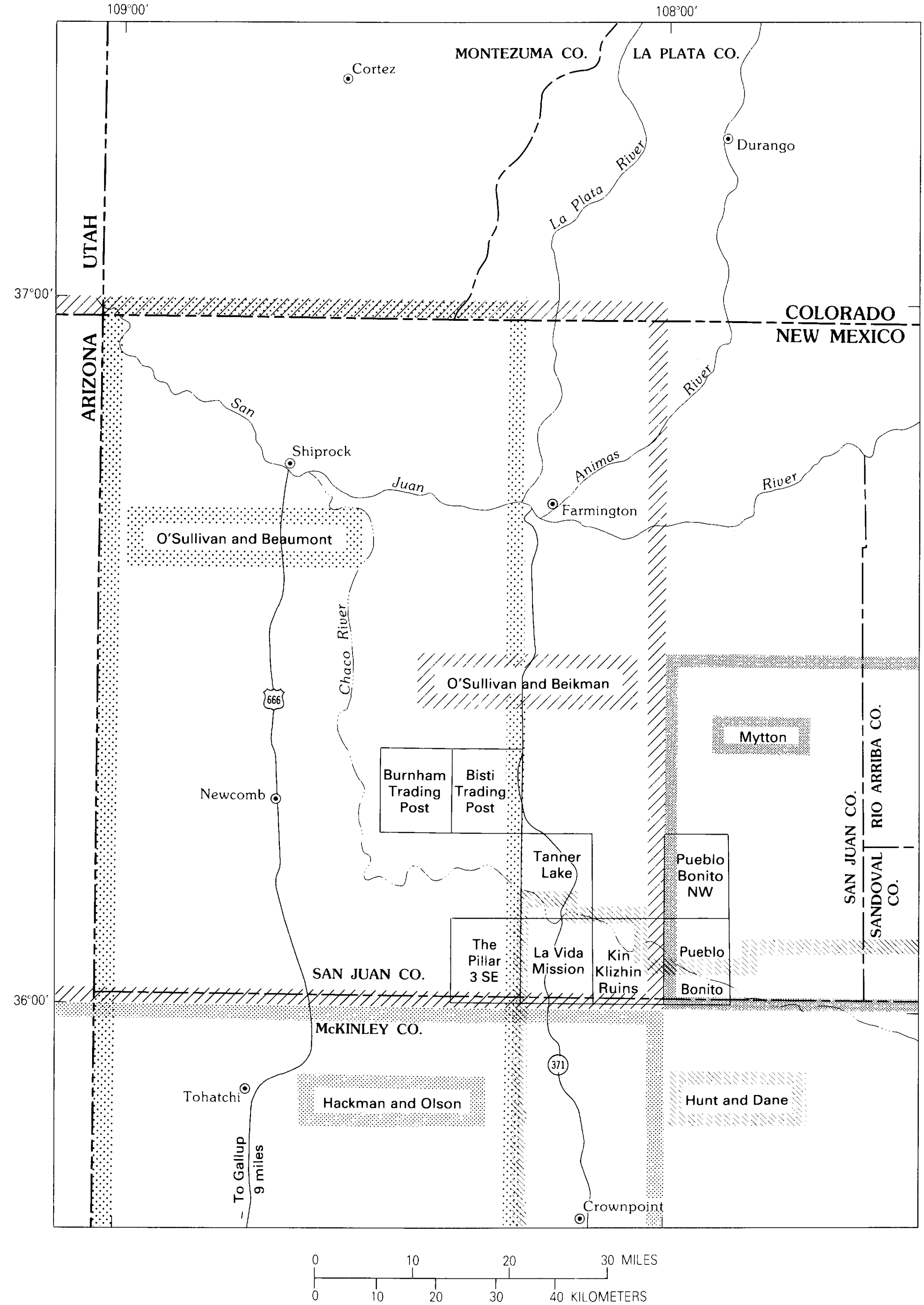


Figure 10. Published geologic maps at scales of 1:100,000 and smaller covering areas that include or are near La Vida Mission quadrangle (see table 3).

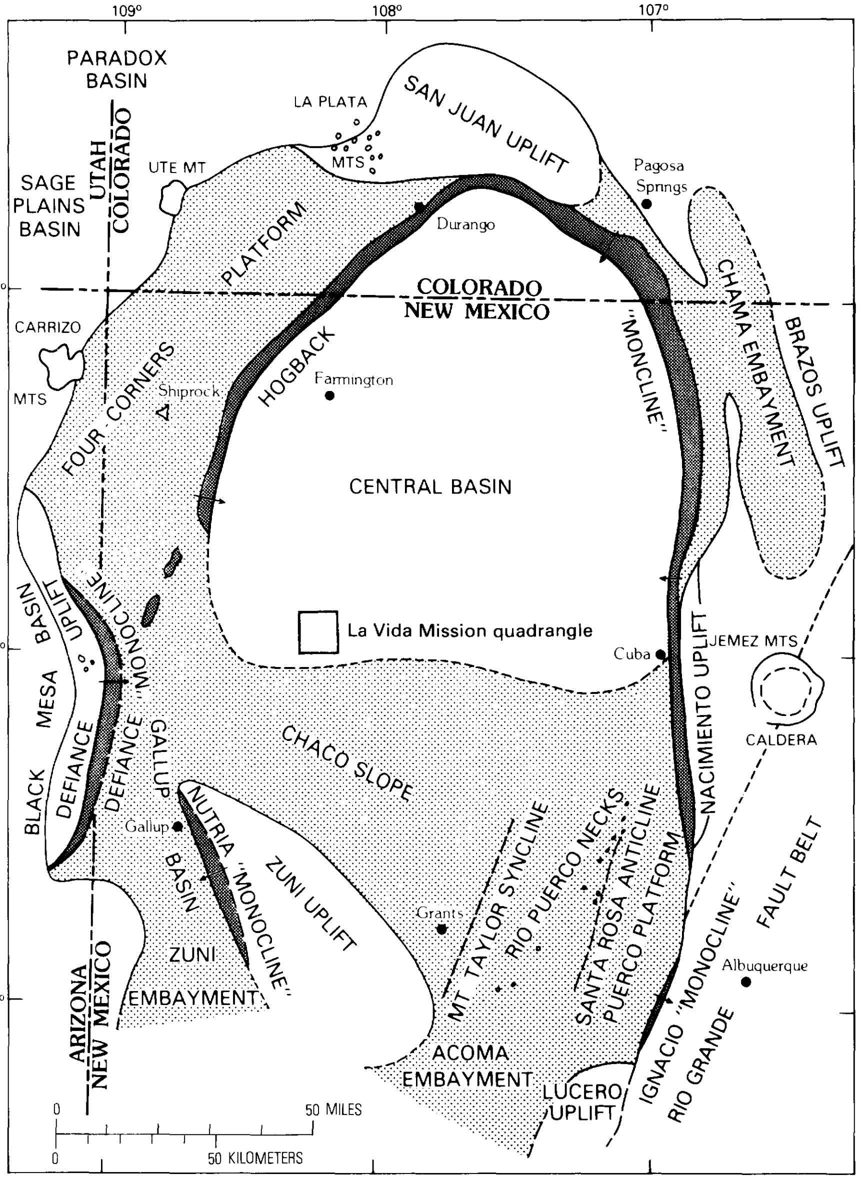


Figure 11. Structural elements of the San Juan Basin (modified from Kelley, 1951, p. 125).

STRUCTURE

The regional structural setting of the La Vida Mission quadrangle was described in the introductory section of this report. Within the quadrangle, the structure is monotonously uniform. Almost everywhere, beds incline very gently to the north to north-northeast. The dips are so low, however, that spot measurements with a Brunton compass are not feasible. Possible error in measurement exceeds the amount of dip to be measured. Calculations of dip on a regional scale likewise are difficult because of lack of key units within the Menefee Formation. Not only are the sandstone units lenticular and lithologically so uniform that correlation of units from one isolated exposure to another is hazardous, but distinctive units within the mudstone-siltstone parts of the Menefee that are recognizable with assurance from place to place are also lacking.

Structural Setting

The La Vida Mission quadrangle is in the southwestern part of the San Juan Basin, one of the major tectonic elements of the Colorado Plateau. The basin lies mostly in northwestern New Mexico, but it laps over into Colorado on the north and Arizona on the west. Kelley (1951) has shown the principal structural features of northwestern New Mexico and adjacent States in a New Mexico Geological Society guidebook. His figure, slightly modified, is reproduced here (fig. 11).

Kelley's figure shows that on three sides, prominent monoclines delimit an inner part of the San Juan Basin, which he called the Central Basin. On the south, however, no structural feature provides a recognizable margin of the Central Basin. Kelley recognized this deficiency, but stated that the area south of his Central Basin, which he named the Chaco Slope, "in part bears a regional relationship to the Central Basin similar to the platforms (on other sides). It differs from them, in its more pronounced regional inclination toward the center of the basin and by the absence of a monocline separating it from the Central Basin" (Kelley, 1951, p. 124–131).

The La Vida Mission quadrangle is near the south edge of the Central Basin as drawn by Kelley (fig. 11). As he noted, there is no flexure or other structure to mark this southern boundary. The implication of the word "slope" in "Chaco Slope" is, however, that dips to the south of the Central Basin are somewhat steeper than those to the north. Such proves not to be the case. Beds in the vicinity of the La Vida Mission quadrangle dip very gently to the north or north-northeast, as do those to the south in the Chaco Slope. Because of the absence of key horizons, discontinuous outcrops, and very gentle dips, it was impractical to directly measure the attitude of the beds over most of the La Vida Mission area. In the northern part of the quadrangle, however, a dip and strike calculated using the base of the Cliff House Sandstone at three widely separated localities gave a regional dip of 1.7° in a direction N. 13° E. Calculations using a deep well in the east-central part of the quadrangle and a series of drill holes located from close to the south border of the quadrangle southward across the Chaco Slope to Mariano Lake emphasize the evenness of the dip across the Chaco Slope and into the Central Basin (fig. 12). Because the concept of a Central Basin separated from a Chaco Slope is useful, even though not structurally valid, Kelley's arbitrary placement of the south margin of the Central Basin has precedence over any other, and is here accepted.

No faults, not even tiny ones, were seen within the quadrangle. The only fold noted is a very small anticline, the axis of which is shown on plate 1 in sec. 29, T. 22 N., R. 13 W. only a few score feet from the west edge of the quadrangle. A considerably larger anticline lies about a mile to the west of the La Vida Mission quadrangle in The Pillar 3 SE quadrangle.

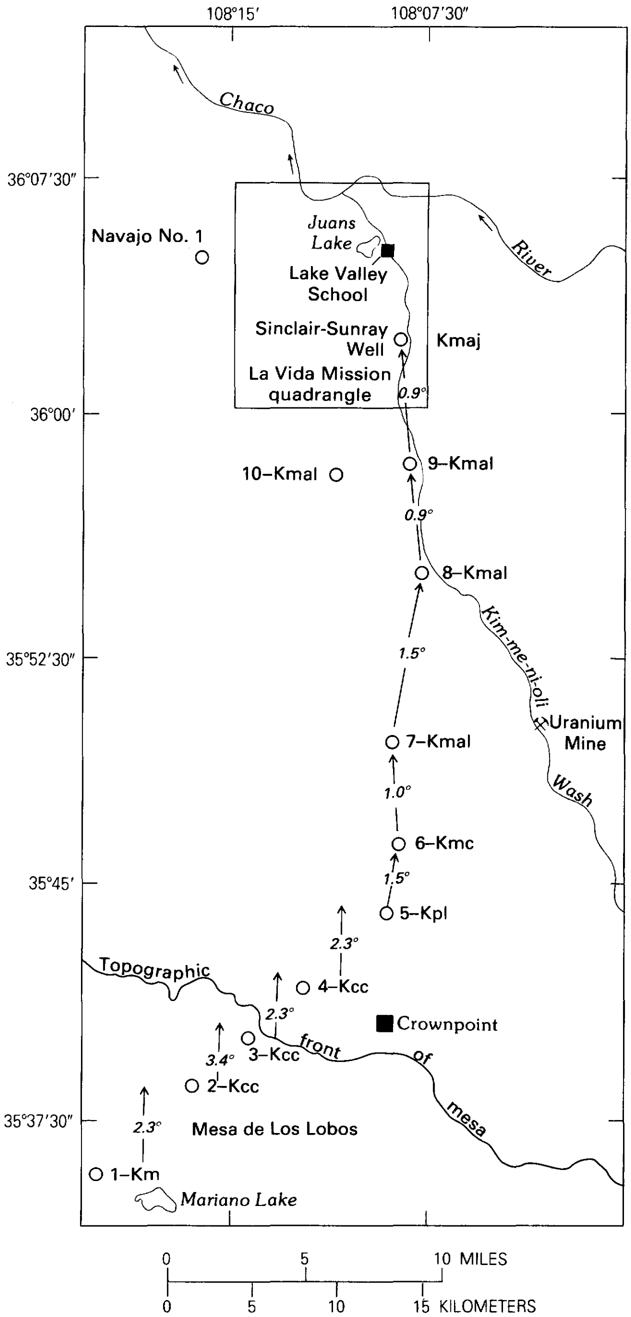


Figure 12. Location of drill holes 1–10 in Mariano Lake-Lake Valley drilling project of the U.S. Geological Survey. Map shows calculated dips between drill holes, between hole 9 and the Sinclair-Sunray well in La Vida Mission quadrangle, and the location of the Navajo No. 1 deep well in The Pillar 3 SE quadrangle. Map also shows the stratigraphic unit at the surface at each hole, as follows: Km, Mancos Shale; Kcc, Crevasse Canyon Formation; Kpl, Point Lookout Sandstone; Kmc, Cleary Coal Member of Menefee Formation; Kmal, lower beds of Allison Member of Menefee Formation; Kmaj, Juans Lake Beds of Allison Member of Menefee Formation.

STRATIGRAPHY

Concealed sedimentary rocks beneath the surface of the La Vida Mission quadrangle include formations of Mesozoic and Paleozoic age. At the south border of the quadrangle along Kim-me-ni-oli Wash they total about 8,520 ft (2,597 m) of concealed beds down to the Precambrian basement.

Data on the rocks making up this sequence have been gathered from rather voluminous literature, but the principal most reliable sources, because of close proximity to the quadrangle, are the lithologic logs of the Southern Union Gas Company Navajo No. 1 deep well located 1.4 mi (2.3 km) west of the quadrangle and a series of nine drill holes in the Mariano Lake-Lake Valley drilling project (fig. 12). Hole No. 10 is an offset of Hole No. 9. The lithologic log of the Navajo No. 1 well, drilled in 1952, was prepared by the American Stratigraphic Company (1952; Amstrat) and is based on samples from the Morrison Formation of Jurassic age to basement. The drill holes, constituting the Mariano Lake-Lake Valley drilling project of the USGS, were drilled in 1981. Sample and geophysical log studies of these holes were released in open file in 1981 (U.S. Geological Survey, 1981a and 1981b). The sequence of rocks penetrated include formations from near the middle of the Menefee Formation (Upper Cretaceous) to the base of the Morrison Formation (Jurassic). The lithology of these subsurface rocks, from basement to the middle of the Menefee Formation of Late Cretaceous age, is described briefly in the following sections and is shown in a generalized stratigraphic column (fig. 13).

Basement Rocks

The Navajo No. 1 well (fig. 13) penetrated 586 ft (179 m) into the basement, of which the lowest 466 ft (142 m) was included in the sample study by the American Stratigraphic Co., as shown in figure 13. Almost all the rock was recorded as gray, greenish-gray, or green quartzite, with minor amounts of slate, shale partings, and micaceous quartzite. The thickness of this quartzite sequence may not be as great as the drilled thickness because of structure. Nonetheless, the sequence must be thick because the drill was still in quartzite when the hole was abandoned.

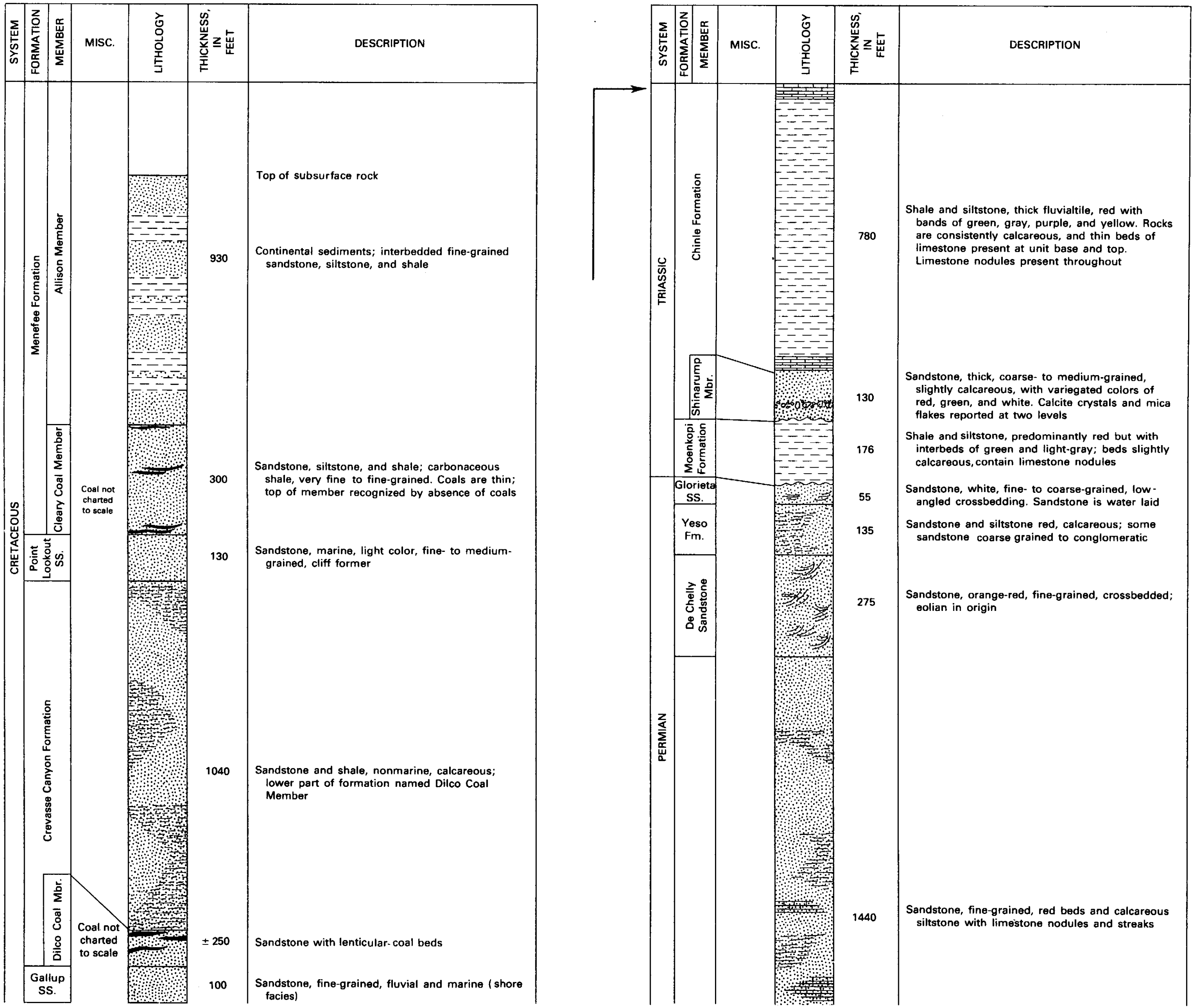
The regional affinity of this quartzite formation is uncertain. Woodward and others (1977) mentioned metaquartzite among other metamorphic rock types in the northwestern part of the Nacimiento Mountains some 75 mi (121 km) east of the La Vida Mission quadrangle. Northward, in the western part of the San Juan Mountains in southwest Colorado, Burbank (1940, p. 196) described the Precambrian Uncompahgre Formation as consisting of "massive to thin-bedded quartzite with minor shale partings; in wide bands alternating with slate or shale bands" and estimated that the formation may be 5,000 to 8,000 ft (1,524 to 2,438 m) thick. In the Animas River Valley in southwestern Colorado on the north flank of the San Juan Basin, the Ignacio Quartzite of Late Cambrian age is up to 200 ft (61 m) thick (Rhodes and Fisher, 1957), but is believed to pinch out in the northwestern corner of New Mexico (Lochman-Balk, 1972, figs. 8, 9). Whether the quartzite beds that were penetrated by the Navajo No. 1 well at the top of the basement are the correlative of the Uncompahgre, the Ignacio, or the quartzite in the Nacimiento Mountains is uncertain. The great thickness of the Uncompahgre and the apparent considerable thickness of the quartzite in the Navajo No. 1 well would seem to favor that correlation.

Rocks of Devonian Age

Rocks of Cambrian through Silurian age are not present in northwest New Mexico on the uplifts flanking the San Juan Basin to the east and west. In southwest Colorado, the Ignacio Quartzite of Late Cambrian age is present on the south and west flanks of the San Juan Mountains (Tweto, 1979) but as previously stated is believed to pinch out in the subsurface in northwesternmost New Mexico. Lochman-Balk (1972) showed the projected line of zero thickness lying northwest of the La Vida Mission quadrangle. No rocks of Ordovician or Silurian age are known in the region. The oldest rocks of Paleozoic age in the San Juan Basin of New Mexico other than the Ignacio are of Devonian age. In the Four Corners area (fig. 11), a subsurface dolomite formation of Late Devonian age was named the Aneth Formation and was described by Knight and Cooper (1955). They showed this formation pinching out in the northwest corner of New Mexico. They also described a basal sandstone member of the overlying Elbert Formation, also of Late Devonian age, which they named the McCracken Sandstone Member; this, too, pinches out or grades into undifferentiated Elbert beds in northwest New Mexico. The upper (or undifferentiated) part of the Elbert, consisting of dolomite interbedded with shale and siltstone, thins to the southeast in the basin. Baars (1972) showed the pinchout of the undifferentiated Elbert a few miles south of the La Vida Mission quadrangle, whereas Turnbow (1961) placed the pinchout approximately through the Navajo No. 1 well site and the La Vida Mission quadrangle. Unfortunately, the log of the well based on the sample studies of the American Stratigraphic Co. is blank from a depth of 8,561 ft (2,609 m) to well below the top of the basement (fig. 13), which is herein interpreted as being at a depth of 8,760 ft (2,670 m). The Late Devonian Elbert Formation, in its type area in La Plata County, Colo., includes interbedded variegated red shale, calcareous shale, limestone, sandy limestone and quartzite (Cross, 1904, p. 248). At its type section it is 54 ft (16 m) thick. In addition, "waxy" green shale is also included in the formation descriptions. Had samples been available from this interval in the Navajo No. 1 well, these lithologies would have been easily recognized. As it is, the presence of a thin Elbert Formation in the subsurface in this vicinity, possibly as much as 20 ft (6 m) thick, remains in doubt.

Rocks of Mississippian Age

Gene M. Stevenson, consulting geologist, Denver, Colo., has informed us (oral commun., 1984) that a


SYSTEM
FORMATION
MEMBER
MISC.
LITHOLOGY
THICKNESS, IN FEET
DESCRIPTION
CRETACEOUS
Menefee Formation
Allison Member
Top of subsurface rock
930
Continental sediments; interbedded fine-grained sandstone, siltstone, and shale
Cleary Coal Member
Coal not charted to scale
300
Sandstone, siltstone, and shale; carbonaceous shale, very fine to fine-grained. Coals are thin; top of member recognized by absence of coals
Point Lookout SS.
130
Sandstone, marine, light color, fine- to medium-grained, cliff former
Crevasse Canyon Formation
1040
Sandstone and shale, nonmarine, calcareous; lower part of formation named Dilco Coal Member
Dilco Coal Mbr.
Coal not charted to scale
± 250
Sandstone with lenticular-coal beds
Gallup SS.
100
Sandstone, fine-grained, fluvial and marine (shore facies)
TRIASSIC
Chinle Formation
780
Shale and siltstone, thick fluvialtile, red with bands of green, gray, purple, and yellow. Rocks are consistently calcareous, and thin beds of limestone present at unit base and top. Limestone nodules present throughout
Shinarump Mbr.
130
Sandstone, thick, coarse- to medium-grained, slightly calcareous, with variegated colors of red, green, and white. Calcite crystals and mica flakes reported at two levels
Moenkopi Formation
176
Shale and siltstone, predominantly red but with interbeds of green and light-gray; beds slightly calcareous, contain limestone nodules
PERMIAN
Glorieta SS.
55
Sandstone, white, fine- to coarse-grained, low-angled crossbedding. Sandstone is water laid
Yeso Fm.
135
Sandstone and siltstone red, calcareous; some sandstone coarse grained to conglomeratic
De Chelly Sandstone
275
Sandstone, orange-red, fine-grained, crossbedded; eolian in origin
1440
Sandstone, fine-grained, red beds and calcareous siltstone with limestone nodules and streaks

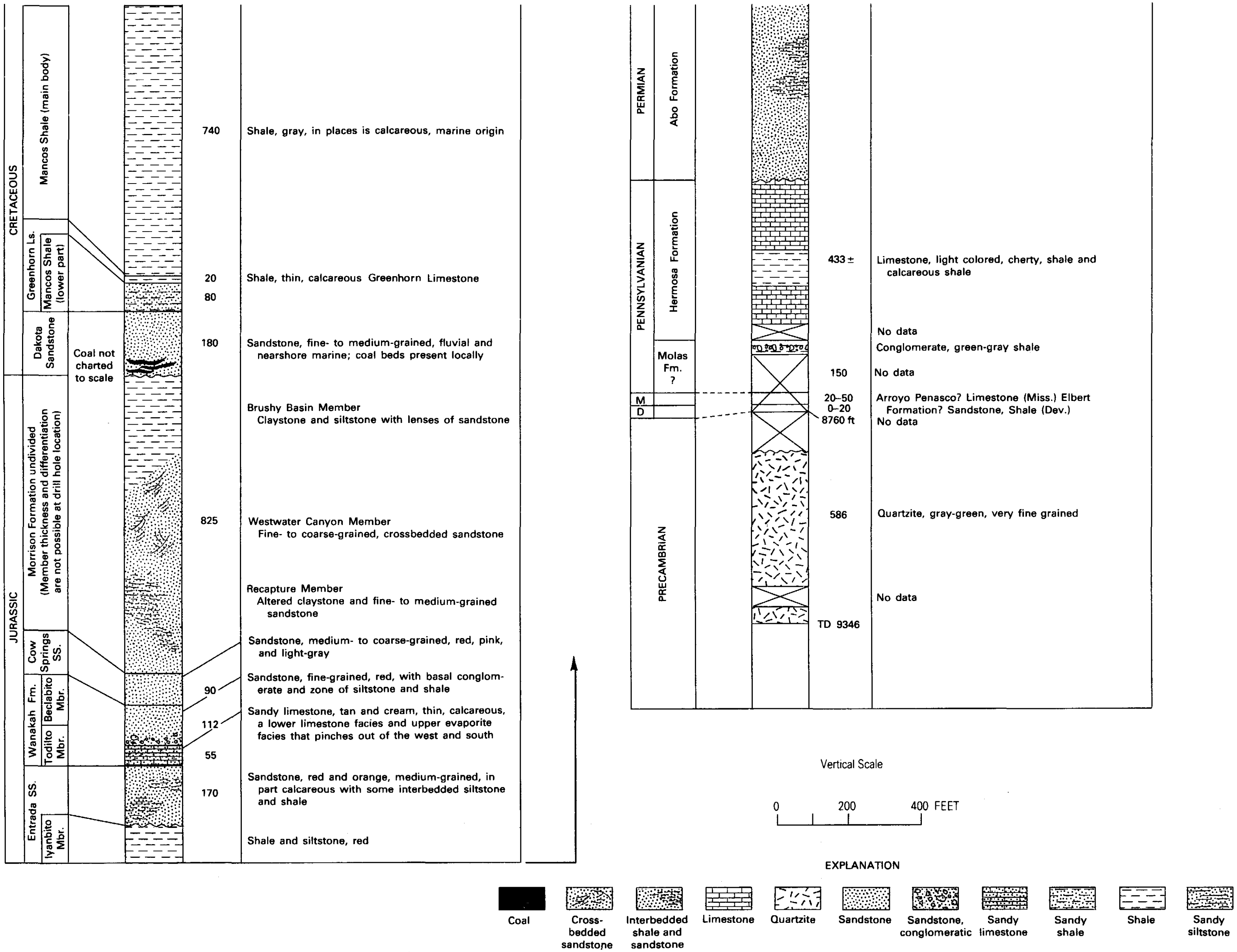


Figure 13. Stratigraphic column showing formations in the subsurface of La Vida Mission quadrangle. Pre-Morrison Formations modified from the log of the Southern Union Gas Company, Navajo No. 1 well (American Stratigraphic Company). Morrison and younger formations interpreted from sample and geophysical logs of the Mariano Lake-Lake Valley drilling project, holes 1–9. Hole 10 is an offset of hole 9 and was not used (U.S. Geological Survey). Lithologies shown in column are generalized.

limestone unit closely overlies the basement in the central San Juan Basin. Based on fossil evidence, he believes that the limestone is almost surely of Mississippian age. His studies of electric and other geophysical logs of deep wells have produced a signature for this unit. He recognized the same signature in the logs of the Navajo No. 1 well, with a top not more than 50 ft (15 m) above basement. In another well 28 mi (45 km) northeast of Navajo No. 1, he stated that the limestone is about 90 ft (27 m) thick. If the Devonian Elbert Formation (previously discussed) is not present directly above basement in the Navajo No. 1 well, a Mississippian limestone thus may be the oldest Paleozoic formation in the vicinity of the La Vida Mission quadrangle, and may be up to 50 ft (15 m) thick. In the columnar section (fig. 13), however, we have assumed up to 20 ft (6 m) of Elbert, leaving a 30-ft (9-m) interval for the limestone unit.

Formations of Mississippian age (Osage age, at least in part) are well documented on the west side of the San Juan Basin in Arizona (Redwall Limestone, *in* McKee and Gutschick, eds., 1969), on the north side of the basin in southwestern Colorado (Leadville Limestone, *in* Armstrong, 1976), and on the Nacimiento Uplift on the east side of the San Juan Basin near Cuba (Arroyo Penasco Formation, *in* Armstrong and Mamet, 1974). Stevenson's subsurface data, cited above, indicate that the sea in which the Mississippian limestone was deposited extended at least as far south in the San Juan Basin as the Navajo No. 1 well. Thus, the seaway probably was connected across the basin from northeast Arizona (Redwall area) to north-central New Mexico (Arroyo Penasco area). These relations can be readily visualized by reference to figure 5 in the Mississippian section of the "Geologic Atlas of the Rocky Mountain Region" (Craig, 1972), although Craig showed the Redwall and Arroyo Penasco seas separated by a land barrier.

Rocks of Pennsylvanian Age

Samples were available for study from the Navajo No. 1 well from a depth of 8,561 to 8,600 ft (2,609 to 2,621 m) (fig. 13). These beds were described in the Amstrat log as consisting of a conglomerate at the top underlain by green, gray, and red shale. These lithologies fit the Molas Formation of Early Pennsylvanian age. The "conglomerate" at the top of the sample interval, at a depth of 8,561 ft (2,609 m), may represent the top of the Molas and may be similar to the "fragments (at the base of the Hermosa Formation) reworked from the underlying Molas" described by Jentgen (1977, p. 129). If the Mississippian limestone and Elbert Formation(?) do not exceed 50 ft (15 m) in thickness, as suggested by Stevenson (oral commun.), then the Molas in the well, and probably also beneath the La Vida Mission quadrangle, may approximate 150 ft (46 m) in thickness.

The Hermosa Formation of Middle and Late(?) Pennsylvanian age overlies the Molas Formation and is widespread in the Four Corners region. It consists of light-colored limestone, cherty limestone, calcareous shale, and shale. In western Colorado and eastern Utah, evaporites (the Paradox Member) are included in the Hermosa, but this facies pinches out in the northern part of the San Juan Basin (Jentgen, 1977). In the Navajo No. 1 well, white to light- and medium-gray limestone is interbedded with light- and medium-gray shale. A little of the shale is described as brown and red. Sandy shale is also mentioned. The thickness of the Hermosa as identified from samples from the Navajo No. 1 well is 377 ft (115 m). If, however, the Molas-Hermosa contact lies at 8,561 ft (2,609 m), the bottom of a 56-ft (17-m) blank interval, as suggested above, then the full thickness of the Hermosa is 433 ft (132 m).

Rocks of Permian Age

Rocks of Permian age in the San Juan basin are extensive and thick. They represent predominantly clastic sediments being shed from rising positive elements, particularly from the Uncompahgre Uplift to the north in Colorado, but to a lesser extent from the Defiance Uplift to the west (Baars and Stevenson, 1977). Isopach maps of Baars and Stevenson indicate that the total thickness of Permian sediments in the area of the La Vida Mission quadrangle is on the order of 1,835 ft (559 m). This is in remarkably close agreement with the thickness in the Navajo No. 1 well, where rocks of Permian age were recorded in the lithologic log as being 1,905 ft (581 m) thick. The Amstrat log divides the rocks of Permian age into a thick Coconino Formation below and a thinner Cutler Formation above. However, four formations, which have been described from outcrops around the margins of the basin, are believed identifiable in the log. These are, in ascending order, the Abo Formation, De Chelly Sandstone, Yeso Formation, and Glorieta Sandstone. In the well, the Abo is a red-bed formation consisting of fine-grained sandstone and calcareous siltstone with limestone nodules and streaks of limestone. Beds of anhydrite also are recorded between 200 and 400 ft (61 and 122 m) above the base. The formation is probably about 1,440 ft (439 m) thick. The overlying De Chelly Sandstone is an orange-red, fine-grained, crossbedded sandstone about 275 ft (84 m) thick. The Yeso Formation, about 135 ft (41 m) thick, is composed of red calcareous sandstone and siltstone. Some of the sandstone is coarse grained to conglomeratic. At the top of the Permian sequence is the Glorieta Sandstone, a white, fine- to coarse-grained sandstone with low-angle crossbedding. In the La Vida Mission area, the Glorieta is probably about 55 ft (17 m) thick (Baars and Stevenson, 1977, fig. 4), of which the lower 30 ft (9 m) consists of coarse sandstone having a porosity between 12 and 20 percent. The Glorieta is water laid (Baars and

Stevenson, 1977, p. 136), whereas the older De Chelly Sandstone is of eolian origin.

Rocks of Triassic Age

Three stratigraphic units of Triassic age are present in southeastern Utah, adjacent Colorado, and northeastern Arizona. These are, in ascending order, the Moenkopi Formation, Shinarump Conglomerate, and Chinle Formation. In 1957, the Shinarump was designated a member of the Chinle Formation (Stewart, 1957).

The Moenkopi Formation and the Shinarump Member of the Chinle were believed to be absent in the heart of the San Juan Basin (McKee, 1954; McKee and Gutschick 1959; O'Sullivan, 1977), although O'Sullivan recognized a red-bed unit in the Zuni Mountains on the south flank of the basin as a possible correlative of the Moenkopi of Arizona. In the Amstrat log of the Navajo No. 1 well, a red-bed unit 176 ft (54 m) thick was designated as Moenkopi, and the overlying 130 ft (40 m) of predominantly coarse sandstone as Shinarump. This identification of the units is tentatively accepted here, and they are described below.

Rocks in the well assigned to the Moenkopi Formation consist of shale and siltstone, predominantly red, but with interbeds of green and light gray. The beds are slightly calcareous and contain limestone nodules. Abundant observations of the formation at the surface on the west side of the San Juan Basin confirm that the formation lies unconformably on rocks of Permian age. The Moenkopi is overlain unconformably by the Shinarump Member of the Chinle Formation. If the assignment of the red beds in the subsurface near the La Vida Mission quadrangle to the Moenkopi proves to be correct, the limits of the formation as previously shown on isopach maps (McKee, 1954, fig. 7; McKee and others, 1959, pl. 3, fig. 1; Stewart and others 1972, pl. 4A; O'Sullivan, 1977, fig. 2) will need to be moved south and east of the Navajo No. 1 well and probably also south and east of all of the La Vida Mission quadrangle.

The Shinarump Member of the Chinle Formation unconformably overlies the Moenkopi Formation. In the Navajo No. 1 well it is 130 ft (40 m) thick and consists of coarse- and medium-grained, slightly calcareous sandstone with variegated colors of red, green, and white. Mica flakes were reported at two levels, as were calcite crystals. No conglomerate pebbles were noted in the log, but otherwise the lithology of this unit and its stratigraphic position seem to fit well the designation of these beds as Shinarump.

The main body of the Chinle Formation is thick and widespread in the Four Corners region. It is believed to underlie all of the San Juan Basin, although its presence has not been established by drilling in the deepest part of the basin (McKee and others, 1959). It has been divided into members that have various names in different areas around the San Juan Basin. In the Navajo No. 1 well, however, data are not sufficient to recognize and define members. In general, the formation consists of fluviatile shale and siltstone, predominantly red, but with some bands of green, gray, purple, and yellow. There are several gaps in the record of the well, but the recorded lithologies show much more shale than siltstone. The rocks are consistently calcareous, and thin beds of limestone are present in the lowest 30 ft (9 m) and uppermost 70 ft (21 m). Limestone nodules or concretions are numerous throughout. The marked contrast in grain size and the presence of the limestone beds and nodules in the main body of the Chinle readily distinguish it from the underlying Shinarump Member and the overlying Entrada Sandstone. In the log of the well, the Chinle exclusive of the Shinarump Member is 780 ft (238 m) thick, although the exact placement of the upper contact was questioned. The total thickness of the Triassic rocks (Moenkopi, Shinarump Member, and Chinle) near the La Vida Mission quadrangle thus is 1,086 ft (331 m). This is considerably less than the thicknesses shown on isopach maps of the region. McKee and others' (1959) figure is about 1,300 ft (396 m), O'Sullivan's (1977) figure is about 425 m (1,394 ft), and Wengerd's (1950) figure is about 2,000 ft (610 m). The differences in thickness estimates may represent, in part, actual changes in thickness of the formation from locality to locality or inadequate data to control projections of thickness lines.

Rocks of Jurassic Age

Jurassic rocks crop out at the margins of the San Juan Basin—to the east and south in New Mexico, to the west in New Mexico and northeastern Arizona, and to the north in southwestern Colorado—and have been penetrated in numerous drill holes in the central part of the basin. In the four marginal areas, stratigraphic columns differ, as do some of the stratigraphic names. The area of outcrop closest to the La Vida Mission quadrangle lies to the south along the north flank of the Zuni Uplift. In this area, the lithologic sequence underlying the Dakota Sandstone in gross character seems to match quite well the Jurassic beds in the Navajo No. 1 well.

In recent decades, extensive stratigraphic work in the Grants-Zuni region in connection with uranium exploration and production has been summarized in a paper by Condon and Peterson (1986). Their columns for the San Juan Basin are reproduced here in figure 14. The column for the southern area is closest to the La Vida Mission quadrangle. In this column, the formation and member names Entrada, Todilto, Cow Springs, Morrison, Recapture, Westwater Canyon, and Brushy Basin are well known because of abundant literature describing these rocks in the southern Colorado Plateau. Less well known are the names Iyanbito, Wanakah, and Beclabito. Iyanbito, a member of the

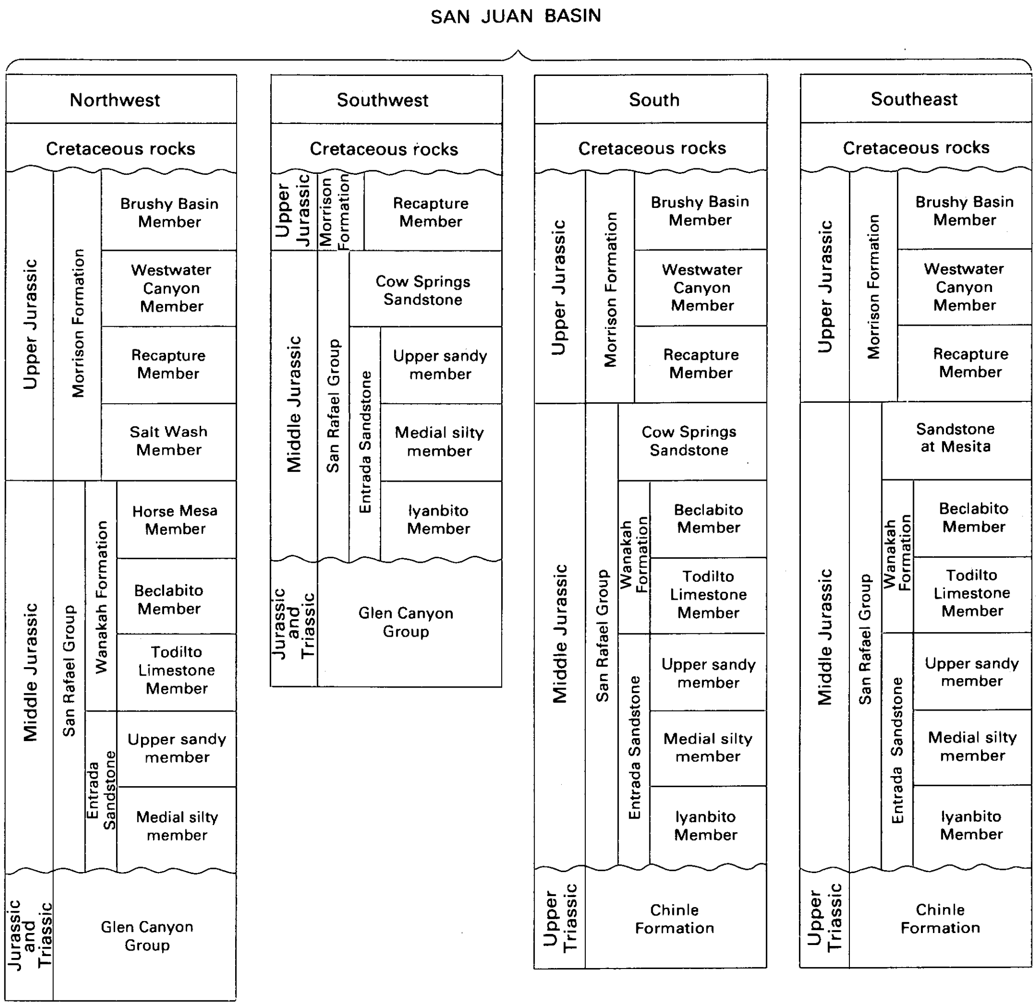


Figure 14. Nomenclature currently used by the U.S. Geological Survey for Jurassic rocks on the south side of the San Juan Basin. (Condon and Peterson, 1986, fig. 2, in part.)

Entrada Sandstone, consists of a sandstone and siltstone sequence lying unconformably above the Chinle Formation of Late Triassic age and conformably below the middle siltstone member of the Entrada of Late Jurassic age (Green, 1974, p. D1). The Wanakah originally was named and designated (Burbank, 1940) a lower member of the Morrison Formation in the Ouray Mining District of Colorado. Later the name Wanakah Formation was applied in northwestern New Mexico to the highest unit of the San Rafael Group (Baker and others, 1947, p. 1668), and is recently being used to include calcareous beds, the Todilto Limestone Member at the base, and a heterogeneous assemblage of sandstone, siltstone, and shale, the Beclabito Member, above (Condon and Peterson, 1986).

In the Amstrat lithologic log of the Navajo No. 1 well (fig. 13), the unit overlying the Chinle consists of 95 ft (29 m) of red siltstone and shale, somewhat calcareous. These beds may be equivalent to the Iyanbito Member of the Entrada (Green, 1974). They are overlain by red and orange medium-grained sandstone, in part calcareous, with a little interbedded siltstone and shale. This unit, the main body of the Entrada, is 170 ft (52 m) thick. A sandy limestone unit, 55 ft (17 m) thick, overlying the Entrada fits the description of the Todilto Member of the Wanakah Formation, and the next higher unit of sandstone, siltstone, and shale 112 ft (34 m) thick, appears to match the Beclabito Member of the Wanakah. In the Amstrat log of this interval, a few feet of "pink conglomerate" are recorded at the base of the Beclabito. A massive unit overlying the Beclabito consists of red, pink, and light-gray, medium- to coarse-grained sandstone and is 90 ft (27 m) thick. This is tentatively assigned to the Cow Springs Sandstone, although it may be equivalent to the Horse Mesa Member of the Wanakah, with which the Cow Springs interfingers (Condon and Peterson, 1986, fig. 4a and p. 17).

The Morrison Formation is widespread in the Rocky Mountains-Colorado Plateau region and is hundreds of feet thick in the San Juan Basin. In New Mexico, it is divided into four members, of which the Salt Wash Member is present only in the northern and northwestern parts of the basin (Condon and Peterson, 1986, p. 21). The overlying members are described by Condon and Peterson (1986, p.

21–23) as follows: (1) Recapture Member—a heterogeneous mixture of sandstone, siltstone, mudstone, claystone, and limestone; (2) Westwater Canyon Member—feldspathic sandstone; and (3) Brushy Basin Member—a heterogeneous unit of claystone, mudstone, and sandstone. These lithologies are recorded in the Amstrat log of the Navajo No. 1 well, but the lithologic descriptions are not precise enough to designate boundaries between the members. In general, the lower part of the Morrison in the well corresponds to the Recapture Member, the middle part to the Westwater Canyon Member, and the upper part to the Brushy Basin Member. The total thickness of the Morrison in the Navajo No. 1 well is 825 ft (251 m). A summary report on the Morrison Formation based on geophysical logs obtained as part of the Mariano Lake-Lake Valley drilling project (Kirk and others, 1986) gives geophysical characteristics of the Morrison in holes 1 through 7–7A (fig. 12), but holes 8–10 did not penetrate the Morrison. Holes 7–7A are 12 mi (19 km) south of the La Vida Mission quadrangle (hole 7A is an offset of hole 7). In hole 6, the northernmost hole that penetrated all of the Morrison, the total thickness of the formation is approximately 720 ft (219 m), in contrast with the 825 ft (251 m) in the Navajo No. 1 well, suggesting that the formation thickens in a northward direction.

Rocks of Late Cretaceous Age

Rocks of Early Cretaceous age are not present in most of the San Juan Basin, including the La Vida Mission area, but Upper Cretaceous rocks are at the surface over much of the basin. They have been the subject of many papers by numerous geologists since the years when rocks of this age were grouped into three major formations: the Dakota Sandstone (Meek and Hayden, 1861), the Mancos Shale (or group) (Cross, 1899), and the Mesa Verde Formation (or group) (Holmes, 1877). The consensus is that the Cretaceous seas advanced from northeast to southwest across the San Juan Basin several times, retreating each time, which resulted in a complex stacking of marine and continental sediments. The sequences vary from locality to locality, and the lithologic units within the sequences vary in thickness from locality to locality. Many writers have described parts of this complex for the areas of their studies in the basin, and formal stratigraphic names have been applied to some of the stratigraphic units.

The proliferation of papers on the Mesaverde Group alone within the San Juan Basin is a measure of (1) the complexity of the interlayered and intertonguing relations, (2) the numerous stratigraphic changes over relatively short distances within the basin, (3) the great thicknesses of most mapped units, whether formal or informal, (4) the need to recognize thinner units and to apply names, whether formal or informal, in order to prepare meaningful bedrock geologic maps and sections, (5) the economic importance of these rocks because of the resources of oil and gas, coal, and uranium in the basin, and (6) the excellent preservation of sedimentary structures, including trace fossils, and other evidence on paleodepositional environments.

Among the many authors who have published on the Late Cretaceous of the San Juan Basin, contributions of the following are of particular relevance to understanding the stratigraphy of the La Vida Mission region: Reeside (1924), Sears (1925), Dane (1936), Sears, Hunt, and Hendricks (1941), Pike (1947), Silver (1951), Cobban and Reeside (1952), Beaumont, Dane, and Sears (1956), Weimer (1960), Baltz, Ash, and Anderson (1966), O'Sullivan, Repenning, Beaumont, and Page (1972), Landis, Dane, and Cobban (1973), Molenaar (1977), and Fassett (1977).

Major Late Cretaceous units that probably are present in the subsurface of the La Vida Mission area include the Dakota Sandstone, Mancos Shale, Gallup Sandstone, Crevasse Canyon Formation with the Dilco Coal Member at the base, Point Lookout Sandstone, and the lower half of the Menefee Formation with the Cleary Coal Member at the base. These formations in the subsurface are best known from the 10 holes (fig. 12) comprising the Mariano Lake-Lake Valley drilling project (USGS Open-File Reports 81–1201 through 81–1210). The holes are spread along a dogleg line from hole 1, which is 28 mi (45 km) south of the La Vida Mission quadrangle, to hole 9, which is 1.8 mi (2.9 km) south of the quadrangle. Hole 10 is an offset to hole 9. In the reports on these rocks, logging of the lithologies and thicknesses was based on studies of the well cuttings because no coring was done in this part of the section. Consequently, the information gained, though very useful, cannot be expected to be precise.

Dakota Sandstone

The Dakota Sandstone of the southwestern San Juan Basin is predominantly a fine- to medium-grained sandstone. In many regions it has been broken into members, but subsurface information for areas in or near the La Vida Mission quadrangle is inadequate to subdivide the formation. Coal beds are present locally, as shown in the drill-hole records. In hole 8, however, which is the hole closest to the La Vida Mission quadrangle that penetrated the Dakota, no coal beds were noted. In this hole, the Dakota is 180 ft (55 m) thick, but it ranges from 220 ft (67 m) to 120 ft (37 m) in the holes to the south, probably in part because of relief on the top surface of the Morrison Formation, on which it is deposited. In contrast with drill hole 8, the Amstrat log of the Navajo No. 1 well, which included only the lower part of the Dakota, recorded two coal beds. The thickness of these beds was indeterminate.

Mancos Shale

The Mancos Shale is a thick formation consisting predominantly of gray marine shale, but with a thin but persistent calcareous unit in its lower part. This calcareous unit, formerly called the Greenhorn Limestone (Greh. in fig. 13), has been renamed the Bridge Creek Limestone Member of the Mancos (Kirk and others, 1986). It appears to be continuous from hole 1 near Mariano Lake, 28 mi (45 km) south of the La Vida Mission quadrangle, to at least as far north as hole 8, 7 mi (11 km) south of the quadrangle. Farther north, holes 9 and 10 did not reach the Bridge Creek, but it was identified on the driller's log of Tidewater Oil Company's No. 1 Santa Fe "D" (1 mi (1.6 km) west of the La Vida Mission quadrangle (sec. 7, T. 21 N., R. 12 W.). The log placed the top of the "Greenhorn" 101 ft (31 m) above the top of the Dakota. This evidence suggests that the Bridge Creek calcareous beds may be ±20 ft (6 m) thick beneath the La Vida Mission quadrangle, with the tongue of underlying Mancos Shale, about 80 ft (24 m) thick, separating it from the Dakota Sandstone. The uppermost part of this tongue appears to be a sandstone or sandy shale.

The main body of the Mancos Shale overlying the "Greenhorn" consists of gray marine shale, in places calcareous. In hole 8 it is 740 ft (226 m) thick. A limestone unit, the Juana Lopez (Sanastee) Member of the Mancos, a little below the middle of the formation, was recognized in drill holes 2, 3, and 4 between 21 and 25 mi (34 and 40 km) south of the La Vida Mission quadrangle. It was not recorded on the lithologic log of holes closer to the La Vida Mission quadrangle that penetrated all of the Mancos, but was identified on the electric log of the Sinclair-Sunray well within the quadrangle (SE sec. 18, T. 21 N., R. 12 W.). In this well, tops of the "Sanastee" and "Greenhorn" were picked (interpreter unknown) at elevations of +2,943 and +2,575 ft (897 and 785 m) A.T., respectively.

Gallup Sandstone

Overlying the main body of the Mancos Shale is the Gallup Sandstone, a cliff-maker at the surface. It is a fine-grained fluvial sandstone. In the subsurface northward from the type area near Gallup, it is a little more than 100 ft (30 m) thick in drill holes near the La Vida Mission quadrangle. In the Sinclair-Sunray well, within the La Vida Mission quadrangle (sec. 18, T. 21 N., R. 12 W.), Molenaar (1983b, figs. 10 and 16, control point no. 105) reported a thickness of about 90 ft (27 m). Along the south edge of the quadrangle the top of the Gallup is at an elevation of about 3,700 ft (1,128 m) above sea level and at a depth of about 2,300 ft (701 m) where Kim-me-ni-oli Wash enters the quadrangle.

Crevasse Canyon Formation

The beds overlying the Gallup Sandstone up to the next prominent sandstone unit, the Point Lookout Sandstone, are named the Crevasse Canyon Formation (Allen and Balk, 1954; Beaumont and others, 1956). This formation consists predominantly of nonmarine sandstone and shale, much of which is calcareous (U.S. Geological Survey, 1981). The lower, coal-bearing part of the Crevasse Canyon Formation is named the Dilco Coal Member. Two coal beds were noted in the Dilco in the cuttings of hole 10, 2 mi (3.2 km) south of the La Vida Mission quadrangle (fig. 12). They are approximately 200 and 300 ft (61 and 91 m), respectively, above the Gallup Sandstone. Their thicknesses are indeterminate. In drill holes to the south (holes 2–8), as many as three coal beds were encountered in this interval. The Dilco Coal Member probably contains coal beds beneath the La Vida Mission quadrangle, but because the unit lies at a depth of about 2,000 ft (610 m) at the south edge of the La Vida Mission quadrangle and is still deeper northward, coal beds of the Dilco are of little current economic interest. In drill hole 10, the Crevasse Canyon Formation, including the Dilco Coal Member, is about 1,040 ft (317 m) thick.

Point Lookout Sandstone

The Point Lookout Sandstone, which overlies the Crevasse Canyon Formation, is a prominent cliff-maker at the surface and is readily identifiable in drill holes north of Crown Point (fig. 12). It consists of light-colored, fine- and medium-grained marine sandstone. In the La Vida Mission region, the Point Lookout is probably about 130 ft (40 m) thick, and is at a depth of about 1,300 ft (396 m) below the surface where Kim-me-ni-oli Wash crosses the south border of the La Vida Mission quadrangle.

Menefee Formation

The Menefee Formation is areally the most extensive Cretaceous formation at the surface in the New Mexico part of the San Juan Basin. It crops out in a narrow belt from the Colorado border southward for nearly 60 mi (97 km) past Shiprock to the town of Newcomb on U.S. 666 (fig. 9). From Newcomb, the belt swings southeastward and widens to nearly 25 mi (40 km). The La Vida Mission quadrangle is in the northern part of this wide belt. The rocks in this region dip very gently north to north-northeast. Approximately the lower half of the formation is in the subsurface beneath the quadrangle, and the upper half forms the surface rock over most of the quadrangle.

The Menefee Formation was named from Menefee Mountain in the southwest corner of Colorado. At the type locality, Collier (1919) described the formation as consisting of about 400 ft (122 m) of beds of sandstone, shale, and coal, in the ratio 55 percent shale, 42 percent sandstone, and 2 to 3 percent coal. The coal is present "in many beds which vary greatly in thickness from place to place" (Collier, 1919, p. 296). In this area the formation overlies a massive sandstone that Collier named the Point Lookout Sandstone, and underlies another sandstone that he named the Cliff House Sandstone. In southwestern Colorado and in the San Juan Basin, these together constitute the Mesaverde

Group, a name first proposed by Holmes (1877) as the Mesa Verde Group.

Many papers on New Mexico have dealt with the rocks assigned to the Menefee Formation, especially in the southern and southeastern parts of the basin. The nomenclature applied by various authors, particularly Sears (1925, 1934), Dane (1936, 1948), and Beaumont (1955), was reviewed and discussed by Beaumont, Dane, and Sears (1956). From this analysis there resulted a nomenclatorial scheme in which the Menefee was divided into two members. A coal-bearing lower member, some 250 to 300 ft (76 to 91 m) thick, was named the Cleary Coal Member. These beds previously had been called the "lower coal-bearing member of the Menefee" (Hayes and Zapp, 1955), in an area in the northwestern part of the San Juan Basin. They also constituted the upper part of the Gibson Member of the Mesaverde Formation of Sears (1925) and of Dane (1936). The remainder of the Menefee, the so-called "barren" member, was to retain the name Allison Member (Beaumont and others, 1956, p. 2157), first proposed by Sears (1925). Dane (1936, p. 95–96), in describing the La Ventana-Chacra Mesa coal field, stated:

> As the top of the Allison Member was not defined, it seems a legitimate extension of the term to apply it to all the continental beds above the Gibson coal member and below the marine sandstone members [Cliff House Sandstone] at the top of the Mesa Verde Formation. This usage includes in the Allison some coal beds in the upper part of the member, whereas the member was originally defined as barren of coal. However, the coal-bearing part of the member does not have the stratigraphic continuity or thickness to warrant its separation as a member, and the coal-bearing beds belong genetically to the continental type of sediments of which the Allison is composed, not to the marine sandstones that overlie them. As a convenient and practicable terminology, therefore, the writer [Dane] uses the name "Allison Member" for all the continental beds of the Mesaverde Formation above the Gibson Coal Member [or Cleary Member of the Menefee of Beaumont where the Point Lookout Sandstone is present].

This usage has been adhered to by recent authors. The total thickness of the Menefee Formation in the vicinity of the La Vida Mission quadrangle is believed to be about 2,175 ft (663 m) based on the driller's log of two wells drilled for oil and one water well within the quadrangle, and on long measured sections of the Menefee beds by Miller and Kirschbaum (Miller, 1984, p. A37–A39, A42–A47). The lower 1,045 ft (319 m) of the formation are in the subsurface at the south border of the quadrangle, and the upper 1,130 ft (344 m) crop out within the quadrangle.

The lower half of the Menefee Formation forms the surface rocks from the south border of the quadrangle for 17 mi (27 km) southward almost to Crownpoint. Because of low dip, low topographic relief, and poor exposures, measurements of surface sections of this part of the Menefee are impractical. Much information on these beds, however, recently became available from the USGS Mariano Lake-Lake Valley 10-hole drilling program (fig. 12). The holes average about 4.5 mi (7.2 km) apart. In the northernmost five holes, the Menefee was penetrated.

Cleary Coal Member

The Cleary Coal member at the base of the Menefee is identified by its coal content. Each of the four drill holes that penetrated all of the Cleary show one or more coal beds in the lowest 30 ft (9 m) above the Point Lookout Sandstone (U.S. Geological Survey Open-File Reports 81–1201, 1204–06). Above that, a few thin coals are present in the next 600 ft (183 m) of beds, but no two holes showed similar stratigraphic position or spacing of these higher coal beds. Kirk and Zeck (oral commun., 1983), on the basis of interpretation of the geophysical log of hole 10, indicated the top of the Cleary above a zone of carbonaceous shale 275 ft (84 m) above the base of the member, although two presumably thin higher coals were present in the overlying 225 ft (69 m) of beds. Because the top of the Cleary is tied by definition to the top of the coal-bearing (or carbonaceous shale-bearing) part of the lower Menefee and because the coal beds and (or) carbonaceous shale zones above the lowest 30 ft (9 m) are clearly lenticular and of limited extent, it results that the placement of the contact between the Cleary Coal Member and the overlying Allison Member varies from place to place. In drill holes 9 and 10, which are closest to the La Vida Mission quadrangle, a coal bed of unknown thickness about 300 ft (91 m) above the Point Lookout Sandstone and 25 ft (8 m) above the zone of carbonaceous shale of Kirk and Zech seems to be an acceptable local marker for the top of the Cleary. Other than the beds of coal and carbonaceous shale, the bulk of the Cleary consists of interbedded very fine to fine-grained sandstone, siltstone, and shale (U.S. Geological Survey, 1981). Black and red chert fragments reported in some samples represent ironstone concretions.

In northwesternmost New Mexico north of the San Juan River, Hayes and Zapp (1955) mapped a threefold division of the Menefee: lower and upper coal-bearing members separated by a barren member. They assigned a thickness of 100 ft (30 m) to the lower member, which, because of its stratigraphic position, they probably would have named the Cleary Member had their publication not predated the naming of the Cleary in 1956. Hayes and Zapp's mapping of their lower member was facilitated by thick coal beds and extensive mining. Because of the problem presented in selecting a top for the Cleary, the member seems not to have been mapped separately on any published maps elsewhere around the San Juan Basin. Coal-bearing beds in the lowest part of the Menefee Formation that would represent a Cleary Member probably are present beneath the La Vida Mission quadrangle, but placement of the coals above the Point Lookout Sandstone and their thicknesses are not known.

Lower Beds of Allison Member (Concealed Part)

By arbitrarily assigning a thickness of 300 ft (91 m) to the Cleary Coal Member, the subsurface part of the overlying Allison Member beneath the La Vida Mission quadrangle is approximately 735 ft (224 m) thick. These beds form the surface rocks from near the south border of the quadrangle for about 16 mi (26 km) to the south. They constitute the unnamed lower beds of the Allison (Miller, 1984, p. A47). No detailed surface mapping and no stratigraphic studies have been made of this part of the Allison Member in this region. It is distinguished from the underlying Cleary by complete absence of, or by rare thin beds of, coal or carbonaceous shale. It is distinguished from the overlying Juans Lake Beds of the Allison Member by its lack of calcareous concretions. The sample studies of drill holes 7–10 of the Mariano Lake-Lake Valley project show that the lithologic constituents of this part of the Allison Member are fine-grained sandstone, siltstone, and gray mudstone the proportions of which are not known. At the surface, some of the sandstone units crop out as low ledges, but prominent cliffs, mesas, and buttes are uncommon, in contrast with the more rugged topography of the La Vida Mission quadrangle. This difference is due largely to greater distance from major drainages but is due partly to fewer and thinner sandstone units.

Allison Member (Outcropping Part)

The outcropping bedrock formations of the La Vida Mission quadrangle consist of the upper half of the Menefee Formation and the Cliff House Sandstone. The total thickness of this sequence is about 1,380 ft (421 m), of which 1,130 ft (344 m) comprise the upper part of the Allison Member of the Menefee Formation and 250 ft (76 m) the Cliff House Sandstone, including a tongue of the Menefee within the Cliff House.

Several authors, including Dane (1936) and most recently Molenaar (1977), have noted that the uppermost part of the Allison Member contains coal beds. Molenaar commented (1977, p. 164), "the upper part of the Allison is very carbonaceous and coaly. This zone is sometimes referred to as the upper coal-bearing unit of the Menefee." In a companion paper in the same publication, Peterson and Kirk (1977, fig. 2), in a restored stratigraphic section, divided the Menefee into three members in the general area here considered. These are the lower coal member, middle barren member, and upper coal member. To the southwest, the lower coal member is shown in the same position above the Point Lookout Sandstone but slightly overlapping the Cleary Coal Member of the Gallup region. The upper coal member is shown forming the uppermost part of the formation but overlapping the barren part of the formation and pinching out in a southwest direction. Other writers have noted the coaly zone in the upper part of the Menefee over a wide area in the southern part of the San Juan Basin (Dane, 1936; Sabins, 1964, p. 302; Lease, 1971, p. 52–56; Siemers and King, 1974, p. 268; Siemers, 1977; O'Sullivan, Scott, and Heller, 1979; Mytton, 1983). This coaly zone has not been mapped in previous publications because of the small scale of the mapping, because the distinction was not germane to the purpose of the investigation, or because no consistent base for the coal-bearing beds was apparent.

The coal-bearing part of the upper Menefee is well displayed in mesas in the northeastern part of the La Vida Mission quadrangle, in buttes in a badlands area in the northwestern corner of the quadrangle, and in adjacent quadrangles to the east and west. Sections measured at these localities consistently have a coal bed within a few feet of the top of the formation and at least one, and in some places several, additional coal beds, most more than 1 ft (0.3 m) thick, in the underlying 200 ft (61 m) of beds. The coal beds are, however, lenticular, so that measured sections in and near the quadrangle show a different spacing of coal beds below the uppermost coal. In many places the coals have burned, leaving a residue of white ash. In these places the original thickness of the coal bed cannot be determined, but the ashy residue can in most places be found by digging at or close to the base of the red clinker zone resulting from the burn.

The problem of a consistent base for the coal-bearing beds in the uppermost part of the Allison Member exists in the La Vida Mission quadrangle. Miller, however, in searching for mappable units within the thick (1,000+ ft (305+ m)) sequence of Menefee beds present at the surface in the quadrangle, noted a thick zone of Menefee sandstone and mudstone characterized by the presence of large limestone concretions. The top of this zone, approximately 100 ft (30 m) below the lowest coal noted in the quadrangle, proved mappable with moderate accuracy. The calcareous concretions are less abundant downward, but the base of the beds below which they are no longer present also proved to be mappable. Thus, a threefold division of the Allison Member results. These subdivisions have been described, and the upper two given formal names (Miller, 1984). These relations are as follows:

Menefee Formation	Allison Member	La Vida Beds—with coal beds, and without calcareous concretions. Juans Lake Beds—with calcareous concretions and without coal beds. Lower beds—without calcareous concretions, and without coal beds.
	Cleary Coal Member	

Subdivisions and lithologies of the exposed rocks of the Allison Member within the La Vida Mission quadrangle are shown in the columnar section (fig. 15).

Lower Beds (Outcropping Part)

The top of the lower beds of the Allison Member is within the quadrangle but near its south edge. The rocks in the uppermost part of the lower member consist of interbedded light-colored, fine-grained, slabby sandstone and gray, evenly bedded mudstone. The sandstone crops out in small ledges and low buttes, but the mudstone is largely concealed by surficial deposits. The sandstone layers vary from a few feet to as much as 15 ft (4.6 m) thick, but most are in the 5-ft (1.5-m) to 10-ft (3-m) range. Crossbedding is rare and low angle; channeling into the underlying beds is likewise rare, and is normally confined to a few inches of relief. The mudstone, which accounts for about half of the rocks, is medium gray where fresh but weathers to light gray. Both the sandstone and mudstone are calcareous. A few beds are somewhat silty, but very few are coarse enough to qualify as siltstone. Calcareous concretions are absent, and ironstone concretions are rare.

The greatest thickness of the lower beds of the Allison Member at the surface within the quadrangle is in its southwest corner, where about 35 ft (11 m) of beds are estimated to be present. In some areas, especially in the southwest corner of the quadrangle, large, low-relief expanses are completely veneered with surficial deposits with no exposures of these lower beds. In a few places, small carbonate- or iron-cemented concretions of sand are present within sandstone units. The concretions are spherical or oval, and some are as large as baseballs. A few show concentric color bands due to iron stain. A good display of these is in the northeast corner of sec. 4, T. 20 N., R. 13 W. about 600 ft (183 m) south of the San Juan-McKinley County line, where they litter a slope beneath a small sandstone ledge out of which they have weathered.

Juans Lake Beds

Conformably overlying the lower beds of the Allison Member are the newly named Juans Lake Beds (Miller, 1984). The Juans Lake Beds form the bedrock of most of the La Vida Mission quadrangle. The name is taken from Juans Lake in the northeast part of the quadrangle, near which the calcareous concretions that distinguish this unit from the underlying lower beds are well exposed. No measured section that includes all or most of the beds was feasible near Juans Lake, however, because of poor exposures due to extensive surficial deposits and because of very low dips that result, in this sequence of beds forming the bedrock, in a belt several miles wide. The upper 450 ft (137 m) are, however, well exposed in the steep slopes of Red Hill just west of the La Vida Mission quadrangle and in the dissected topography for 1¼ mi (2 km) southwest of Red Hill. The measured section at this locality was designated the type section of the beds (Miller, 1984, p. A42–A46). The poorly exposed lower part of the Juans Lake beds, totaling about 300 ft (91 m), is similar to the upper part except that calcareous concretions are less abundant as are ironstone concretions and petrified wood.

The predominant lithologies of the Juans Lake Beds, as with other parts of the Menefee, are sandstone and mudstone, with minor amounts of silty mudstone, siltstone, and rare carbonaceous shale. The sandstone beds are fine grained, very light colored, and calcareous. Using the rock color chart (Goddard and others, 1948), the following colors were identified: light gray, very light gray, yellowish gray, pinkish gray, grayish yellow, and white. Most of the bedding is planar, but low-angle crossbedding is common. Sandstone units vary from a few inches to as much as 24 ft (7 m) thick. Channeling at the base of the sandstone units into the underlying beds was seen at a few localities but is not prominent, relief on the undersurfaces of the sandstone units being measured mostly in inches. One channel, however, is 17 ft (5 m) deep. Almost all the outcrops of the Juans Lake Beds are capped by, or consist entirely of, one of the sandstone units. All the sandstones are lenticular, and few are traceable for as much as a mile (1.6 km). Hence, correlation of sandstone units from isolated outcrop to isolated outcrop proved hazardous, and attempts to trace even the thickest ones over large areas were abandoned. In the type section of the Juans Lake Beds, 196 ft (60 m), or 45 percent, of the total is sandstone distributed in 13 sandstone units ranging from a few feet to 24 ft (7.3 m) thick. Coal beds are very rare in the Juans Lake Beds, but a few were seen in the upper part of the beds. All are very local, and most are only a few inches thick. The thickest found is at a location on section line 2–3 west of Tsaya Trading Post (pl. 1). Here, a local coal bed is 12 in (30 cm) thick, but a few hundred feet away it has thinned to 7 in (18 cm).

Ironstone (siderite) concretions are present in some of the sandstone beds but are not nearly as abundant as they are in the mudstone units. Minute carbonized plant fragments are also common in some of the sandstone units, but nowhere were pieces of plants large enough for identification found. Pieces of petrified wood lying loosely on the surface are common, having weathered out of the sandstone outcrops. The petrified wood is drab colored, mostly in tones of light gray. Two large logs of petrified wood, horizontally in place where they were washed in and dropped, are well exposed at the south tip of a small butte in the northeast quadrant of sec. 19, T. 21 N., R. 12 W. The longer of the two (fig. 16) extends completely through a 6-ft- (1.8-m-) wide spur. There are 9 ft (2.7 m) of the log still in place, with at least 3 ft (0.9 m) more broken off and forming debris on the slope below. The oval log is 8 in by 12 in (20 cm by 30 cm) in diameter. A smaller log at nearly the same level is close by to the west. At only one location

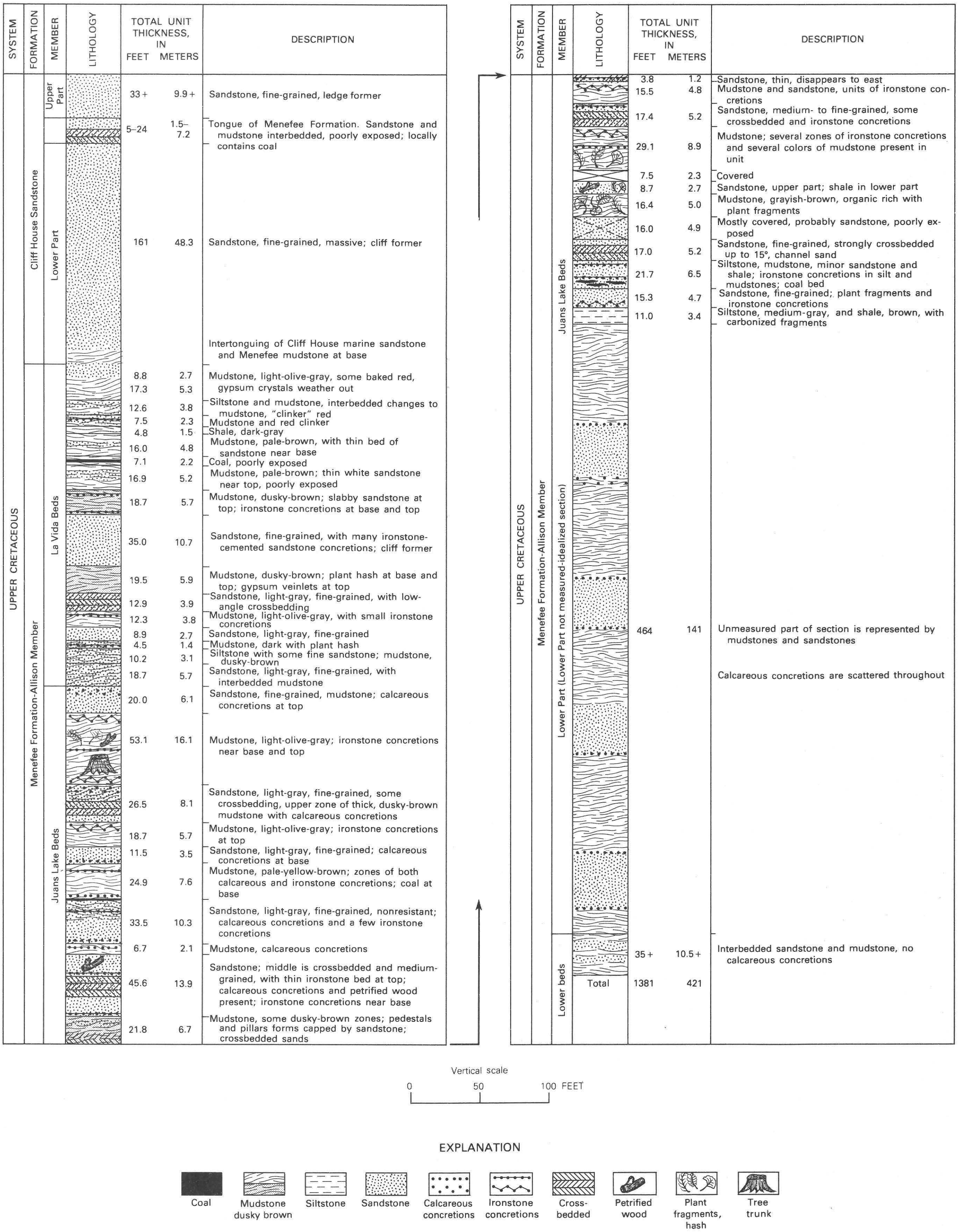


Figure 15. Stratigraphic column of the exposed part of the Menefee Formation and of the Cliff House Sandstone. Detailed lithologies shown are based on published measured sections near La Vida Mission quadrangle (Miller, 1984). (Location of measured section shown in fig. 9, loc. A.)

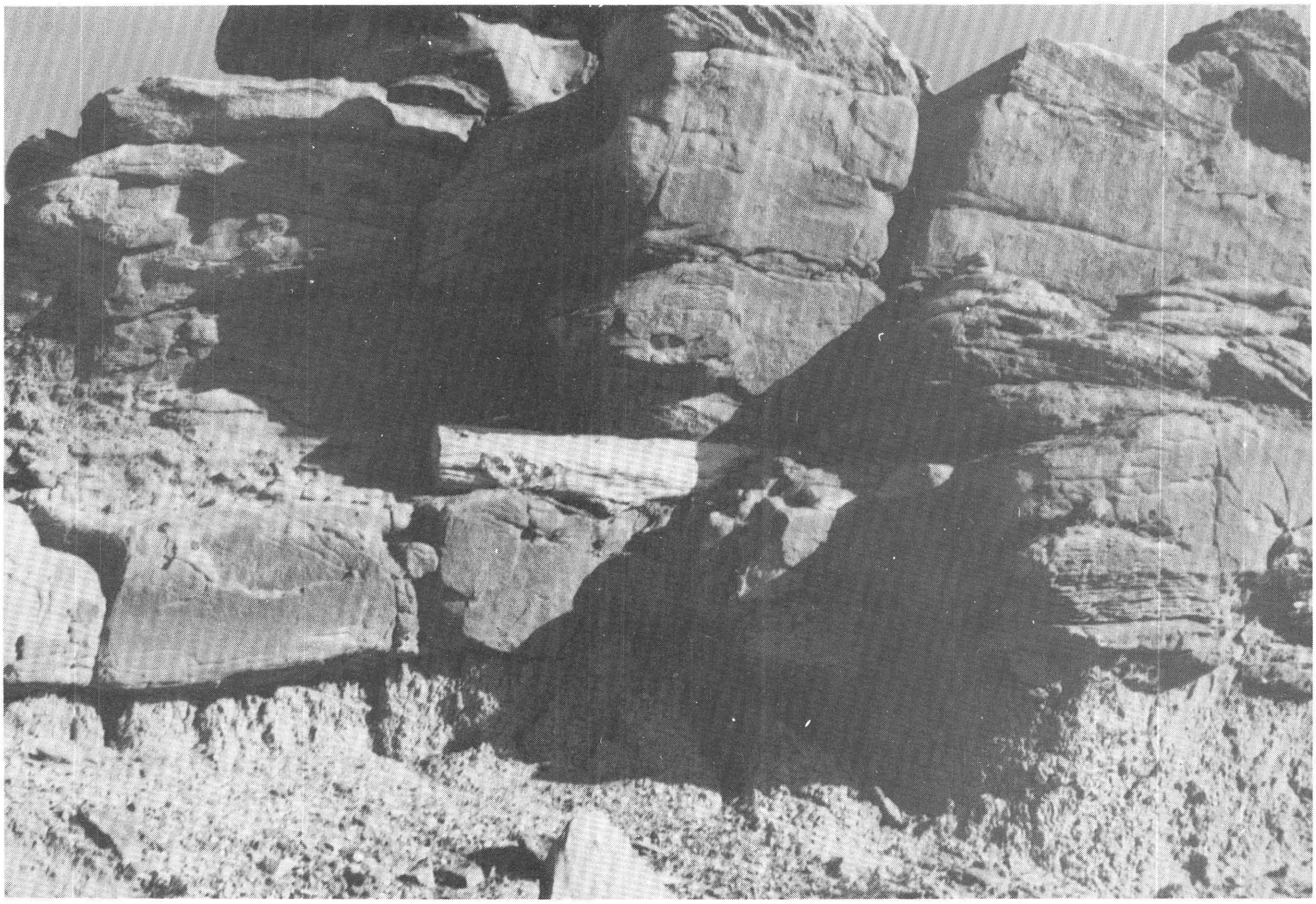


Figure 16. Silicified (petrified) log in the Juans Lake Beds (NE¼ sec. 19, T. 21 N., R. 12 W.). The preserved part of the log in place is 9 ft (2.7 m) in length, extending completely through a 6-ft (1.8-m)-wide spur. An additional 3 ft (0.9 m) of the log has broken off, forming debris on the slope below. (Photograph by Nancy T. Gardner.)

in the area was a tree trunk found in place. This was in mudstone in a prominent steep-sided gully on the west side of Red Hill (sec. 5, T. 21 N., R. 13 W., elev. 6,100 ft (1,859 m), The Pillar 3 SE quadrangle). The carbonized tree trunk was almost upright and 7 in (18 cm) in diameter.

Gray mudstone accounts for 185 ft (56 m) of the beds in the type section, or 44 percent of the total measured section. The fresh mudstone is dark gray, but it weathers to light gray. Almost all the mudstone is calcareous. In much of the mudstone, bedding is obscure but where visible is very even bedded. Some 5 percent of the beds in the type section of the Juans Lake Beds are gray siltstone, and about 3 percent are shale, much of which is carbonaceous. Plant fragments are abundant in some of the shale.

Although the lower part of the Juans Lake Beds below the measured type section is largely concealed within and near the La Vida Mission quadrangle, the few outcrops suggest that the lithologies of the beds are similar and also that the proportion of lithologies probably is quite similar to the proportions in the middle and upper parts as exposed in the type section.

Calcareous concretions that characterize the Juans Lake Beds are spectacular, bun-shaped masses, many of them several feet in diameter. They occur in layers, most of them close above or close below one of the sandstone units (fig. 17). A few have been seen in mudstone not near any sandstone bed. Circulation of water laden with calcium carbonate through the more porous sandstone supplied abundant mineral matter to promote the growth of the concretions, probably not long after deposition of the sediments.

It should be emphasized that the concretions are *not* composed of sandstone cemented by calcium carbonate. They are dense, hard, and cryptocrystalline limestone, with a distinctive conchoidal fracture pattern. The fresh color of the limestone is light gray, but the rock weathers to a light yellowish brown (grayish orange 10 YR 7/4 on color chart), which makes the concretions easy to recognize when gazing across a landscape. In places where the concretions are particularly abundant and broad erosion surfaces on the top of an underlying sandstone have developed, the surface looks like a giant cabbage patch, with concretions spaced a few tens of feet apart. A few of the calcareous concretions have ironstone cores of irregular shapes. Near the base of the Juans Lake Beds, the calcareous concretions are almost identical in outward appearance to those described above,

Figure 17. Zone of calcareous concretions on dirt road on north bank of Chaco River 350 ft (107 m) southwest of new State Highway 371 (NW¼ sec. 26, T. 22 N., R. 13 W.). Large concretion in foreground is 6 ft (1.8 m) in diameter and 27 in (69 cm) thick. Nearby but not in the picture is a concretion 12 ft (3.7 m) in diameter. Other concretions to the left are at the same horizon. Note hammer for scale.

but the calcium carbonate of which they are composed is finely granular rather than cryptocrystalline, and conchoidal fracture is poorly developed.

Ironstone (siderite) concretions are much more abundant than calcareous concretions in the Juans Lake Beds. These occur also in the lower beds and in the La Vida Beds of the Allison Member. Their colors range from pale brown, through grayish brown, to dusky brown and nearly black. They may be widely scattered at one horizon, or so close together that they coalesce to make a continuous thin bed. Most are smooth and oval shaped and do not exceed a few inches in longest dimension. However, concretions as large as 6 ft (1.8 m) have been seen. Internal banding is lacking. Closely spaced incipient joints within the concretions open up on exposure at the surface so that in many places the slopes directly below a layer of ironstone concretions are littered with tiny angular chips.

A common lithology in the Juans Lake Beds is bands from a few inches to as much as 10 ft (3 m) thick of an organic-rich mudstone. On the rock color chart, almost all these beds were closest to dusky brown (5 YR 2/2). A few seemed closer to grayish brown (5 YR 3/2), a slightly lighter tone of brown. Because of their distinctive color, we referred to these beds as dusky-brown mudstone, a designation we are continuing here. Plant fragments, some carbonized, are abundant in many of these beds. Crystals of gypsum that have weathered out of the dusky-brown mudstone and accumulated on the slopes below are quite common. The dusky-brown color makes these beds very prominent on slopes or in cliffs, because of the contrast with the nonorganic light- and medium-gray enclosing mudstone. Similar organic-rich mudstone has been described elsewhere by Shomaker and Hiss (1974) under the name "humate." In the eastern part of the San Juan Basin near Cuba, humate has been mined on a small scale and used as a soil conditioner. Siemers and Wadell (1977) have published an exhaustive study of the nature of humate from that region. In the Juans Lake Beds, a coal bed less than 1 in (2.5 cm) thick was seen in one dusky-brown mudstone unit. Most of these units, however, contain no coal beds although films and veinlets of coal are present locally. Although coal beds are almost completely absent in the Juans Lake Beds,

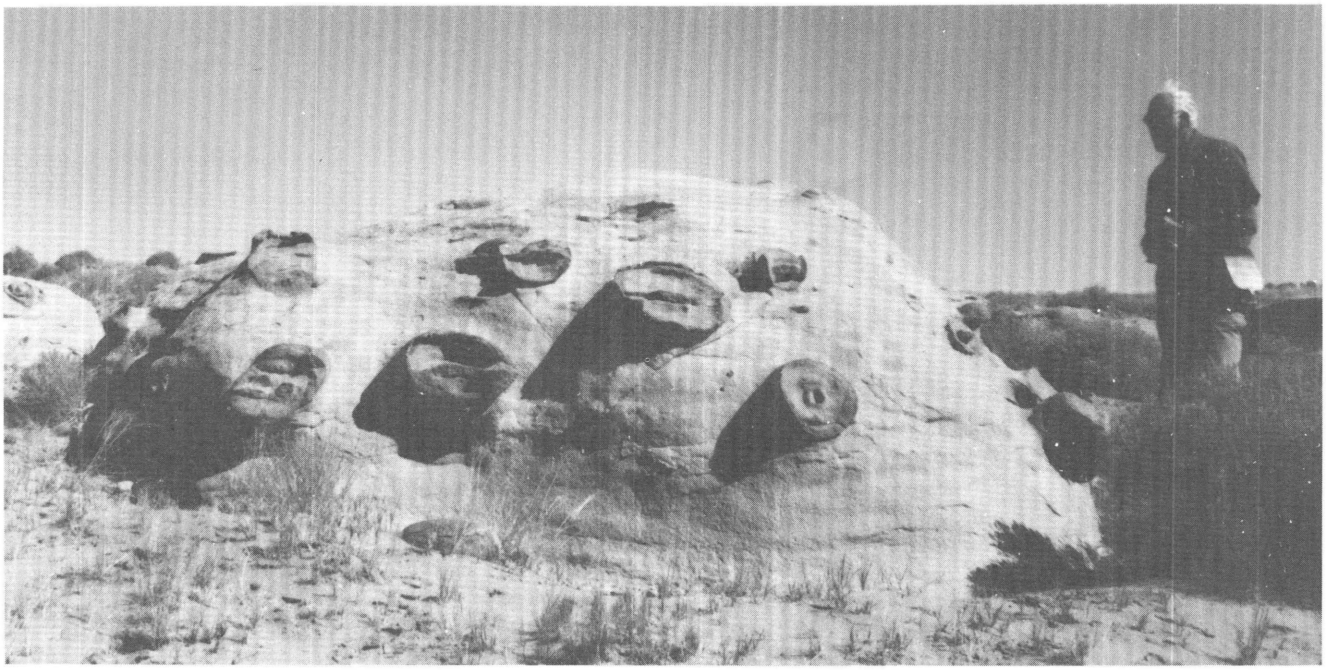


Figure 18. Iron-stained, calcareous sandstone concretions in a crossbedded sandstone in the Juans Lake Beds, 1,000 ft (305 m) south of center of sec. 22, T. 21 N., R. 13 W. (Photograph by Nancy T. Gardner.)

dark-colored carbonaceous shale in beds a few inches thick is common. Plant fragments are abundant in some of this shale. Some 5 percent of the beds in the type section of the Juans Lake Beds are gray siltstone, and about 3 percent are shale.

Also present in addition to the calcareous and sideritic concretions of pure mineral matter, but much less common, are concretions of sand, cemented by calcium carbonate or iron. A spectacular example of some of the largest of these is shown in figure 18. When these large concretions weather out of the bedrock, they disintegrate rapidly, so they are seen only in outcrop. In a few places, smaller sandstone concretions from the size of marbles to baseballs are abundant in bedrock and litter surfaces.

La Vida Beds

The La Vida Beds of the Allison Member of the Menefee Formation were named by Miller (1984) from the La Vida Mission School near the north edge of the quadrangle. They lie conformably on the Juans Lake Beds and are disconformably overlain by the Cliff House Sandstone. In some places, however, mudstone and thin beds of sandstone of Menefee type are interbedded with thicker bedded, cleaner sandstone of Cliff House type in a transition zone as much as 20 ft (6 m) thick. Except where transition zones are present or where talus from the Cliff House has buried it, the contact between the Cliff House beds and the La Vida Beds is sharp and clear. The La Vida Beds are distinguished from the underlying Juans Lake Beds by containing coal beds in the upper part. As previously noted, it is impossible to locate a consistent base for the coal-bearing part of the upper Allison (Upper Menefee) because of the lenticularity of the coal beds. The base of the La Vida Beds has, therefore, been drawn at the top of the beds carrying calcareous concretions. This proved a mappable horizon because the concretions are abundant in the uppermost part of the Juans Lake Beds.

The type section for the La Vida Beds is in the Whiterock Mesa area in The Pillar 3 SE quadrangle just west of the La Vida Mission quadrangle (Miller, 1984). There the beds are 232 ft (71 m) thick. Although no other well-exposed sections of the La Vida Beds were found in or near the La Vida Mission quadrangle, several other thickness measurements of the beds, based on mapping, were approximately 200 ft (61 m).

The dominant lithologies of the La Vida Beds are gray mudstone and light-colored sandstone, with a few beds of siltstone, shale, and coal. In the type section, the proportions are 59 percent mudstone, 33 percent sandstone, 4 percent siltstone, and 2 percent each carbonaceous shale and coal. The mudstone is almost identical to the mudstone of the Juans Lake Beds, except that it appears more calcareous, judging from the fact that weathered-mudstone slopes on the La Vida Beds are recemented at the surface by calcium carbonate due to capillary action and evaporation, thus forming a hard surface that on steep slopes is treacherous underfoot. In contrast, weathered-mudstone slopes in the Juans Lake Beds tend to be composed of loose dust. Ironstone concretions are abundant in the La Vida Beds, as in the Juans Lake Beds. In the lower part of the La Vida sequence, dusky-brown mudstone zones are present but do not contain associated coal beds. In the middle and upper parts of the beds, however, many dusky-brown mudstone zones enclose or are in contact with a coal bed. These dusky-brown zones in the upper part may be as much as 15 ft (4.6 m) thick. Loose chunks of petrified wood are common on the surface but difficult to find in the bedrock. Most chunks are only a few inches in diameter.

The lowest coal beds in the La Vida Beds are only a few inches thick, and some extend laterally only a few hundred feet. In the upper part of the La Vida Beds, however, the coal beds are thicker and more extensive laterally. The coal-bearing part of the La Vida Beds crops out in four separate areas in the northern part of the quadrangle. Because of known lenticularity of the coal beds and different numbers and spacing of the coal beds, correlations between the four coal-bearing areas are uncertain or not feasible. However, the topmost bed in each of the areas is only a few feet below the base of the Cliff House Sandstone. Because there appears to be very little erosion of the underlying beds at this contact, this top coal may be the same bed in all four places. The beds of the upper part of the Allison Member of the Menefee Formation are described in greater detail in the section on coal resources.

Fossil Content

The Allison Member of the Menefee Formation is very poor in identifiable fossils except for chunks of petrified wood, which are more abundant in the La Vida Beds than in the Juans Lake Beds. These chunks represent logs washed into their present location and later silicified. When weathering and erosion expose the logs, they break up into small chunks, mostly less than 1 ft (0.3 m) long. As previously noted, however, two large logs in bedrock are exposed in a narrow spur at the south edge of the top of a mesa in the middle of sec. 19, T. 21 N., R. 12 W. (fig. 16). Plant material is abundant, particularly in dusky-brown, organic-rich beds, but is so macerated as to discourage collecting; nor were whole fossilized leaves found in the beds of carbonized shale. Shelled fossils were found at only one locality, in a local sandstone 4 ft (1.2 m) thick about 60 ft (18 m) below the top of the Menefee. The bed crops out in two places about 300 ft (91 m) apart at an elevation of 5,940 ft (1,811 m) on both sides of a teardrop-shaped peninsular spur from the upland in the south-central part of sec. 20, T. 22 N., R. 12 W. The abundant fossils are all of the ostreid (oyster) type. Directly above and below the fossiliferous sandstone are beds of dusky-brown, organic-rich mudstone, and 8 in (20 cm) above the upper dusky-brown unit is a 5-in (13-cm) bed of carbonaceous shale and coal. The fossiliferous sandstone probably was deposited in a small body of brackish or fresh water near the outer edge of a delta. This situation is described more fully in the section on environments of deposition.

Cliff House Sandstone

The Cliff House Sandstone crops out in the high cliff north of the Chaco River in the northeast corner of the La Vida Mission quadrangle, and it caps mesas south of the river near the east border of the quadrangle. It also forms the bedrock north of the river in the highest parts of the sloping upland in the north-central part of the quadrangle. In the badlands in the northwestern part of the quadrangle it caps the highest butte in the area, which is in the south-central part of sec. 29, T. 22 N., R. 13 W. The authors refer to this prominent feature informally as "white knob" to distinguish it from numerous slightly lower buttes which are capped by sandstone of the Menefee Formation and which display much red color from burned coal beds. The name "knob" also serves to distinguish it from a much larger feature, Whiterock Mesa, a mile to the northwest in The Pillar 3 SE quadrangle.

The Cliff House Sandstone consists of thick, massive-bedded, marine sandstone in its lower part and a thinner marine sandstone at the top. These two are separated by a tongue of Menefee-type continental mudstone and fine-grained sandstone which locally contains coal beds. Figure 19 shows a measured section of the Cliff House Sandstone near the mouth of Tsaya Canyon a few hundred feet north of the La Vida Mission quadrangle (fig. 9, loc. B). The sandstone in both the lower and upper units is consistently clean and is fine to very fine grained. Colors of the unweathered sandstone are off-white, very light gray, very pale orange, and other very light colors. Most of the sandstone is in units at least 10 ft (3 m) thick in which bedding is not visible or is indistinct, but some thinner units have prominent parallel bedding. Low-angle crossbedding is present in a few units, but is not conspicuous. The contact at the base of the formation in most places is disconformable, with only minor amounts of erosion of the top Menefee beds before deposition of the basal Cliff House. This is attested to by the fact that the highest coal bed of the Menefee, which is believed to be extensive throughout much of the area, consistently lies only a few feet below the contact in most places. In a few places the interval is as much as 15 ft (4.6 m). Only at one locality, at the north edge of the quadrangle 1,950 ft (594 m) east of the common boundary of sections 19 and 20, was a channel seen that eliminated the top beds and the top coal of the Menefee and bottomed below the coal. In other places, transition zones of mudstone and thin-bedded sandstone of Menefee type interbedded with more massive bedded sandstone of Cliff House type separate the two formations. These transition zones represent an oscillating shoreline before continuous marine sedimentation took over.

Sandstone of the Cliff House is calcareous, except where weathering has leached all the carbonate. In some zones, carbonate-cemented sandstone concretions are abundant. They weather out and litter some bedding plane surfaces. Most are the size of walnuts or golf balls, but

FORMATION	TSAYA CANYON SECTION	THICKNESS, IN FEET	DISCRIPTION
Cliff House Sandstone			Top of section. No beds exposed above.
		33+	Sandstone, very light gray, very massive, fine-grained, subrounded
Tongue of Menefee Formation		3.1	Mudstone, pale-brown, thin stringers of grayish-yellow clay
		14.4	Mudstone, pale-brown, gypsum, platy and crystalline
		3.1	Coal poorly exposed
		10	Mudstone, grayish-brown, organic-rich
		0.2	Coal deeply weathered
		2.8	Sandstone, fine-grained, gnarled
		4.8	Mudstone, moderate, brown, organic-rich
		0.8	Coal, deeply weathered
		1.2	Mudstone, grayish-brown, plant fragments
		6	Sandstone, very pale orange in irregular beds
		0.8	Coal, deeply weathered
		2.4	Mudstone, grayish, plant fragments
		2.2	Sandstone, very pale orange in irregular beds
		2.2	Mudstone, pale-brown, weathered
Cliff House Sandstone		29	Sandstone, fine-grained, forms prominent white cliff visible for miles
		18	Sandstone, weathers to thin plates; shelves back
		20	Sandstone, fine-grained, shelving; iron-cemented sandstone concretions and a few *Ophiomorpha* burrows in lower part

FORMATION	TSAYA CANYON SECTION	THICKNESS, IN FEET	DISCRIPTION
Cliff House Sandstone		28	Sandstone, shelving, a few alcoves, minor crossbedding, less than 5°. *Ophiomorpha* burrows
		5.8	Sandstone, beds ±1" thick. Iron- and calcite-cemented concretions
		5.5	Sandstone, shaly, weak unit
		34	Bench, at top littered with iron-cemented concretions, some hollow. Sandstone, fine-grained, very pale orange. Abundant *Ophiomorpha* burrows beginning 10' above base. Pitted, small and large pits
		13	Sandstone, deeply weathered, not crossbedded; upper part forms ledge
		8	Sandstone, fine-grained, very massive bed, pinkish-gray. In places weathers pitted with irregular shapes
Menefee Formation		1.9	Slumped, burned shale, ash
		1.9	Shale, pale-red 0.4' carb shale
		1.8	Mudstone, dusky-brown
		2.8	Sandstone, nonresistant
		1.5	Mudstone, pale-brown
		2.8	Sandstone, one massive bed
		4.5	Mudstone, grayish-brown
		5.1	Sandstone, fine-grained, speckled, impure
		6.8	Mudstone, pale-yellowish-brown
		1.8	Sandstone, evenly bedded, laminated
		1.1	Coal, deeply weathered
		4	Mudstone, grayish-brown, organic-rich
		4.6	Covered
		0.6	Coal, bloom only

Vertical scale

0 25 50 FEET

EXPLANATION

Mudstone | Coal | Sandstone | Shale | Shale with ash unit | Mudstone, dusky-brown

Figure 19. Measured section of the Cliff House Sandstone near the mouth of Tsaya Canyon in Tanner Lake quadrangle. Section begins at valley floor at 5,890 ft (1,795 m) (NE1/4 sec. 24, T. 22 N., R. 13 W.) and terminates at top of upper cliff at 6,165 ft (1,879 m) (SW1/4 sec. 18, T. 22 N., R. 12 W.). (Location of measured section shown in fig. 9, loc. B.)

larger concretionary masses are common. Some of these masses of concretionary or semiconcretionary sandstone weather into fantastic shapes (fig. 20). On the east wall of Tsaya Canyon just north of the La Vida Mission quadrangle, differential cementation probably is responsible for the numerous pits, hollows, and alcoves in the cliff face (fig. 21). Drainage down the cliff from the top has also resulted in fluted drapery on the cliff face. Where the Cliff House Sandstone has been eroded into shelving ledges, differential weathering in some units has resulted in pitted surfaces of

Figure 20. Semiconcretionary mass of weathered sandstone in the Cliff House Sandstone on the east side of the lower Tsaya Canyon (1,500 ft (458 m) east-northeast of the center of sec. 24, T. 22 N., R. 12 W., Tanner Lake quadrangle). (Photograph by Nancy T. Gardner.)

large and small indentations, and also in overhanging ledges and alcoves.

The lower and upper units of the Cliff House Sandstone in the measured section are 161 ft (49 m) and 33+ ft (10.1+ m) thick, respectively. No measurement was possible of the interval between the highest Cliff House bed in the measured section and the base of the Lewis Shale farther north. Based on the appearance of the topography, however, we believe that only a few feet of Cliff House beds are missing. This opinion is reinforced by the thinness of the upper sandstone unit, which is only 18 ft (5.5 m) in a core hole 4½ mi (7.2 km) northwest of the measured section (Shomaker and others, 1971, fig. 22).

The lower and upper sandstone units are separated by a slope-forming (weak) unit of Menefee-type beds that resembles the La Vida (coal-bearing) Beds of the Allison Member. This unit consists dominantly of gray and dusky-brown mudstone and thin units of sandstone which are indistinguishable from mudstone and sandstone of the La Vida Beds. In most places, one or more coal beds are present. In the Tsaya Canyon section there are four coal beds in the 54-ft (16-m) thick unit (fig. 19 and table 4). To the northwest in the core hole referred to above, however, this same unit was only 28 ft (8.5 m) thick, with one coal bed at the base. To the southeast at the north border of the

Table 4. Cliff House Sandstone in La Vida Mission quadrangle and adjacent parts of Tanner Lake and The Pillar 3 SE quadrangles

	Feet	Meters
Lewis Shale		
Cliff House Sandstone		
Upper unit	18–33+	5.5–10.1+
Menefee-type unit	5±–54	1.5±–16.5
Lower unit	161	49
Menefee Formation		
Allison Member		
La Vida Beds	232	71

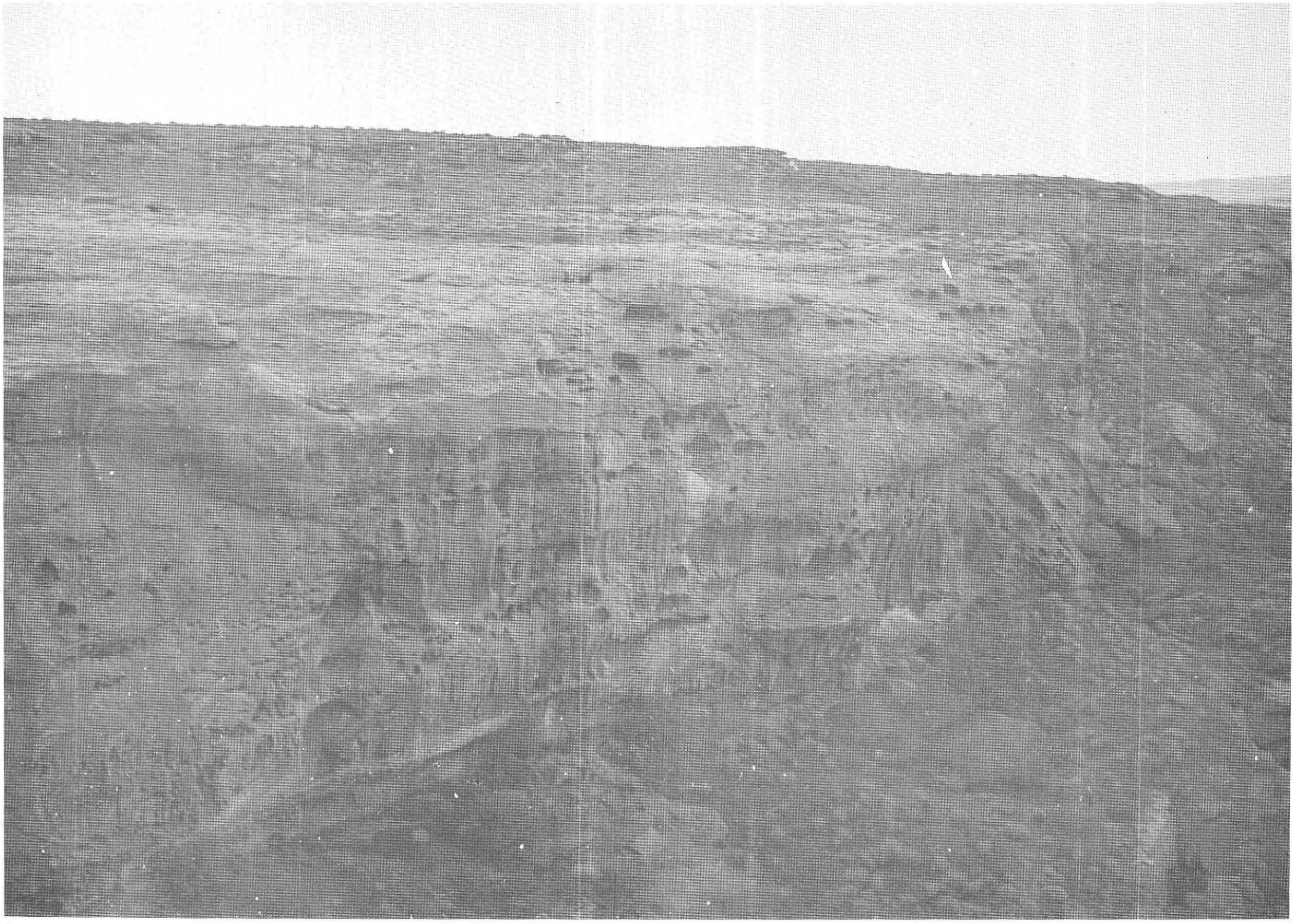


Figure 21. Cliff House Sandstone on the east side of lower Tsaya Canyon, Tanner Lake quadrangle, showing pitted surface and fluted weathering of the cliff (fig. 9, loc. B). (Photograph by Nancy T. Gardner.)

La Vida Mission quadrangle (sec. 20), the unit has thinned from 54 ft (16 m) to 24 ft (7.3 m) and consists almost entirely of dusky-brown, organic-rich mudstone, with a little carbonaceous shale and a very thin coal. Where the unit crosses the east border of the quadrangle one-half mile to the southeast, it is buried by talus but cannot be much, if any, more than 5 ft (1.5 m) thick. The upper part of the Cliff House Sandstone is not present in the northwestern part of the La Vida Mission quadrangle, but most of the formation is well exposed at Whiterock Mesa 1 mi (1.6 km) to the west in The Pillar 3 SE quadrangle. Here the Menefee-type unit crops out near the highest point of the mesa and consists of a 17-ft (5.2-m) unit of gray and dusky-brown mudstone and a thin, lenticular sandstone. No coal beds are present at this locality. In the Kin Klizhin Ruins quadrangle to the east (O'Sullivan and others, 1979), the Menefee-type unit, which is no more than 5 ft (1.5 m) thick at the border of the two quadrangles, thins to extinction. However, a similar unit about 100 ft (30 m) stratigraphically lower begins 0.3 mi (0.5 km) east of the border with the La Vida Mission quadrangle, and thickens eastward. It was mapped by O'Sullivan, Scott, and Weide (1979) almost continuously across the Kin Klizhin Ruins quadrangle.

It thus develops that, in the region of the La Vida Mission quadrangle, two different tongues of Menefee-type sediments are present within the Cliff House Sandstone, one near the top of the formation and one approximately 100 ft (30 m) lower. They serve for mapping purposes to divide the Cliff House Sandstone into upper and lower parts, but these units are not the same in the La Vida Mission, Tanner Lake, and The Pillar 3 SE quadrangles as they are to the east in the Kin Klizhin Ruins quadrangle. The unit of the Menefee-type sediments in the Cliff House east of the La Vida Mission quadrangle in the Kin Klizhin Ruins quadrangle has been interpreted by O'Sullivan, Scott, and Weide (1979) as a "northward" extending tongue of continental rocks of the Menefee Formation within the Cliff House, but with the connection with the main body of the Menefee to the "south" lost through erosion. Still farther east, Mytton (1983), in a geologic map of the Chaco Canyon quadrangle (1:100,000), noted that the Cliff House Sandstone intertongues with the Menefee Formation. Thus, in this region

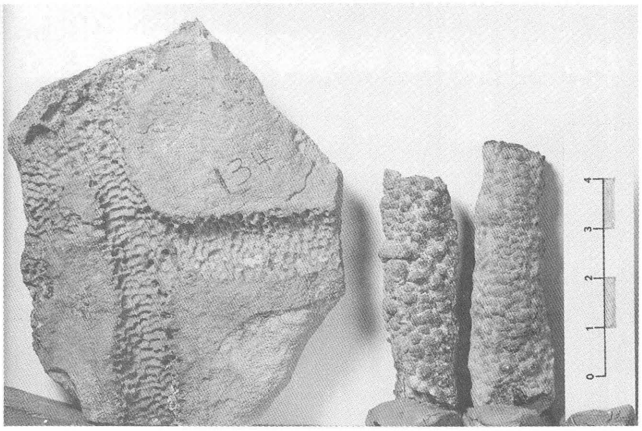


Figure 22. Mold and casts of the burrows of *Ophiomorpha nodosa*, a shrimplike animal that inhabited the littoral and shallow-water sands of the Cliff House Sandstone. Weathered-out specimens like these are common. Scale is in inches.

the shoreline of the shallow sea in which the Cliff House sands were being deposited retreated at different times in different places, to permit resumption of fluvial deposition and even to allow formation of swamps in which peat could accumulate. These retreats were followed by readvances and resumption of deposition of the Cliff House marine sediments. These oscillations of the shore were probably in a northeast-southwest direction. They are discussed later in this report.

The Cliff House Sandstone has a large complement of identifiable fossils, all of which are marine. In the La Vida Mission quadrangle, fossils indicating the presence of one animal—a burrowing-type shrimplike animal named *Ophiomorpha nodosa*—were found in many places and in many parts of the Cliff House. The animal itself is not fossilized, but three-dimensional molds and casts of its burrows are. The animal lived in littoral or nearshore, sandy environments. Its burrows consist of both horizontal and vertical tubes. Examples of a mold and casts of *Ophiomorpha* are shown in figure 22, and an example of multiple crisscrossing burrows is shown in figure 23. The lifestyle of these exotic animals has been described by Hester and Pryor (1972) and by Pryor (1975). Near the top of the upper sandstone in the northeast corner of the La Vida Mission quadrangle and the adjacent Tanner Lake quadrangle, abundant fossils are present, most in shallow pockets

Figure 23. Burrows of *Ophiomorpha nodosa* on a bedding plane surface near the top of the Cliff House Sandstone. Scale is 7 in (18 cm) long.

beveled across by an erosion surface. Included in the coquinalike assemblages are pelecypods, gastropods, cephalopods, fragmentary bryozoa, and sharks teeth. An extensive fauna from the Cliff House at Chaco Culture National Historical Park has been described by Siemers and King (1974). Their collections came from fossiliferous zones from base to top of the formation, whereas, except for *Ophiomorpha*, we found fossils only in the zone near the top of the upper sandstone unit. Our failure to find more fossiliferous zones may have been due in part to the nearly vertical cliff faces that form most of the Cliff House outcrops in the La Vida Mission area, and partly because the emphasis of Siemers and King was on fossil collecting whereas ours was on mapping.

Environments of Deposition

Numerous writers have discussed the paleogeography and environments of deposition of the formations of the Mesaverde Group in the San Juan Basin. Among the most important contributions are the following: Sears and others (1941), Cobban and Reeside (1952), Beaumont and others (1956), Hollenshead and Pritchard (1961), Gill and Cobban (1969, 1975), Hayes (1970), Fassett (1974, 1977), Siemers and King (1974), Williams and Stelck (1975), Molenaar (1977, 1983a), Seimers (1977), Tabet and Frost (1979), Devine (1980), and Cumella (1983).

The following interpretations depend principally on the regional studies of Sears and others, Gill and Cobban, Williams and Stelck, and Fassett. To these are added observations and information gathered by the authors in and near the La Vida Mission quadrangle.

In Late Cretaceous time, the western interior seaway extended from the Arctic Ocean to the Gulf of Mexico. To the west lay a rising Cordilleran highland bordering the Pacific Ocean and shedding abundant sediments both westward into the Pacific and eastward into the interior seaway (Williams and Stelck, 1975). To the east, the seas advanced and retreated across the low-lying continental platform many times, or as Fassett (1977) has expressed it, "SCI-SWO" (sea came in, sea went out).

Reasons for the advances and retreats of the Late Cretaceous seas across the western margin of the seaway were proposed by Sears and others (1941, p. 104–105) and subsequently accepted by other investigators (Fassett, 1977 p. 197). Sears and others' explanation can be paraphrased as follows: Vertical movement of the seaway was in a single direction. During slow subsidence of the trough floor and of the nearby land, the sea maintained its tendency to deepen; variations consisted only of variations in the rate of trough subsidence and of supply of debris. According to this concept, the formation of transgressive or regressive deposits depended on the relative rates of sinking and of sedimentation. When the influx of sediments from the source area exceeded the rate at which the trough was sinking, the strandline moved seaward and continental sediments were laid down. Conversely, when the influx of sediments slackened and the rate of sinking exceeded the deposition of sediments, the strandline moved westward, or in some areas southwestward, and marine deposits were laid down in the advancing sea. Since the inception of the concept of plate tectonics, movement of plates in Late Cretaceous time has been suggested as a mechanism, causing worldwide changes of sea level.

The formations of the Mesaverde Group present a classic example of transgression followed by regression, followed by another transgression of an interior sea. The Point Lookout Sandstone is the shallow-water, nearshore, marine sandstone deposited as the seas withdrew. The overlying Cleary Coal Member at the base of the Menefee Formation represents the fluvial deposits of mudstone and sandstone on a low-level coastal plain. It also includes peat deposits that accumulated in large swamps. With continuing retreat of the sea, the swamps were drained or filled, and fluvial mudstone and sandstone deposits accumulated on the upper delta plain. In a few places, small and ephemeral interchannel swamps persisted, resulting in very thin, local coal beds (lower beds and Juans Lake Beds of the Allison Member). Still later, the rate of sedimentation slackened and the sea readvanced. New large swamps formed on the lower coastal plain, and peat again accumulated along with the fluvial clastics (La Vida Beds of the Allison Member). Finally, the advancing sea flooded the coastal areas, and littoral and shallow-water marine sands were deposited (Cliff House Sandstone).

The Late Cretaceous seaway extended across the western interior in a general north-south direction, but with an eastern bulge of the strandline in western and southern New Mexico. As a result of this bulge, the seas advanced across the San Juan Basin area in a southwest direction and receded in a northeast direction (Gill and Cobban, 1969; Fassett, 1974, p. 227).

Paleogeographic maps showing the relations of interior seas and land areas bordering the seas for various intervals of Late Cretaceous time have been published by Cobban and Reeside (1952) and by Gill and Cobban (1969). These and other contributions were brought together in a series of colorful paleographic maps in the "Geologic Atlas of the Rocky Mountain Region" (Mallory, ed., 1972). The southwestern part of the map for Mid-Campanian time (fig. 45 in the Cretaceous chapter), when the upper part of the Menefee Formation and the Cliff House Sandstone were being deposited, is reproduced here as figure 24. To the land and sea relations shown on the map from the atlas we have added the location of the La Vida Mission quadrangle and the stratigraphic names used in this report. Note the "coal swamps" in northwestern New Mexico, which were

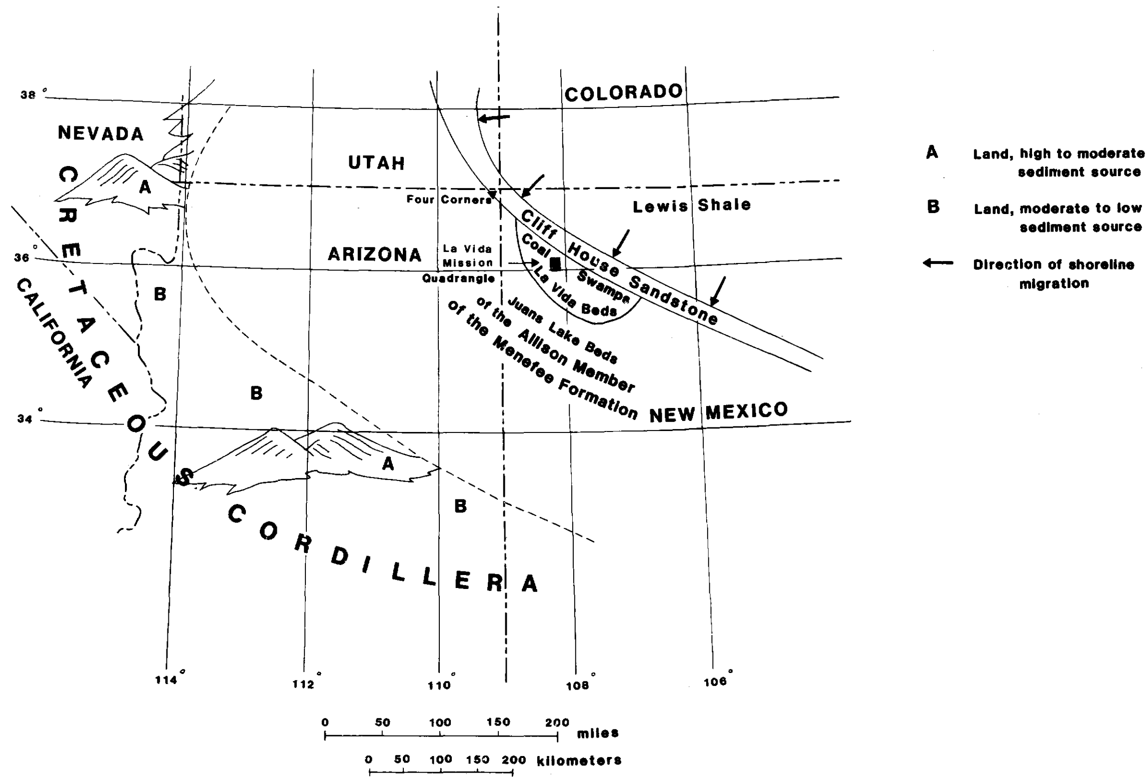


Figure 24. Paleogeography of Southwestern United States in Mid-Campanian time when the upper part of the Menefee Formation and the Cliff House Sandstone were being deposited. (Adapted from Mallory, ed., 1972, southwestern part of fig. 45, Cretaceous System.)

present when the upper two-thirds of our La Vida Beds were being deposited. Note also the source of sediments from the highlands to the southwest.

The lithologic features of the surface rocks in the La Vida Mission quadrangle that contribute to the regional understanding of the environments of deposition of the Menefee Formation and Cliff House Sandstone are discussed below.

1. No sediments deposited in the area in the exposed upper half of the Menefee are coarser than fine grained, indicating that the source of the clastics to the southwest (Gill and Cobban, 1969; Williams and Stelck, 1975) was remote. The paleographic maps of these authors suggest that the source was as much as 200 mi (322 km) distant.
2. All the Menefee sediments we tested are calcareous. In the La Vida Mission quadrangle, we were able to observe the prevalent calcareous content of the mudstone and sandstone of the Menefee only in the upper half of the formation. However, the clastic sediments of the lower half, which in the quadrangle are in the subsurface, are probably also calcareous. Hence, the source of these sediments probably included thick limestone formations. Hayes (1970) recorded that during Late Cretaceous time southeastern Arizona and adjacent New Mexico were being uplifted and eroded to expose strata as old as Precambrian, together with Paleozoic sediments and Mesozoic volcanics and epiclastics. Hayes (1970, p. B35) stated that "after the tectonism of postulated late Turonian age, southeastern Arizona was an eroding mountainous area, and probably through Coniacian, Santonian, and into Campanian time it was a prime source area for the continental sediments of the Mesaverde Group of New Mexico and northeastern Arizona." The stratigraphic sequence in southeastern and east-central Arizona includes thick limestone formations of late Paleozoic age (Wilson and others, 1969; Mallory, 1972). Some or all of four formations—Kaibab Limestone (Permian), Hermosa Limestone (Pennsylvanian), Redwall Limestone (Mississippian), and Jerome Formation (Devonian)—may have been at the surface and eroding to contribute calcium carbonate to the northeast-flowing streams draining into the area of the present San Juan Basin, thus accounting, at least in part, for the pervasive calcareous content of the clastic sediments of the Menefee.
3. Carbonized fragments of vegetation are present in some of the Menefee mudstone and also in some sandstone units, giving the sandstone a speckled aspect. This

organic material probably was picked up when migrating streams invaded an area of decaying vegetation and macerated the plant material.

4. The dusky-brown, organic-rich mudstone (humate) units, which are as much as 15 ft (4.6 m) thick, are common in both the Juans Lake Beds and the La Vida Beds of the Allison Member. Coal beds in the La Vida Beds are intimately associated with the dusky-brown mudstone. They may be at the base or top, or within, the dusky-brown zones. In the Juans Lake Beds, no coal beds of significant thickness are present in the dusky-brown mudstone, although films and veinlets of coal are present. The northeast-flowing rivers and streams that drained the deltaic surface at times picked up fragmentary organic debris, which comingled with the load of mud being carried, and deposited it downstream on low-lying areas to form the dusky-brown mudstone units. During sedimentation of the La Vida Beds, favored places to dump the organic-rich mud were the swampy areas, which when not so invaded were the locus for the formation of peat.
5. At times, tree trunks and branches were picked up by flood waters and carried downstream together with sand and silt. When dropped as the flood receded, the woody material may have been carbonized, but more of it was silicified. In places, chunks of silicified (petrified) wood litter the surface, but in only a few places are the logs and branches seen in outcrop. Silicified wood is not, however, associated with the dusky-brown mudstone or with the coal beds.
6. Deposition of the continental sediments of the Menefee was terminated by inundation by the sea waters advancing from the northeast (fig. 24). In most places the advance was continuous and steady, without reworking of the top beds of the Menefee. Hence, the contact between the highest continental beds and the basal littoral sediments of the Cliff House Sandstone is sharp, with little erosion of the underlying beds. In some places, however, the advance of the sea was oscillatory, resulting in intertonguing of the Menefee-type, well-bedded sandstone and mudstone and the Cliff House-type massive sandstone before continuous marine deposition took over.
7. In the La Vida Mission quadrangle, the only fossils we found in the lower and middle parts of the Cliff House Sandstone were the molds and casts of the shrimplike burrowing animal named *Ophiomorpha* (fig. 22). Studies of a very similar modern form (*Callianassa*) have shown that burrowing animals of this type live in a littoral or very shallow water environment (Weimer and Hoyt, 1964; Hester and Pryor, 1972; Pryor, 1975). Near the top of the Cliff House, however, abundant fossils are present, including pelecypods, cephalopods, gastropods, bryozoa, and sharks teeth, indicating a deeper water but still nearshore environment. Our observations of the Cliff House were, however, confined to the lowermost beds of the formation, except for a very small area in the northeastern corner of the quadrangle. More thorough search for fossils in the middle part of the formation may disclose fossiliferous beds there.

Quaternary Deposits

Surficial deposits of Quaternary age (glacial and postglacial) that mantle bedrock of the La Vida Mission quadrangle have been divided into eight types of mapped units: gravel deposits on terraces, gravel deposits on pedimentlike surfaces, wind-blown (eolian) stabilized sand, stabilized eolian sand and sedentary soil intermingled, sand dunes (live), slope wash, alluvium, and one fan deposit.

Deposits of talus are abundant on the steep slopes below the numerous cliffs of the area. In most places they do not form a continuous mantle, and barren areas between the talus piles reveal the bedrock. However, talus deposits were not mapped because in many places they cover coal beds, and the lines on the map representing the coal beds would be difficult to decipher if talus deposits were shown. Likewise, areas of clinker, formed by baking of beds of mudstone overlying burning coal beds, are not shown on the map because they would obscure the rendition of the coal beds. Outcrops of bedrock are numerous but small and isolated from each other by the surficial deposits in most parts of the quadrangle. Only in the intricately dissected badlands area in the northwestern part of the quadrangle is bedrock extensively exposed.

Terrace Deposits North of the Chaco River

Terrace deposits are exposed at five levels north of the Chaco River. From the top downward, the heights above river level are 330 ft (101 m), 210 ft (64 m), 130 ft (40 m), 65 ft (20 m), and 20 ft (6 m). (All readings are approximations as indicated by the rounded numbers in feet.) In the vicinity of Chaco Culture National Historical Park, upriver and about 10 mi (16 km) east of the La Vida Mission quadrangle, at least seven surfaces covered by gravelly sand are present. These surfaces are likewise distinguished from each other by the height of the erosion surface above the Chaco River or other major tributary drainages (O'Sullivan, Scott, and Weide, 1979; Weide and others, 1979; Mytton, 1983; Strobell and others, 1985). These have been numbered, from highest to lowest, 1 through 7, although none of the areas of the publications cited have representatives of all seven. The elevations above river level of the terraces in the La Vida Mission quadrangle do not seem to match those of Strobell and others (1985). In order not to imply correlation where none is intended, the terraces in the La Vida Mission quadrangle are designated and mapped as follows on plate 1: high terraces (Qth), the 330-ft (101-m) and 210-ft (64-m) surfaces; intermediate terraces (Qti), the 130-ft (40-m) and 65-ft (20-m) surfaces; and low terraces (Qtl), the 20-ft (6-m) surfaces.

High Terraces (Qth)

In the northeast corner of the quadrangle, a narrow, gravel-covered terrace is present at an elevation of 6,240 ft (1,902 m) only 20 ft (6 m) below the broad, flat upland at the top of the Cliff House cliff. Here the terrace is about 330 ft (101 m) above present river level. It does not extend into the adjacent quadrangles to the north and the east (pl. 1). The gravel covering the terrace, labeled Qth on plate 1, consists of rounded bulbous and flattened oval pebbles ranging in size from 1/2 to 2 1/2 in (1.3 to 6.4 cm). The pebbles consist of quartzite and chert of various colors. Most of the quartzite pebbles are light to dark brown and dark gray, and chert colors range from milky white through smokey gray and red. In addition, chunks of petrified wood up to 2 in (5.1 cm) in size are numerous. These are smooth but not rounded, suggesting that they have been transported short distances.

In the north-central part of the La Vida Mission quadrangle, the lower high terrace gravel crops out along the old road and close to the new highway to Farmington (sec. 23, T. 22 N., R. 13 W.). This deposit (also labeled Qth) is at an elevation of 6,060 ft (1,847 m) and about 210 ft (64 m) above present river level. Size range of the pebbles is nearly identical to that of the higher high terrace pebbles, but the average size seems a little smaller. Lithologically, the rock types are also the same, including chunks of petrified wood.

Intermediate Terraces (Qti)

The higher of the intermediate level terraces (Qti on pl. 1) is on the same spur of the upland as the lower high terrace described above and about 1,500 ft (457 m) west of the new highway (sec. 23, T. 22 N., R. 13 W.) at an elevation of 5,980 ft (1,823 m). It is some 130 ft (40 m) above river level and 80 ft (24 m) below the lower high terrace. The size and shape of the pebbles are similar to those in the two high terrace deposits. In addition to similar quartzite and chert constituents as in the higher gravels, a few pebbles of ironstone (siderite) are present, probably locally, derived from concretions in the Menefee Formation, whose contact with the Cliff House Sandstone is about 35 ft (11 m) above the terrace level. Also, one hollow spherical sandstone concretion, which was also locally derived from the Cliff House Sandstone, was found in the gravel.

The lower of the intermediate level terraces is preserved in two places in the northeast corner of the quadrangle (secs. 19 and 20, T. 22 N., R. 12 W.). These gravel-capped, nearly flat surfaces are about 65 ft (20 m) above river level at an elevation of about 5,955 ft (1,815 m). They were encountered early in the mapping, and the gravels were not sampled. Presumably their constituents are similar to the gravels veneering the higher terraces.

Low Terraces (Qtl)

The low terrace system is best developed on the spur contained by the south-extending loop of the Chaco River in secs. 26 and 27, T. 22 N., R. 13 W. This terrace is almost 1,000 ft (305 m) wide at the widest part of its belt. It lies about 20 ft (6 m) above river level. Size range of the pebbles is similar to that of the pebbles in the higher terraces. Poorly rounded pebbles are, however, more abundant than in the higher gravels, suggesting shorter distances of transport before deposition. Chert and quartzite pebbles are the dominant lithologies, but a few sandstone pebbles derived from the Menefee are included, as are a few pebbles from ironstone concretions in the Menefee. Gravel from this low terrace deposit was quarried in 1979–80 at a site west of the highway, crushed, and used in building the express highway nearby. After being abandoned, the site was restored so perfectly that the quarry location is no longer apparent; its former location is shown on the geologic map (pl. 1). The best exposure of the low terrace gravels is in a roadcut on the west side of the new highway just north of the bridge across the Chaco River (fig. 25). Here, lenses of sand are interbedded with the pebbly gravel, showing fluctuations in the energy of transport of the river at the low terrace level and more than one episode of gravel deposition. The exposed gravel-sand deposit on the low terrace surface at this site is nearly 15 ft (4.6 m) thick, and a few more feet of covered gravel may be present at the base. A tiny outlier of the main low terrace belt north of the Chaco River caps a small hill in the southeast corner of sec. 23, T. 22 N., R. 13 W., where remnants of the once more extensive gravel cover are preserved. Another tiny remnant of the low terrace gravel system is also preserved south of the Chaco River in T. 22 N., R. 12 W., about 300 ft (91 m) south of a dirt road and on the section line between sections 29 and 30. It consists of a thin veneer of gravel on top of a small, low hill at low terrace level.

Sources of the Gravels

The principal constituents of the terrace deposits bordering the Chaco River are quartzite, several varieties of chert, and petrified wood. On the high terraces, pebbles of these lithologies make up practically the entire deposit. The low terraces have pebbles of these rock types and, in addition, lesser amounts of fine-grained sandstone and of ironstone.

The fine-grained sandstone and ironstone pebbles are locally derived. The ironstone pebbles come from ironstone concretions in the upper part of the Menefee Formation, above the level of the low terraces. Most of the sandstone pebbles probably come from sandstone beds in the upper part of the Menefee, but some could come from the

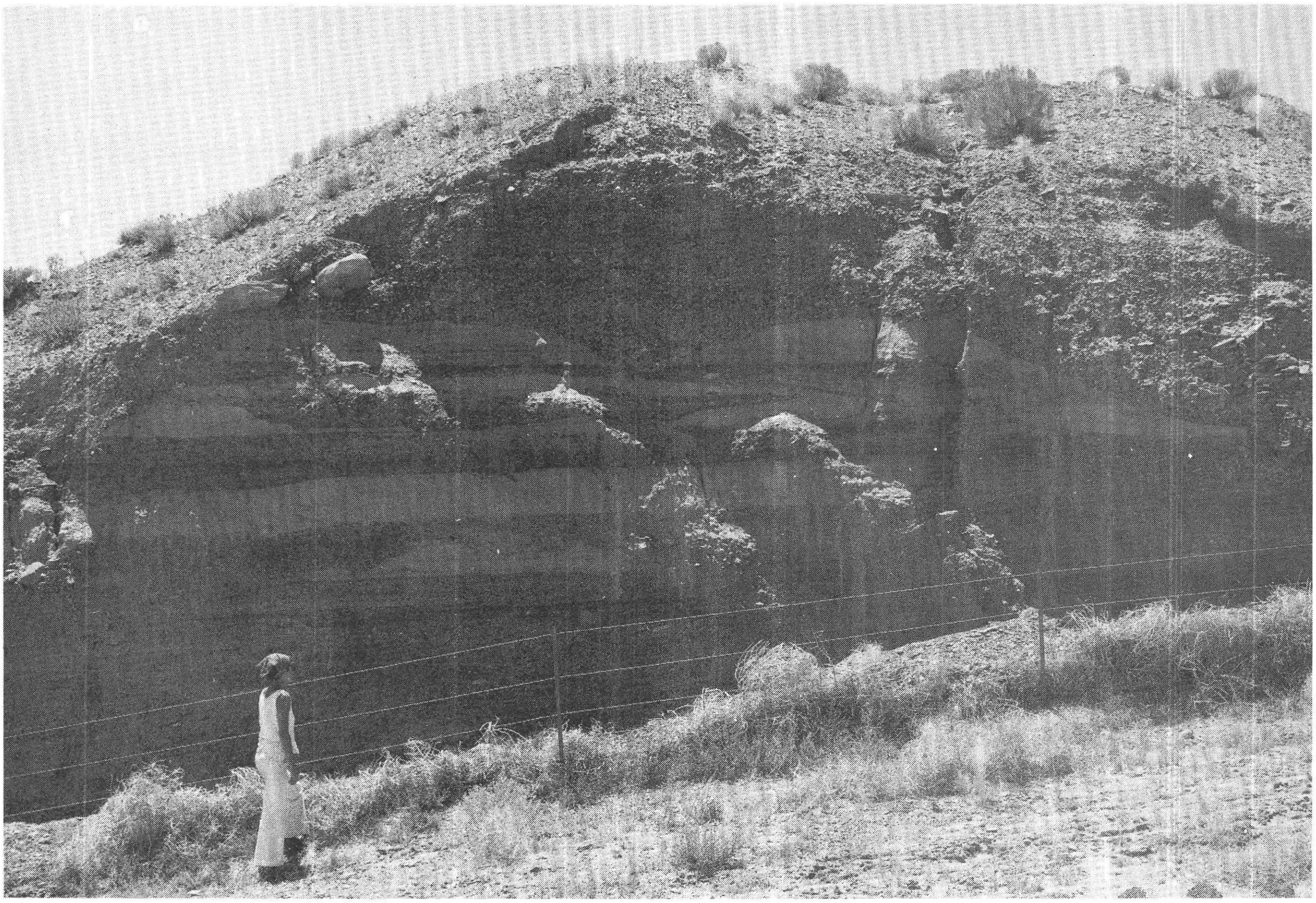


Figure 25. Low terrace gravel in roadcut of State Highway 371, 1,000 ft (305 m) north of Chaco River bridge. Interbedded light-colored lenses of medium- and coarse-grained sand and darker colored layers of gravel. Gravel consists of flat, subrounded pebbles of fine-grained sandstone 0.5–4 in (1.3–10 cm) in size and tiny rounded pebbles of ironstone. Horizontal beds are overlain and crosscut by younger gravel consisting of well-rounded pebbles of red quartzite and quartz, and including pieces of petrified wood and slabs of fine-grained sandstone. The quartzite, quartz, and sand were carried in from outside the area. The other constituents are locally derived.

overlying Cliff House Sandstone. All pebbles are water worn, but some are irregularly shaped, with rough surfaces indicating very little transportation.

The only nearby source of the abundant chert and quartzite found in all the terraces is the Ojo Alamo Sandstone of latest Cretaceous or Paleocene age. The nearest belt of rocks of this formation is 17 mi (27 km) northeast of the La Vida Mission quadrangle at Ojo Alamo store on a wash of the same name. This wash is a southwest-flowing tributary of the Chaco River. Bauer (1917, p. 276) described the formation at this, the type locality, as consisting of "two conglomeratic beds and the shale lenses which they include" and ranging in thickness from 63 to 110 ft (19 to 34 m). He noted further that 70 percent of the conglomeratic pebbles are of "jasper, various colored chert, or pink and white quartzite" (p. 276). Bauer noted, however, that of the remainder of the gravel in the Ojo Alamo type area, "pebbles of sandstone, andesite, felsite, porphyrite, gneiss and schist, are fairly common, and pebbles of granite and obsidian are also present" (p. 276). Except for sandstone locally derived, we did not find pebbles of the rock types of the second quotation where we collected from the terrace gravels in the La Vida Mission quadrangle. Presumably, the less resistant rocks of the Ojo Alamo Sandstone were winnowed out during transportation of the harder pebbles to their present resting place in the Chaco River terraces. Reeside (1924, p. 68) corroborated Bauer's description of the Ojo Alamo, and in a measured section at the type locality also noted the presence in the upper part of the formation of large silicified logs. There seems little doubt that the Ojo Alamo conglomeratic pebble beds provided the chert, quartzite, and perhaps some of the petrified wood found in the high terrace deposits along the Chaco River in the La Vida Mission quadrangle area. At the time the high and intermediate level terrace gravels in the La Vida Mission quadrangle were being deposited, the Ojo

Alamo source beds probably were somewhat closer to the Chaco River and have been stripped back to their present location by late Tertiary and Pleistocene erosion. Mytton (1983) and Weide and others (1979) have also attributed to the Ojo Alamo Formation the chert and quartzite pebbles in deposits of gravelly sand mantling "pedimentlike surfaces" in Chaco Culture National Historical Park.

Gravel Deposits South of the Chaco River (Qg)

Widely separated small deposits of gravel are present south of the Chaco River. They cap small mesas and buttes, each of which rises prominently above its surroundings. These gravel remnants are designated Qg on the geologic map (pl. 1). All these deposits are within a belt about a mile wide west of Kim-me-ni-oli Wash and roughly paralleling the wash. No similar deposits were found east of the wash or west of the belt. The gravels in these deposits differ markedly from the terrace gravels of the Chaco River, all but one of which are north of the river. They form a veneer only a few feet thick over the bedrock that caps the mesa or butte. The gravel may litter the top surfaces, or it may be largely obscured by wind-blown sand and best seen around the rims of the heights.

The gravels consist of pebbles of fine-grained sandstone and of siderite (ironstone). The sandstone pebbles are subrounded and up to 6 in (15 cm) in size, but most are in the 1- to 2-in (2.5- to 5-cm) range. The siderite pebbles are less than 1 in (2.5 cm) in size. Both rock types are locally derived from the Menefee Formation, which has abundant similar sandstone and abundant ironstone concretions in the mudstone units. Some of the gravel deposits are cemented by caliche. This cementing material consists of calcium carbonate derived by solution from the underlying calcareous sandstone and redeposited in the gravel by evaporation near the surface.

Elevations of the gravel-covered surfaces are not randomly distributed. They become lower toward Kim-me-ni-oli Wash and also, but less rapidly, toward the Chaco River, as shown by the contours drawn between the elevations of the gravel deposits (fig. 26). The contours delineate a restored surface, which is pedimentlike and is a remnant of a larger pediment sloping away from a high area to the west and southwest, and toward ancestral Kim-me-ni-oli Wash and the Chaco River.

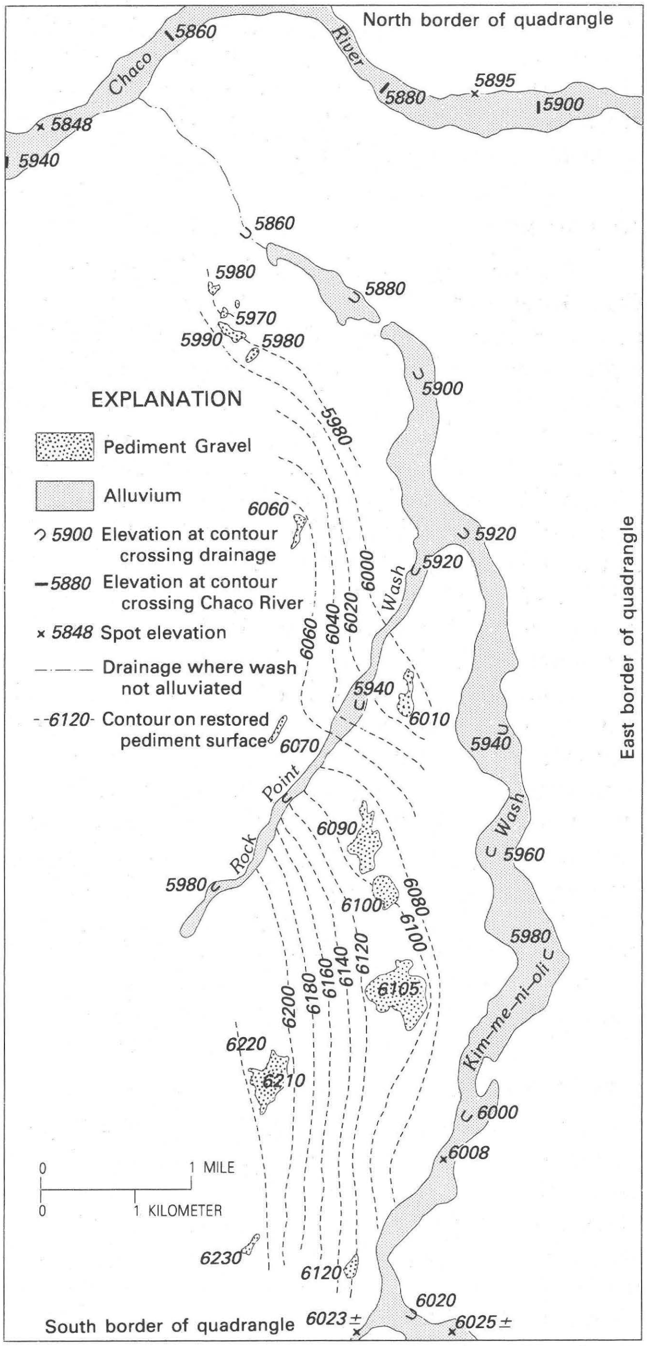


Figure 26. Location of remnant gravel deposits south of the Chaco River, and the contoured pedimentlike surface on which they were deposited.

Holocene Deposits

Surficial deposits of Holocene (postglacial) age that mantle much of the bedrock surface of the La Vida Mission quadrangle have been divided into four mapped units. These are alluvium, stabilized wind-blown (eolian) sand, live sand dunes, and slope wash. The processes that were active in forming each of the units are still operative in molding the modern landscape. In addition, soil, derived from weathering of the bedrock, mantles other large areas. In mapping these soil-covered areas, a distinction was made between soil on extensive large, flat or gently sloping surfaces of low relief, and soil in small areas but still large enough to map. Taken together, the Holocene units cover most of the surface of the La Vida Mission quadrangle. On published maps of nearby quadrangles, a Holocene unit named "Naha Alluvium of Hack" has been mapped (O'Sullivan, Scott, and Heller, 1979; O'Sullivan, Scott, and Weide, 1979; Schneider and others, 1979; Scott, O'Sullivan, and Heller, 1979). Some parts of the areas mapped here as soil or alluvium may include surficial cover of the type designated Naha on those maps. The less formal names used here seem to fit better the surficial geology as we found it, and are easier to understand.

Alluvium (Qal)

Alluvium is present on the nearly flat valley floors of Chaco River, Kim-me-ni-oli Wash, and Rock Point Valley, a major tributary of the wash. Only at times of hard rains or melting snow is there any water in these drainages. As a result, on most days of the year one may walk across these streams dry-shod. Narrow, shifting, shallow channels wander across the alluviated flood plain of the Chaco River. Widespread hard rains, however, fill the flood plain from bank to bank. Floods are sufficiently frequent that vegetation on the flood plain is minimal. Within the La Vida Mission quadrangle, the flood plain at its widest is 2,000 ft (610 m) wide. The alluvium consists predominantly of fine-grained sand.

Alluvium along Kim-me-ni-oli Wash and in Rock Point Valley is derived entirely from the sandstone and mudstone of the Menefee Formation. Normal drainage and deposition has been affected, and in some places totally altered, by the presence of earth dams, which have modified the patterns of sedimentation. The effect of these dams has been deposition of silt and mud along with the fine-grained sand. In the summer and fall months when fieldwork for this report was done, no ponded water was retained behind any dam, though there may be ponds usable for watering stock in the spring.

Wind-Blown (Eolian) Sand, Stabilized (Qes)

In many parts of the La Vida Mission quadrangle, bedrock is covered by wind-blown sand that has been stabilized by vegetation. The sand grains are subangular and frosted, and range in size from fine to medium. Most of the sand grains are derived from weathered beds of sandstone in the Menefee Formation, but some may have come from older weathered sandstone formations to the southwest, the direction from which hard winds blow. Except for locally generated winds blowing away from thunderstorm centers, almost all the sandstorms observed by us moved from southwest to northeast across the landscape, carrying unstabilized sand and silt considerable distances. This directional pattern for hard winds is consistent and widespread in northwestern New Mexico and northeastern Arizona (Hack, 1941, fig. 2; Cooley and others, 1969, fig. 14). Resultant sculpturing of the landscape in a northeast direction as the result of wind erosion and deposition is readily apparent in aerial photographs.

The vegetation on stabilized eolian deposits in most places consists of shrubs, such as Russian thistle (tumble weed), broom weed, and snake weed. The individual shrubs commonly are 1 to 2 ft (0.3 to 0.6 m) high and a few feet apart. Sand blown against the shrubs forms knobs about a foot above the surrounding troughs, with steep slopes on the southwest and tapering off to the northeast. In some places, grass (bunch grass) has grown on the sandy areas and serves as a stabilizing agent. This grass is the principal forage for the abundant sheep, which are herded from one grassy area to another by the Navajo shepherds and their dogs. Along the Chaco River, however, bushes as much as 7 or 8 ft (2.1 or 2.4 m) high, growing on and stabilizing the sand, form belts of almost impenetrable brush.

Areas of stabilized sand are numerous in the quadrangle, and range in size from those too small to map to ones covering many acres. Surfaces of these large areas are nearly flat, or gently sloping, with low relief. Except near the margins of the areas, it is not possible to tell how thick the sand cover is, but the lack of outcrop within mapped stabilized sand areas suggests that the sand must be several feet thick in most places, and may average a good deal more.

In some places, stabilized sand patches are intermingled with soil (residual soil) too intricately to map separately. In the southwest corner of the quadrangle (pl. 1), these areas are extensive. They have been mapped separately and labeled on plate 1 "stabilized eolian sand and [residual] soil intermingled" (Qess).

Sand Dunes (Qsd)

Dunes that have very little or no vegetative cover are sparse throughout the quadrangle but are particularly interesting because of the beauty of their rippled surfaces, and because they can move over and engulf other landforms or manmade structures. Two of the dunes large enough to map have repeatedly moved over old State Highway 371, which traverses the quadrangle from south to north (topographic map). One dune is in the east-central part of sec. 21, T. 21 N., R. 13 W. During the course of our fieldwork this dune engulfed the highway several times, and each time had to be cleared by bulldozer to keep the road open. Because of the better access provided by the new highway across much of the quadrangle, the old road remained blocked for days or weeks, causing considerable inconvenience to the residents whose homes fronted on the older road. The second dune, in sec. 36, T. 22 N., R. 13 W., periodically moved across the now largely abandoned old highway (topographic map). The largest dune in the quadrangle is in the west-central part of sec. 18, T. 21 N., R. 12 W. This dune, elongated in a northeast direction, is 1,150 ft (351 m) long and 150 ft (46 m) wide. Figure 27 is a photograph of a part of this dune taken near its northeast tip.

Small patches of active sand, most too small to map, have formed in numerous places on northeast-facing slopes of mesas, buttes, or scarps, by loose sand blown off the top surfaces and settling out on the lee side of the declivity.

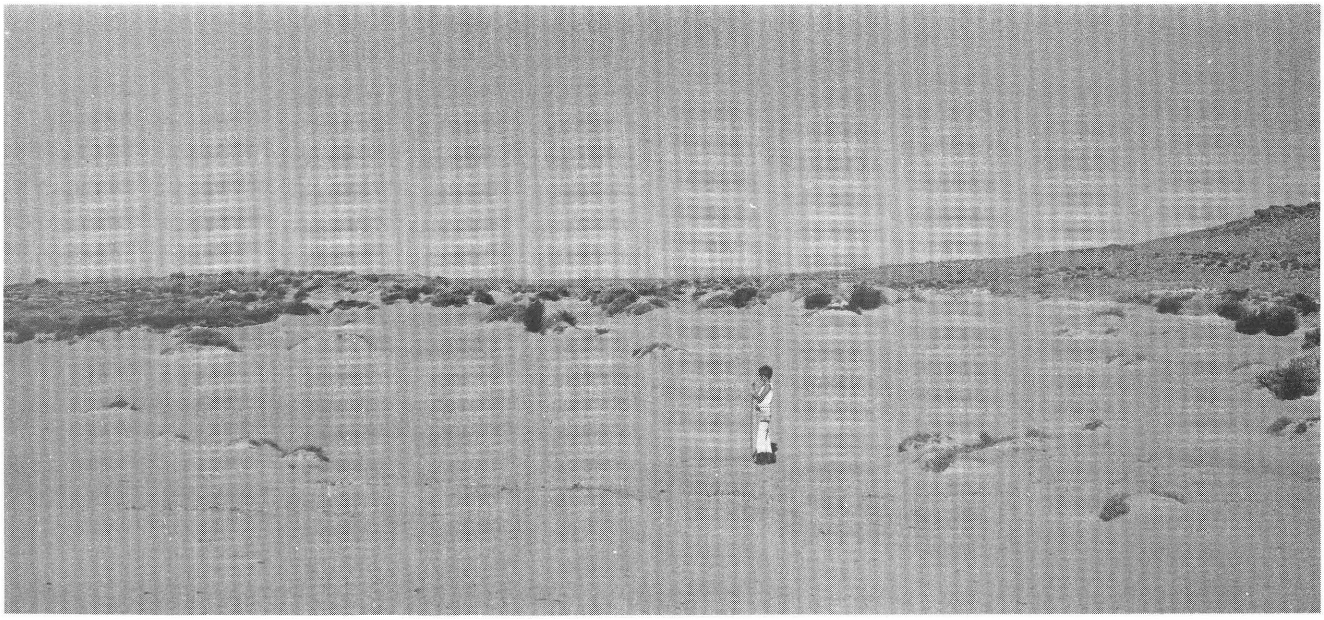


Figure 27. Large sand dune (sec. 18, T. 21 N., R. 12 W.). Dune is 1,150 ft (351 m) long and 150 ft (46 m) wide. Photograph taken near the northeast tip of the dune, looking southwest.

Although these are not strictly dunes, the largest of these bare sand accumulations are shown on plate 1 with the same symbol (Qsd) as the dunes. As noted earlier, the elongation of the active dunes and smaller sand bodies tends to be to the northeast, because of the consistency of the direction of hard winds from the southwest. In areas of considerable local relief, however, this directional trend may be considerably altered by the effect of the topography. This is particularly true of the small sand bodies that accumulate on the lee side of cliffs and steep slopes.

Slope Wash (Qsw)

Numerous areas in the quadrangle, both large and small, consist of gently sloping, almost smooth surfaces that have been formed by sheet-flood erosion. This phenomenon is common in desert regions where much of the rainfall is torrential and where there is little vegetation to stabilize the mantle of unconsolidated material. When the rain falls on inclined smooth surfaces so fast that it can neither seep underground nor coalesce into channels, it rushes downslope as a sheet of water picking up mud, silt, sand, and even rock fragments, which it deposits as velocity slackens. The resulting surface is bare of vegetation, except that small plants an inch or two high may grow if the interval between hard rains is sufficiently long.

In the La Vida Mission quadrangle, areas of slope wash develop most readily where mudstone of the Menefee Formation has weathered to form an easily eroded mantle. Some of the slope-wash surfaces consist of the deposited mud the flood has left behind, but some are paved with sand or rock fragments from nearby weathered beds of sandstone in the Menefee. Still others, and they are numerous, have a veneer of angular chips of ironstone derived from the disintegration of ironstone concretions. When freed from their matrix in the mudstone, the concretions shatter along incipient fractures into tiny, angular fragments that are small enough to be picked up and moved downslope by the sheet floods. In several slope-wash areas, we observed a zonation of the surface materials, with small chunks of sandstone from a nearby sandstone outcrop forming a narrow band at the upper edge of the slope-wash area. Next downslope is a wide belt veneered with ironstone chips from concretions, and the lowest zone is a surface area of mud carried farthest downslope after all the rock debris had been deposited. In aerial photographs, the color or shade of slope-wash areas is determined by which of the three types of transported material mantles the surface.

Margins of the slope-wash areas commonly are irregular, with slope-wash material interfingering intricately with stabilized eolian sand or soil. Hence, the mapped margins of the slope-wash areas represent generalizations of the border relations.

Soil Units

Many parts of the quadrangle are devoid of bedrock exposures, yet are not covered by material of any of the types described above. Rather, the mantle consists of fine-grained sand or mud derived from weathering of the Menefee bedrock, with little or no movement of the mantle materials across the surface. Many of these areas support growths of low shrubs or bunch grass. Wind action causes the loose material to bunch up around the base of shrubs in a manner similar to the stabilized eolian sand. We sometimes had problems deciding whether to map stabilized sand and silt or soil. Our criteria for distinguishing between the two materials, which usually resolved the problems, are listed below:

Stabilized eolian sand (Qes)

1. Hummocks around shrubs, and troughs between shrubs with as much as 1 to 2 ft (0.3 to 0.6 m) of relief.
2. No rock chips on surface.
3. Hard walking on loose sand; also, one must walk a sinuous path between clumps.

Soil (sl and ss)

1. Cover is soil derived from bedrock, which may be mud, silt, or fine-grained sand.
2. Where sand, the surface commonly has hummocks around shrubs, but troughs between are shallow (not as deep as in stabilized eolian sand areas).
3. Small fragments of sandstone from bedrock, caliche chips, or ironstone chips abundant or sparse in troughs.
4. Ants bring up chips of bedrock, especially ironstone chips, around their holes.
5. Slight to firm crust on surface.
6. Easy walking in an almost straight line.
7. Varying amounts of caliche have developed at some places, cementing the surface material.

Whereas boundaries around areas of slope wash, dune sand, or alluvium are clearly defined, the sandy soil areas and stabilized eolian sand areas may grade from one to the other.

The thickness of the soil cover is indeterminate in most places, but the fact that no bedrock is exposed within large mapped areas of soil leads to the assumption that the soil cover must be several or more feet thick.

To accentuate the contrast between large areas of soil cover on gently sloping surfaces and the abundant small areas of soil, the geologic map (pl. 1) shows two categories: "sl" for large areas and "ss" for small areas.

Fan (Qf)

A small but prominent alluvial fan is located in the northern parts of secs. 26–27, T. 22 N., R. 13 W. A sharply incised drainage crosses the gravel-covered low terrace of this area, picking up some of the gravel en route. Where it debouches onto gentle slopes just above the Chaco River, it has spread out, building a triangular-shaped, typical alluvial fan. This fan is a minute example of a common feature along the mountain fronts of the arid southwest.

Landslide

Landslides big enough to map are rare in the quadrangle. The only prominent one is located in the southwest corner of sec. 30, T. 22 N., R. 12 W. (topographic map). Here, a steep-sided, topographically anomalous knob is conspicuous on the southwestern slopes of North Mesa. It is capped by a massive sandstone that is not present on the mesa slopes to either the northwest or the southeast. Lithologically, the sandstone resembles the Cliff House Sandstone, the base of which is 100 ft (30 m) higher, just below the crest of the mesa. The sandstone of the knob appears to be the only remnant of a landslide that broke off from the Cliff House cliff and slid to its present position.

Sandstone Dikes

Sandstone dikes are not common geologic phenomena, though they have been reported in various parts of the world, including California (Diller, 1890; Jenkins, 1925) and Japan (Hayashi, 1966). In the La Vida Mission region, sandstone dikes were found in five places, one within the quadrangle (pl. 1) and the others close by. Table 5 shows the locations of the occurrences.

All the dikes are within the coal-bearing part of the La Vida Beds and only a few tens of feet below the top of the Menefee Formation. Although bedding and transverse surfaces of Menefee beds were seen in myriad places in the region, no sandstone dikes were noted below this relatively thin zone near the top of the formation.

At all the occurrences except locality 2 (table 5), the dikes are exposed on smooth, gently sloping surfaces, so the depth of penetration of the dikes could not be observed. They vary in thickness up to 2 ft (0.6 m) and in linear

Table 5. Locations of sandstone dikes in La Vida Mission quadrangle and adjacent parts of Tanner Lake and The Pillar 3 SE quadrangles

[Location of quadrangles shown in fig. 9]

Quadrangle	Location
1. La Vida Mission	SE¼NE¼NE¼ sec. 25, T. 22 N., R. 13 W., 800 ft (244 m) southeast of classroom building of La Vida Mission School; elevation about 6,000 ft (1,829 m). See plate 1.
2. Tanner Lake	SE¼SE¼NW¼ sec. 23, T. 22 N., R. 13 W., 1,000 ft (305 m) northwest of new State Highway 371 and 500 ft (152 m) north of south border of quadrangle; elevation about 5,960 ft (1,817 m).
3. Tanner Lake	On section line, secs. 22–23, T. 22 N., R. 13 W. Exposure is 1,300 ft (396 m) north of south border of Tanner Lake quadrangle; approximate elevation 5,940 ft (1,811 m).
4. Tanner Lake	On section line, secs. 14–23, 1,200 ft (366 m) east of section corner 14–15–22–23, T. 22 N., R. 13 W.; elevation about 5,980 ft (1,823 m).
5. The Pillar 3 SE	NW¼SE¼SW¼ sec. 29, T. 22 N., R. 13 W., 300 ft (91 m) west of La Vida Mission quadrangle and 700 ft (213 m) west of base of "white knob"; elevation about 6,370 ft (1,942 m).

extension from a few score feet to as much as 200 ft (61 m). All extend in nearly straight lines across the surface. Inclination of the dikes at the surface is very steep to vertical. The sides of the dikes are smooth, with no gradation into the enclosing rock. Insofar as could be observed, there is no lateral penetration of the sandstone composing the dikes into the enclosing rocks by way of secondary fissures or openings.

The dikes are composed of fine-grained sandstone, the most common grain size for Menefee sandstone units, and the wall rocks are mudstone or sandstone. The dikes were not formed by filling of cracks resulting from desiccation of the enclosing sediment, because desiccation cracks develop in polygonal patterns. Rather, they seem to have formed by filling of cracks that result from tension, with sand from above. The tension may be the result of differential creep, or of other local stresses that formed joints in the semiconsolidated sediments.

Hayashi (1966) classified dikes by shape and by genesis. In his classification, the dikes of the La Vida Mission region fall in his shape category "straight-wall clastic dike" and in his genesis category "infilling clastic dike." His definition of infilling clastic dikes is "clastic materials accumulated into cracks, joints, or other such structures under the influence of gravity."

At locality 1 (table 5), which is within the La Vida Mission quadrangle, a sandstone dike crosses a spur at the north end of North Mesa near La Vida Mission School. It is 1 ft (0.3 m) thick at the surface. In the Tanner Lake quadrangle, sandstone dikes were observed at three localities, all of which are along the same belt of outcrop and only short distances north of the La Vida Mission quadrangle. At locality 3 (table 5), two en echelon linear dikes about 200 ft (61 m) apart trend northeast. They are 1–2 ft (0.3–0.6 m) thick, with linear extents up to 250 ft (76 m). The northernmost of the two dikes is intersected almost at right angles by a third short dike. At locality 4 (table 5), at least five sandstone dikes were noted. Dimensions were not measured. At locality 5, which is in The Pillar 3 SE quadrangle, only a few tens of feet from the west edge of the La Vida Mission quadrangle, a sandstone dike only a few score feet long was seen from above but not visited.

The sandstone "dike" at locality 2 (table 5) is like the other four occurrences in that it involves the uppermost part of the La Vida Beds, close below the base of the Cliff House Sandstone. Unlike the others described above, however, the occurrence is within an erosional channel, the exposed part of which is at least 25 ft (8 m) deep and 100 ft (30 m) wide. This channel is itself unusual in that it is by far the largest to be noted in the La Vida Mission region. It trends in a northern direction, but was seen only in cross section so its exact direction could not be measured. The channel is filled with massive, fine-grained sandstone. The sandstone contains iron-cemented sandstone concretions, which are common in the littoral beds of the lower Cliff House Sandstone but rare in the sandstone beds of the Menefee. Before filling of the channel, however, a slide occurred on its west bank, probably the result of oversteepening or undercutting. This slide brought into the channel a chaotic mix of the enclosing top beds of the Menefee. These beds consist of dusky-brown mudstone, a segment of a coal bed 21 in (53 cm) thick, and fine-grained sandstone. After the slide, the channel was filled by littoral sand of the advancing Cliff House sea. Figure 28 is a sketch of a part of the slide that includes the coal bed. The original peat bed must have been dewatered and lithified sufficiently to be coherent at the time that a segment broke off and became incorporated in the slide. Apparently it shattered during the slide, and sand from above was squeezed into a crack completely across the bed and into the underlying mud. Sand also infiltrated or was squeezed along bedding planes in the semilithified peat to as much as 4 ft (1.2 m) from the crack. The sketch does leave room for speculation as to the sequence of events.

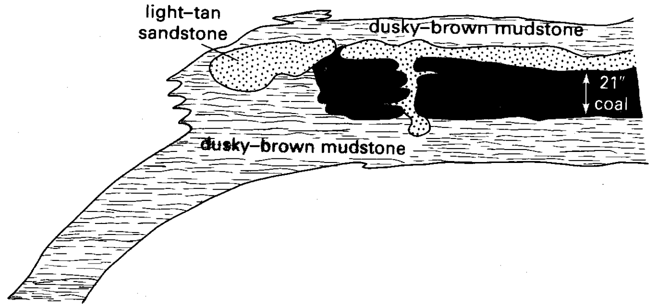


Figure 28. A sandstone dike cutting a coal bed in a landslide on the bank of a channel at the top of the Menefee Formation.

COAL RESOURCES

In 1983, the U.S. Geological Survey updated and revised its coal resources classification system in Circular 891 (Wood and others, 1983). The salient criteria for evaluating coal resources presented in that circular that are especially applicable to this investigation are summarized below.

The distinction between resources and reserve base is shown graphically in figure 29, which is part of figure 2 of Circular 891. Resources of coal are "naturally occurring concentrations or deposits of coal in the Earth's crust, in such forms and amounts that economic extraction is currently or potentially feasible." The reserve base "may encompass those parts of a resource that have a reasonable potential for becoming economically available...." Reserves of coal are defined as "virgin and (or) accessed parts of a coal reserve base which could be economically extracted or produced at the time of determination...."

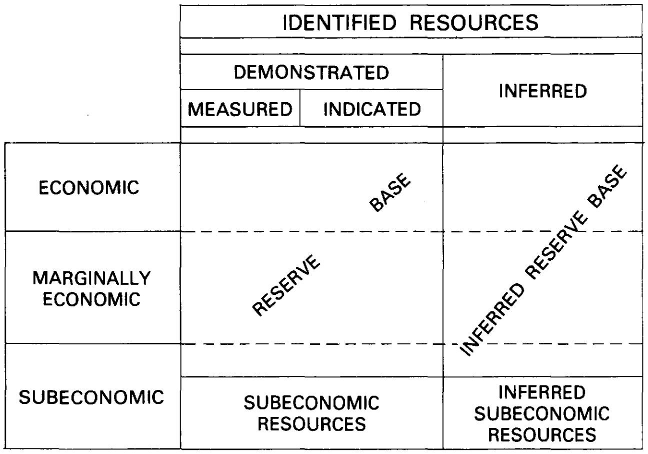


Figure 29. Categories of identified coal resources. (Source: Wood and others, 1983, U.S. Geological Survey Circular 891, fig. 2 (in part).)

The parameters set forth in Circular 891 that are pertinent to the calculation of tonnages of coal resources in the La Vida Mission quadrangle are as follows:

1. Rank of coal (although the rank probably ranges from bituminous to subbituminous coal in the area, criteria for bituminous coal are used for all resource estimation in this report; see section on "Rank of Coal").
2. Overburden (0–500 ft, 500–1,000 ft, and so forth).
3. Thickness of beds for bituminous coal: 14–28 in; 28-42 in; and 42–84 in.
   a. Partings greater than 3/8 in (1 cm) are excluded from measurement.
   b. Where partings are greater than the thickness of underlying coal benches, the coal bed is considered as having split into two coal beds.
4. Degree of reliability of estimate (measured, indicated, inferred).

Additional guidelines for measurement of areas underlain by coal beds and for calculation of tonnages are set forth in Circular 891 (p. 35–46), but they are quite elaborate and are not reproduced here. Because the English system of measurements in the thinking about and data recording on coal (feet, inches, acres, tons) in the United States is so firmly entrenched, the metric equivalents of the coal measurements are not given in the following section of text, figures, and table.

Inasmuch as the coal that exceeds the minimum requirements for thickness of beds and depth of burial, in order to qualify as a reserve, underlies very small areas within the La Vida Mission quadrangle, the potential for commercial mining within the quadrangle is negligible. Hence, all the tonnages calculated below are categorized as subeconomic resources.

Because so much of the coal is burned at the outcrop, leaving residual ash, and because the coal beds are covered by thick talus from the overlying Cliff House Sandstone in many other places, there are few locations where coal bed thicknesses could be measured. These are shown in figures 30, 31, and 33. On these maps, where two coal benches are separated by partings more than 1 in thick, the form "X inches of coal/Y inches of parting/Z inches of coal," from bottom up (for example, 18/12/30), is used in the figures. In some places, a coal bed believed to have two benches has only the upper bench exposed. The lower bench was dug out when the tools at hand were adequate or when the presumed thickness of the lower bench warranted returning to the site with pick and shovel. Where the thickness of a presumed lower bench of a coal bed was not determined, the data for the bed are shown as, for example, ?/?/40. If a lower bench was exposed but thickness of a presumed upper bench was not determined, the sequence would be, for example, 40/?/?.

At many places where the coal has burned at the outcrop, we were able to dig out and measure the thickness of the ash bed resulting from the burn. Although there obviously is no consistent arithmetic relation between thickness of coal and thickness of residual ash, in the one locality where we were able to establish a relationship, a coal bed 21 in thick produced 6 in of ash where the bed had burned 25 ft away. We surmise from this that, for Menefee coal beds in the area, undisturbed residual ash beds more than 6 in thick probably have resulted from burning coal beds on the order of 2 ft or more thick, that is, of significant thickness. Because of the possibility of undetected squeezing or slumping of the ash beds, the converse may have some validity but is much less dependable, that is, that thin ash beds are necessarily evidence of thin coal beds. Most places where we had or could make good exposures of the ash beds, they showed no laminations, and the bases and tops of the beds were even surfaces. In addition, the roof rock, in most places baked mudstone, likewise was not jointed, broken, or shattered, indicating a gentle settling of the roof as the coal bed burned.

Coal Beds

Coal mining on a large scale in the San Juan Basin has had a resurgence in recent years with the application of the technology and equipment to strip mine coal. With renewed interest in coal for the generation of electricity because of dwindling petroleum reserves, it has become increasingly important to identify and describe the coal resources of the San Juan Basin, with emphasis on strippable coal beds. One of the little known areas containing coal is the La Vida Mission quadrangle, where coal beds in the upper part of the Menefee Formation of Late Cretaceous age are present.

In other parts of the basin, coal beds in the upper part of the Menefee Formation have been reported in several publications (for example, Dane, 1936, p. 96; Bozanic, 1955, p. 97; Beaumont and others, 1956, p. 2160; O'Sullivan, 1980; Mytton, 1983). These coal beds have not been mapped and have been judged too thin and (or) too lenticular to merit much attention. O'Sullivan, however, in a U.S. Geological Survey open-file report (1980, p. 9), reported a "poorly exposed," 4.2-ft-thick coal bed with "no partings noted" in the Kin Klizhin Ruins quadrangle adjacent to the La Vida Mission quadrangle on the east. Earlier, Lease (1971, p. 56–57) had reported a Menefee coal bed 7 ft thick in an abandoned mine near the south edge of the Tanner Lake quadrangle, which adjoins the La Vida Mission quadrangle on the north. This occurrence is discussed in the section on "Coal Beds North of the Chaco River." In the present investigation, a coal bed at the north edge of the La Vida Mission quadrangle is 62 in thick with no partings, and coal beds more than 3 ft thick have been measured at several places on the slopes of the mesas south of the Chaco River.

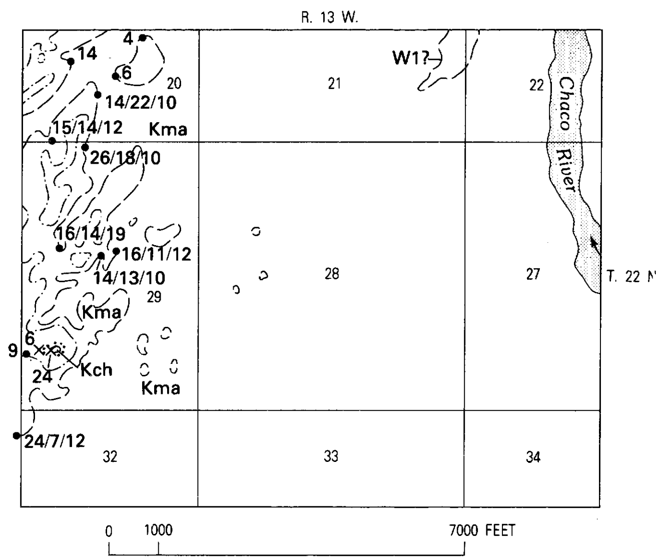
The coal beds in the upper part of the Menefee are present at two stratigraphic locations. One of these is in the La Vida Beds, which constitute the uppermost part of the main body of the formation. The other interval of coal-bearing rocks is in a thin tongue of the Menefee in the upper part of the overlying Cliff House Sandstone. Coal beds of significant thickness are present in this tongue nearby in the Tanner Lake quadrangle, but only carbonaceous shale and films of coal are included in the tongue within the boundaries of the La Vida Mission quadrangle. In the La Vida Beds, there are coal beds in four separate areas within the quadrangle, as follows: west of the Chaco River in the northwestern part of the quadrangle, north of the river in two areas, and south of the river in three mesas in the northeastern part of the quadrangle. These coal occurrences are described later in three sections, by area.

Correlation of coal beds between widely separated areas of outcrop is hazardous and has not been attempted because of inconsistent numbers of coal beds and their lenticularity. So as not to imply correlation, the coal beds in the different areas have been given different designations. Those in the western area (fig. 30) are labeled W1, W2, W3, and W4, those in the eastern area (fig. 33) El and E2, and those in the areas north of the Chaco River (fig. 31) N1 and N2. Additional coal beds, which are thinner and less extensive laterally than the mapped coal beds, are present in some places. These beds are not shown because of space limitations, but those more than 14 in thick are mentioned in the following discussion.

Zones of organic-rich, dusky-brown mudstone (described in the section on Juans Lake Beds of the Allison Member) are present in the coal-bearing La Vida Beds of the Allison Member. Many of the coal beds are sandwiched in zones of this dusky-brown mudstone or are in sharp contact with the mudstone above or below. Some coal beds, however, have no associated dusky-brown mudstone, and, conversely, numerous zones of dusky-brown mudstone have no associated coal beds. It is true that the environment that favored development of peat-forming swamps was also susceptible to incursions of muddy waters bearing comminuted plant trash that may have preceded or followed the regimen of peat formation or both.

Coal Beds of the Western Area

The upper Menefee coal beds in the western area are located in sections 20, 21, 22, 29, and 32 of T. 22 N., R. 13 W. (fig 30). Although four coal beds were identified in this area, the upper two (W3 and W4), both burned at the outcrop, are present only on the steep slopes of "white knob" and underlie only small fractions of an acre. Hence,



EXPLANATION

Kch — Cliff House Sandstone

Kma — Allison Member of Menefee Formation

Geologic contact

Top coal (W4)—Ash only; also base of Kch

Higher coal (W3)—"White Knob coal"; ash only

Middle coal (W2)—"Upper clinker coal"; ash only

Lower coal (W1)—"Lower clinker coal"

24/7/12 — Location where coal bed thickness was measured. Example shows, from bottom up, 24" coal/7" parting/12"coal

×6 — Location where burned coal bed was measured. Example means 6" ash

Figure 30. Location of mapped coal beds and thicknesses of coal beds and partings in the western area. Numbers are in inches.

Table 6. Coal resources of La Vida Mission quadrangle
[In thousands of short tons. Includes only important coal beds]

Area/Subarea	Township/Range	Coal bed	Thickness of coal (inches) 14–28	28–42	42–84	Total	Remarks
Western	22 N., 13 W.	W1	260	530	—	790	See figure 30.
North of Chaco River							
Northeast	22 N., 12 W.	N2	632	—	—	632	
North-central East area	22 N., 13 W.	N1	—	34	—	34	
West area	22 N., 13 W.	N1	—	282	—	282	Data point in Tanner Lake quadrangle.
	22 N., 13 W.	N2	—	—	417	417	
Eastern							
North mesa	22 N., 13 W.	E1 Lower bed	—	135	—	135	In northwestern part of mesa; elsewhere covered or burned.
		Upper bed	90	—	—	90	
	22 N., 12 W.	E1 Lower bed	—	145	—	145	
		Upper bed	168	—	—	168	
	22 N., 13 W.	E2	—	—	—	—	Believed absent.
	22 N., 12 W.	E2	132	417	296	845	
Middle mesa	22 N., 12 W.	E1 Lower bed	—	335	—	335	
		Upper bed	—	435	—	435	See figure 33.
	22 N., 12 W.	E2	76	—	—	76	
South mesa	22 N., 12 W.	E1	—	641	—	641	
	22 N., 12 W.	E2	—	—	—	—	Impure, not measured.
	21 N., 12 W.	E2	—	—	—	—	Too thin to qualify as resource.
Total			1,358	2,954	713	5,025	

possible unburned tonnage beneath the knob is negligible. They are not shown in figure 30 because of space limitations. Their location is the same as the line for the base of the Cliff House Sandstone.

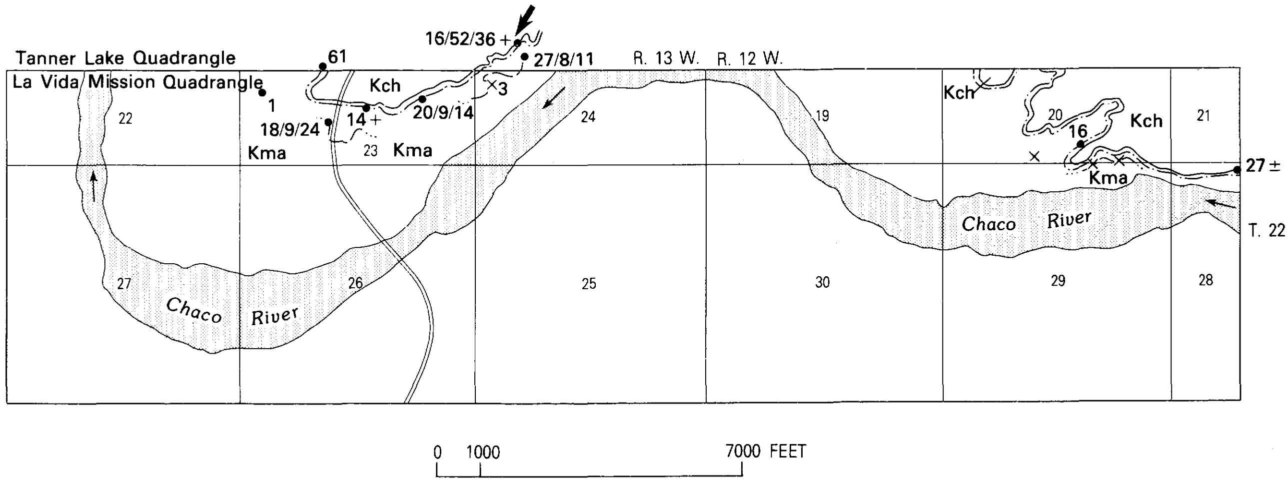
The third coal bed from the top (W2) underlies an area around "white knob," which extends westward into The Pillar 3 SE quadrangle. It also underlies three low ridges of small areal extent in sections 29 and 20, and a tiny knob in the extreme northwest corner of the quadrangle. The total area underlain by the W2 coal in the five separate areas is 45 acres. The W2 coal is, however, also burned at the outcrop, leaving 6 to 8 in of ash to mark the former location of the coal bed. Because the overburden is thin, the coal may be largely or completely burned in the subsurface.

The W1 coal bed is the only one known to have significant thickness. The bed is split into two benches by a parting of dusky-brown mudstone. Together, the benches of coal reach a maximum thickness of 36 inches in the northwest corner of section 32 and also near the north edge of section 29. In these locations, the lower bench is about 2 ft thick and the upper bench ranges from 10 to 19 in thick. The thicknesses of the two benches vary erratically, as does the thickness of the parting between the two. In calculating tonnages of coal in place, it was expedient to consider total thickness of the coal in the two benches, even though locally the thickness of the upper bench is less than 14 in and in some places the thickness of the parting somewhat exceeds that of one or both benches. Using the criteria for calculating tonnages set forth in USGS Circular 891 (Wood and others, 1983), the W1 coal bed in one large digitate-shaped area and one small area in the northwest corner of the quadrangle (fig. 30) underlies 202 acres; the volume of the coal in the combined benches is about 614 acre-ft. Using the average specific gravity and weight of unbroken coal of 1,800 short tons per acre-foot, the calculated total tonnage of coal in place is 790,000 short tons (table 6). Overburden everywhere except beneath "white knob" is a few tens of feet. None of this coal is considered a minable resource under existing economic conditions, because of the thinness of beds and small area.

The W1 coal bed also underlies several tiny buttes east of the main belt of outcrop (fig. 30), but it has burned at the outcrop, and perhaps completely beneath the caprock of the buttes. It also underlies a larger butte just west of the Chaco River at the north border of the quadrangle. Here also the coal is burned at the outcrop.

Coal Beds North of the Chaco River

North of the Chaco River, two parts of an extensive upland developed on the Cliff House Sandstone and younger formations in the Tanner Lake quadrangle extend short distances southward into the La Vida Mission quadrangle. In the northeast corner of the quadrangle (secs. 20, 21, 28, 29, T. 22 N., R. 12 W.) (northeastern subarea), the Cliff House Sandstone makes a nearly vertical cliff 200 ft (61 m) high that forms the front of the upland overlooking the Chaco River. The uppermost part of the Menefee



EXPLANATION

Kch — Cliff House Sandstone

Kma — Allison Member of Menefee Formation

Geologic contact

Upper coal (N2)

Lower coal (N1)

18/9/24 — Location where coal bed thickness was measured. Example shows, from bottom up, 18" coal/9" parting/24" coal

× — Location where burned coal bed was observed. Number beside symbol, where shown, indicates measured thickness of ash in inches

Location of measured section

Figure 31. Location of mapped coal beds and thicknesses of coal beds and partings in the areas north of the Chaco River. Numbers are in inches.

Formation (La Vida Mission Beds) is partly exposed between talus slopes at the base of the cliff. In a northwest direction away from the river, this cliff breaks down into a series of smaller cliffs and benches. In this subarea, only one coal bed of significant thickness is present above river level (N2 in fig. 31). Near the east border of the quadrangle, the N2 bed is 27 in thick, but 1,000 ft (305 m) to the west, on the west side of a sharp spur, it has thinned to 16 in. Where this horizon is exposed elsewhere along the belt of outcrop to the northwest, the coal has burned. Within the northeastern subarea, the N2 coal bed has a total area of 195 acres. Using an average thickness of 21.5 in (1.8 ft), a total tonnage of coal in place was calculated to be 632,000 short tons (table 6). It should be noted that the N2 coal discussed here is not the same coal described and shown by Lease (1971), which is within the tongue of Menefee lithology in the upper part of the Cliff House Sandstone almost 200 ft (61 m) stratigraphically higher. The coal mapped and isopached by Lease in his figure 21 has lensed out north of the La Vida Mission quadrangle. A lower coal (N1) is about 50 ft (15 m) below the N2 bed, but where it is not covered it has burned at the outcrop, which is marked by a clinker zone. Evidence suggests that this coal bed is thin, but whether it is more than 14 in thick anywhere in this northeastern subarea is not known.

The second coal-bearing subarea north of the Chaco River is in the north-central part of the quadrangle (pl. 1 and fig. 31, secs. 23, 24, T. 22 N., R. 13 W.). It consists of a broad spur of the Cliff House upland that slopes gently southwest and is surmounted by the new "express" Highway 371. Much of this spur is covered by a mantle of gravel of Quaternary terrace deposits. Along the northwest wall of Tsaya Canyon, however, the N2 coal crops out at the base of a low cliff of Cliff House Sandstone. In the Tanner Lake quadrangle in sections 24 and 13, this coal was mined and, according to Lease (1971, p. 56), was as much as 7 ft thick. The only mine shown on the Tanner Lake topographic map or noted by us is 500 ft (152 m) north of the La Vida Mission quadrangle. It has long been abandoned, and is unsafe to enter. At the mine, the bed lies 9 ft (2.7 m) below the base of the Cliff House. At the mine mouth, only the uppermost 3 ft of the coal bed are now visible. Close by, an

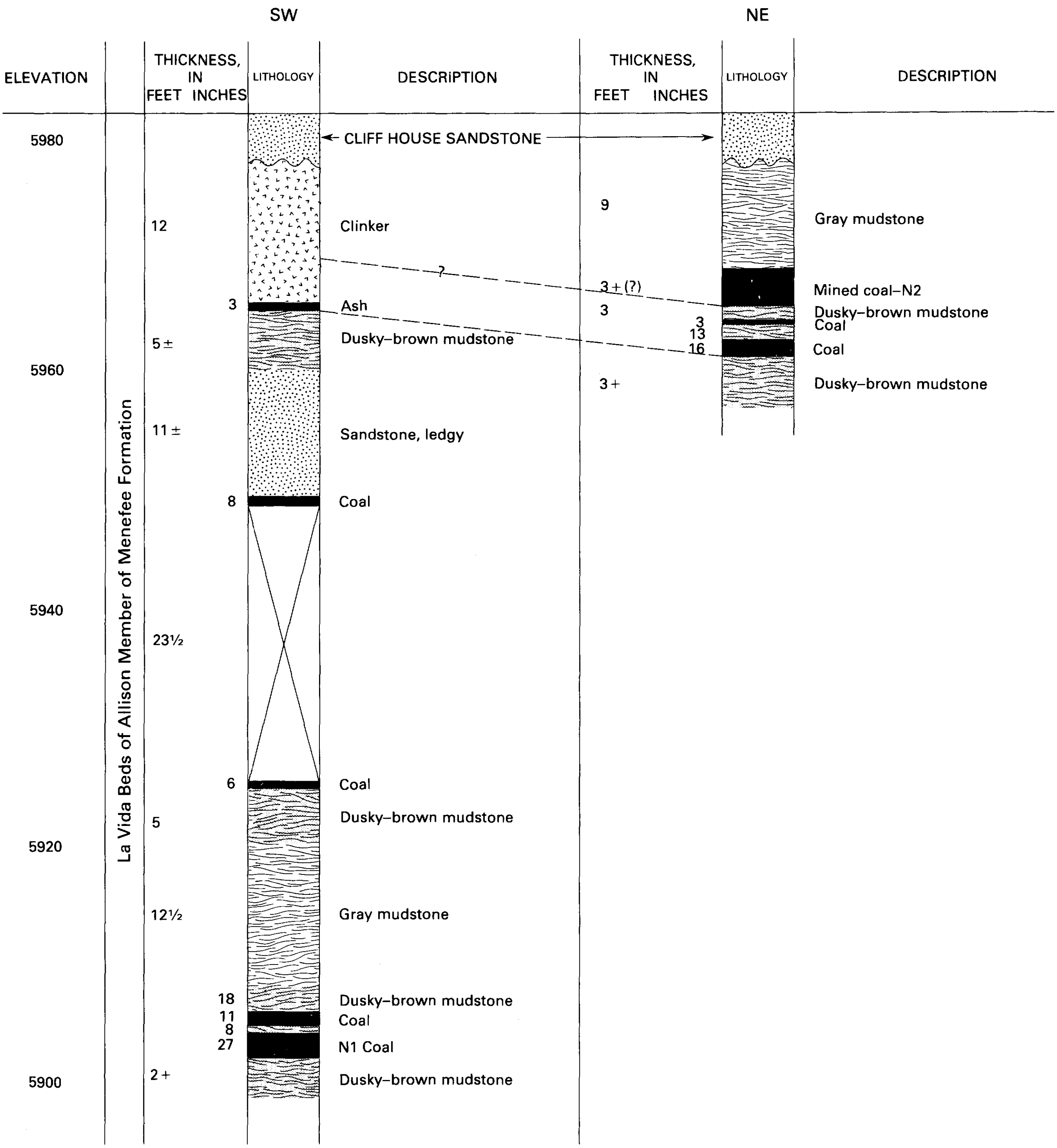


Figure 32. Measured sections several hundred feet apart of N1 and N2 coal beds near an abandoned coal mine in Tanner Lake quadrangle (sec. 24, T. 22 N., R. 13 W.). Sections are about 500 ft (152 m) north of La Vida Mission quadrangle.

outcrop of dusky-brown mudstone below the coal-mine bed does not seem to allow space for an additional 4 ft of coal below the 3 ft of visible coal. Inasmuch as the mine was abandoned and probably also was unsafe to enter when Lease visited it, the reported 7 ft of coal may have been an exaggerated hearsay report, or it may have been a measurement or estimate from the top of the 3-ft (or more?) coal bed to the base of an underlying coal bed 16 in thick (fig. 32).

In the sections measured by us near the mine mouth (fig. 32), the top of the 16-in coal bed lies 4.3 ft (1.3 m) below an approximate base of the coal-mine bed. This 16-in bed was not found anywhere else to the southwest within the La Vida Mission quadrangle. Unless evidence from drilling or extensive trenching at the outcrop is undertaken, the reported 7 ft of coal at the coal-mine site must remain in doubt.

Within the La Vida Mission quadrangle (fig. 31), only three places were found in the north-central subarea where the N2 coal is showing. On the eastern side of section 23, and closest to the mine discussed above, the coal bed is 12 ft (3.7 m) below the base of the Cliff House Sandstone. Here it is 43 in thick but includes a 9-in parting of dusky-brown mudstone near the middle. A short distance to the west, a small bloom of coal through a mantle of lag gravel shows 14 in of coal, probably part of the upper bench of the bed, but neither the base nor the top of the coal at this location could be dug out with the tools at hand. The greatest thickness of the N2 coal bed was found in the Tanner Lake quadrangle about 50 ft (15 m) north of the north edge of the La Vida Mission quadrangle. Here an excellent exposure of the bed 6 ft (1.8 m) below the base of the Cliff House Sandstone has 45 in of coal in sight, and we dug out an additional 16 in below ground level. Dusky-brown mudstone overlies and underlies the bed, which is here without partings. Northward 400 ft (122 m) along the outcrop in the Tanner Lake quadrangle, the coal bed is completely cut out by a channel sandstone at the top of the Menefee. Where the coal bed reappears on the north side of the channel, it is only 33 in thick, and it thins still more to the northwest along the outcrop.

In summary, the outcrop of N2 coal in the central area north of the Chaco River is entirely within section 23. At the east edge of the area, two benches of coal, 20 and 14 in thick, are separated by a 9-in parting. At the west edge, the bed is 61 in thick without partings. Our evidence shows that the bed thins in a northwest direction, as well as to the east and southeast of Tsaya Canyon. No holes that reached the bed have been drilled north and northeast of the localities here described, so the bed's thickness in the subsurface in these directions has not been ascertained.

A lower coal bed, shown N1 in figure 31, lies about 60 ft (18 m) below the N2. It may be a continuous bed, but was found in only two places. In the section measured near the coal mine in the Tanner Lake quadrangle (fig. 32), the bed is in two benches separated by 8 in of dusky-brown mudstone. The lower bench is 27 in thick, the upper 11 in thick. Just west of and below the new highway in section 23, a coal bed that may be the same N1 bed is well exposed. The coal is also in two benches separated by 9 in of dusky-brown mudstone. The lower bench is 18 in thick, the upper 24 in thick. Continuity of the N1 bed between the two outcrops is uncertain, but if the bed is continuous, the amount of coal in this bed within the quadrangle is 282,000 short tons.

In the northeast corner of the quadrangle, the greatest thickness of the N2 coal is about 27 in. It is overlain by as much as 250 ft (76 m) of massive sandstone of the Cliff House. The tonnage calculated here for the N2 bed within the quadrangle is 632,000 short tons. In the north-central area north of the river, overburden ranges from 0 ft at the outcrop to 90 ft (27 m) along the new highway at the north edge of the quadrangle. Averaging the two available measurements of thickness of coal of 61 and 34 in, the calculated tonnage for the N2 bed is 417,000 tons. Thus, total tonnage of coal in the two areas north of the Chaco River is 1,365,000 short tons (table 6). Within the quadrangle, this coal in the La Vida Beds must be considered subeconomic because of the thinness of the coal in the northeastern area and the small acreage in the north-central area.

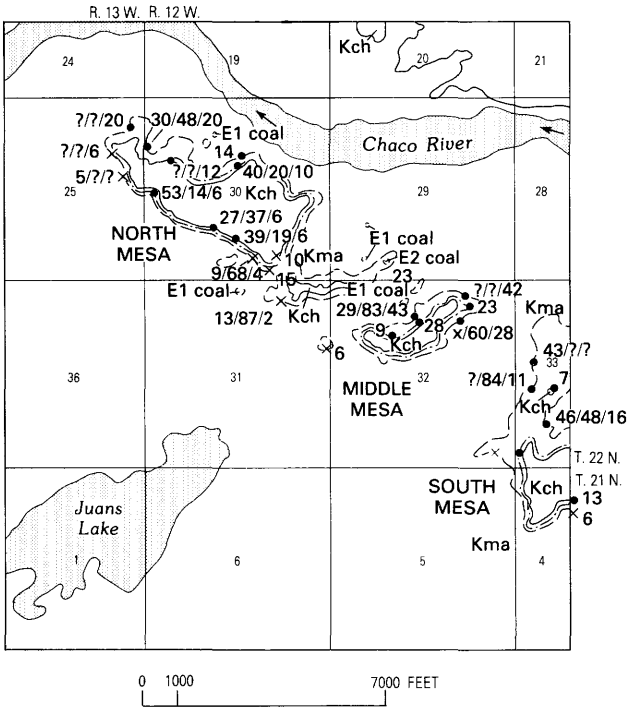
Coal Beds of the Eastern Area

Coal beds in the eastern area crop out near the crest and on the slopes of three mesas aligned from northwest to southeast in the northeastern part of the quadrangle. We have informally named these north, middle, and south mesas to facilitate referring to them (fig. 33). Each of these mesas is capped by massive sandstone beds in the lowest part of the Cliff House Sandstone.

Coal exposures around the mesas are few because talus from the overlying Cliff House beds mantles most of the slopes, and because the coal beds, where they have been exposed, have burned extensively, leaving an ash residue. Approximate locations of the coal are marked by the orange-red baked shale (clinker) above the coal. The clinker is so abundant above the burned beds and in the talus that the mesas, viewed from a distance, have a bright-red tone.

Persistent coal beds, labeled E1 for the lower and E2 for the upper, are present around all three mesas. Between the E1 and E2 beds, other coal beds are found locally at several horizons. We did not attempt to map these intermediate coal beds because none had lateral persistence. Most of the intermediate coal beds were 0.5 to 1.5 ft thick, but in a few places an intermediate coal bed more than 2 ft thick was noted.

North mesa is the largest of the three mesas and has the largest area underlain by coal beds. The E1 coal bed crops out on the lower slopes of the mesa (fig. 33), but is burned at most places where the bed surfaces. Only in the northern part of the mesa were we able to find unburned coal. At the best exposed locality, the bed is split in two by a 4-ft parting of dusky-brown mudstone. The lower bench of coal is 30 in thick, the upper 20 in. At two localities nearby, only one of the two benches was found, probably the upper one. To the southeast, in two exposures this upper bench has 12 and 14 in of coal, and to the northwest, 20 in (fig. 33). At the south tip of the main part of the mesa, the ash from the burned coal is 15 in thick, suggesting a thick bed in this area. Other measurements of ash from the E1 bed are thinner, which may or may not indicate that the coal is thickest at both ends of the mesa and thins toward the center. We found only one ash bed around the southern part of the mesa, suggesting that one of the two benches of the N1 coal to the north or the parting between them has lensed out. The E1 coal also underlies a narrow eastward-curving



EXPLANATION

Kch	Cliff House Sandstone
Kma	Allison Member of Menefee Formation
———	Geologic contact
—·—·—	Upper coal (E2)
— — —	Lower coal (E1)
39/19/6 •	Location where coal bed thickness was measured. Example shows, from bottom up, 39" coal/19" parting/6" coal. Question mark means observed but not measured
×	Location where burned coal bed was observed. Number beside symbol, when shown, indicates measured thickness of ash in inches

Figure 33. Location of mapped coal beds and thicknesses of coal beds and partings in the eastern area. Numbers are in inches.

peninsula at the southeast end of the mesa but is burned at the outcrop. It is also present but burned beneath the caprock of two small buttes north of the peninsula.

The E2 coal bed around north mesa lies from a few feet to as much as 15 ft (4.6 m) below the basal Cliff House Sandstone that caps the mesa (fig. 33). Our E2 coal is the same as the lower coal of Lease (1971, p. 56). The E2, or the ash where it has burned, was found around the southeastern part and on both sides of the mesa, but is absent around the northwest tip of the mesa. There the coal bed has graded laterally into carbonaceous shale and dusky-brown mudstone. The thickest measurement (fig. 33) was on the southwest side of the mesa near its northwest end. Here, 53 in of coal are overlain by 14 in of carbonaceous shale and a rider coal bed 6 in thick. The rider coal bed was found at several other locations, but nowhere is it more than 1 ft thick. The main coal bed thins southeastward from the 53-in location, and elsewhere where measurable it does not exceed 40 in. It is 23 in thick at a knob on the east end of the peninsula of the mesa.

At middle mesa, both E1 and E2 coal beds are present, and locally one or more intermediate beds, which we called beds E1½, were measured but not mapped. The E1 coal bed actually is two beds separated by 5 to 7 ft of dusky-brown mudstone (fig. 33). The lower bed is 29 in thick on the north side of the mesa. Elsewhere it could not be dug out with the tools at hand. The upper E1 bed was measured in three places and is 43, 42, and 28 in thick. The E1 bed also underlies isolated knobs at the west end and north side of the mesa, but in those locations it has burned at the outcrop.

The E2 coal bed at middle mesa is everywhere separated from the basal bed of the Cliff House Sandstone by from a few feet up to 15 ft of intervening beds, which in most places are dusky-brown or gray mudstone. The coal bed was measured in three places around the mesa (fig. 33). It is 28 in thick on the north side of the mesa, but only 9 in thick nearby to the west. At the east tip of the mesa it is 23 in thick. Abrupt thinning of the E2 coal here and elsewhere is not attributable to partial removal by erosion before deposition of the basal Cliff House Sandstone.

Around south mesa, the outcrop of the E1 coal is on the lower slopes of the mesa on its south side, but it extends 0.6 mi (1 km) north of the mesa along a gently sloping spur (fig. 33). The main coal bed is 43 in thick on the west side of the spur near the northernmost extension of the outcrop and 46 in thick on the opposite side of the spur 2,000 ft (610 m) to the south. A rider coal bed 4 to 7 ft (1.2 to 2.1 m) higher is probably the upper E1 coal bed of middle mesa. It is only 11 and 16 in thick at the two locations where we could measure it. Elsewhere around south mesa, the E1 bed is burned where it surfaces, but the resulting ash beds do not exceed 6 inches in thickness. This suggests but does not prove that the E1 bed thins in a southerly direction along the outcrop and beneath the mesa.

The E2 coal bed on south mesa lies near the top of the mesa slopes and less than 15 ft below the base of the caprock of Cliff House Sandstone. It is 20 in thick at the north tip of the mesa, but only 4 in thick nearby, to the southwest. On the east side of the mesa, in a reentrant less than 300 ft (91 m) east of the eastern border of the quadrangle, it is but 13 in thick. South mesa, together with the E1 and E2 coal beds, extends eastward into the adjacent Kin Klizhin Ruins quadrangle. In that quadrangle, the area underlain by the E2 coal bed near the crest of the mesa is small, but the area underlain by the E1 bed is comparable in size to that within the La Vida Mission quadrangle. Resources of coal in the eastern area are shown, by mesa, in table 6. Total calculated tonnage for the eastern area is 2,870,000 short tons. Total calculated tonnage for all coal-bearing areas within the La Vida Mission quadrangle is 5,025,000 short tons.

Representative Sections of the Coal-Bearing Areas

Representative sections of the coal-bearing part of the La Vida Beds for each of the three areas (western, northern, eastern) are shown in figure 34. Correlation of coal beds between the eastern area and the area north of the Chaco River seems straightforward. The E1 and E2 (eastern) beds are correlative with the N1 and N2 (northern) beds. Correlations between these areas and the western area are not as clear. It seems probable that the E2 and N2 beds correlate with the W4 bed, because of similar placement close beneath the base of the Cliff House Sandstone and because the N2 is more than 5 ft thick in its westernmost exposure, and though burned at the outcrop, the W4 has left behind a very thick (24-in) ash bed.

Correlation of the E1 (eastern lower) and N1 (northern lower) coal beds is probable because of similar stratigraphic placement (fig. 34), but which one, if any, of the lower coal beds of the western area is correlative with the E1 and N1 is unknown. The thick sandstone and mudstone units in the western area do not appear to correlate with similar lithologic units in the northern area. The W1 and N1 may represent the same coal bed, with the burned W2 and W3 beds of the western area the same as the 6-in and 8-in beds in the section (fig. 32) north of the Chaco River, but this is highly speculative.

Summary of Coal Resources

The coal resources of the La Vida Mission quadrangle (table 6) are placed in the subeconomic category (Wood and others, 1983, U.S. Geological Survey Circular 891, fig. 2) for the following reasons:

1. The coal beds are lenticular, as demonstrated by comparison of the western area, where four coal beds are present, and the northern area, 3 mi distant, where only two coal beds more than 6 in thick are present.
2. The coal beds thicken and thin erratically. The thickest bed, N2 of the northern area, is 61 in at the north edge of the quadrangle but only 43 in thick, including a 9-in parting, half a mile to the east. In the Tanner Lake quadrangle 200 ft (61 m) north of the 61-in locality, the coal bed has been completely eliminated by a channel sandstone at the base of the Cliff House Sandstone, but on the northwest edge of the channel the coal bed is only 21 in thick.
3. Six areas underlain by coal beds are present in the quadrangle. All are separated from each other by intermediate areas where older rocks beneath the coal-bearing sequence are at the surface. The largest coal-bearing subarea is north mesa in the eastern area, where 211 acres are underlain by 538,000 short tons of measured coal in the E1 bed and 845,000 short tons of coal in the E2 bed. Additional data obtained by trenching and (or) drilling may be expected to enlarge the tonnage for the E1 bed, which is at the foot of the mesa, but the figure for the E2 bed, which is near the crest of the mesa, is not subject to much change.
4. All the coal beds are extensively burned at the outcrop, so few measurements of thickness of the beds have been possible. Although thick ash beds suggest that the unburned coal was likewise thick, no regional ratio between ash and unburned coal has been established. Nor are there any data on distance of the burns inward from the outcrop. This is probably determined by amounts of fracturing of the coal, thickness of overburden, and number and spacing of joints in the overburden.
5. Five of the six areas are scenically handsome. This is especially true of the western area, which is a superb example of badlands erosion and is rendered colorful by the abundant red and orange clinker where coal beds have burned.
6. The north-central subarea north of the Chaco River is bisected by new State Highway 371 so that the subarea could not be treated as a unit, should mining be contemplated.

For one or any combination of these reasons, the tonnages that have been calculated for each mapped coal bed in each of the six subareas are considered noneconomic. The available data from which the calculations were derived are shown in figures 30, 31, and 33, and the statistics on the coal beds are shown in table 6.

Rank of Coal

Rank of coal is determined by the percentage of fixed carbon on a dry, mineral-matter-free basis or by the heating value of the coal on a moist, mineral-matter-free basis. Coals having more than 69 percent of fixed carbon constitute medium- and low-volatile bituminous coal and anthracite. Below 69 percent fixed carbon, the heating value of the coal determines the rank. These ranks comprise high-volatile bituminous coal, subbituminous coal, and lignite (Averitt, 1974, table 4).

Proximate analyses, as performed by the U.S. Bureau of Mines and other coal laboratories to determine rank accurately, require unweathered samples. These may be garnered from underground mines, deep strip mines, or core holes. Unfortunately, samples of the coal beds within the La Vida Mission quadrangle are not obtainable from any of these sources. A few core holes have, however, penetrated

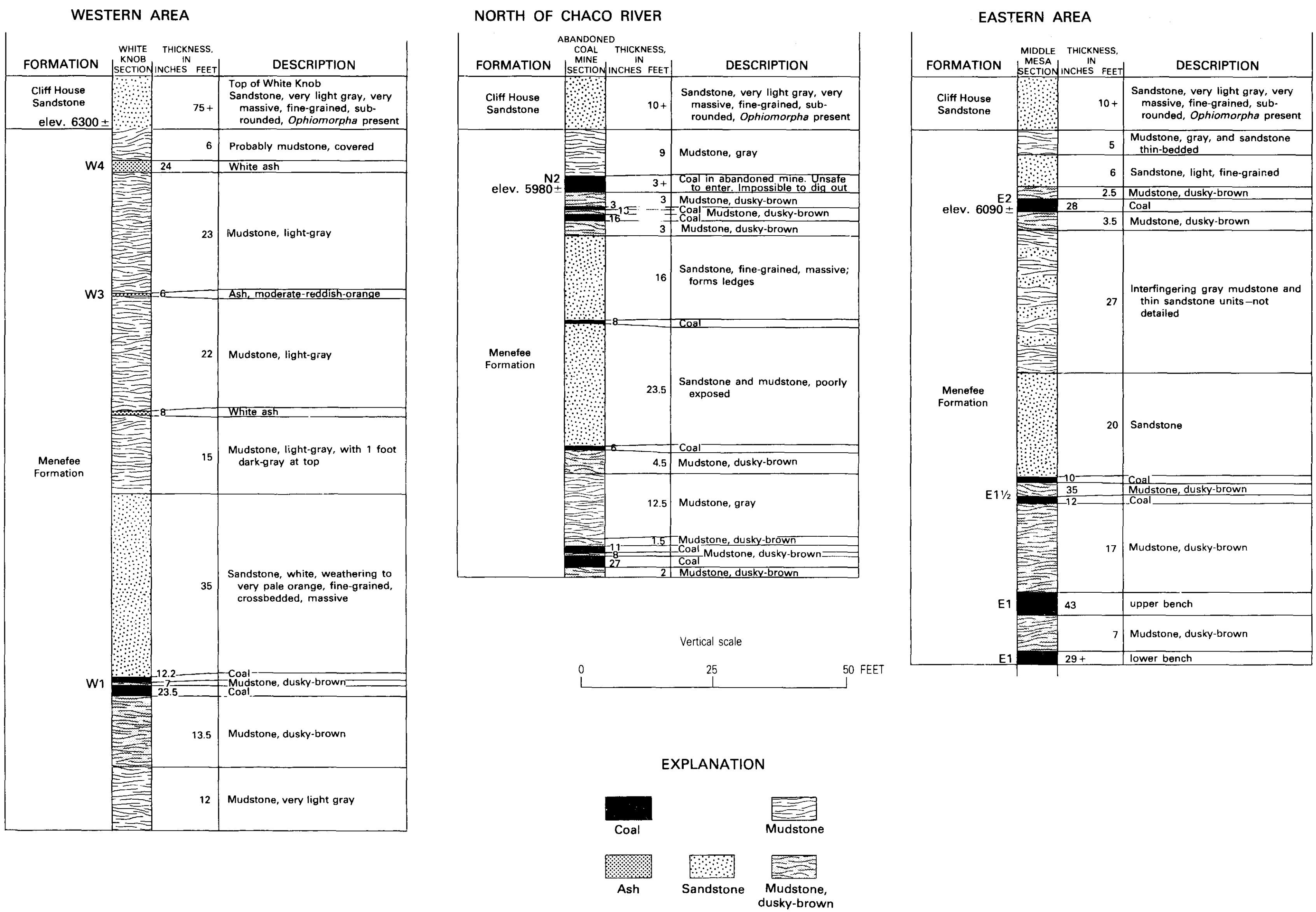


Figure 34. Representative sections for each of the three coal-bearing areas (western, northern, and eastern). The N2 and E2 coal beds probably are the same bed, and the N1 and E1 may be the same bed. Other correlations are speculative.

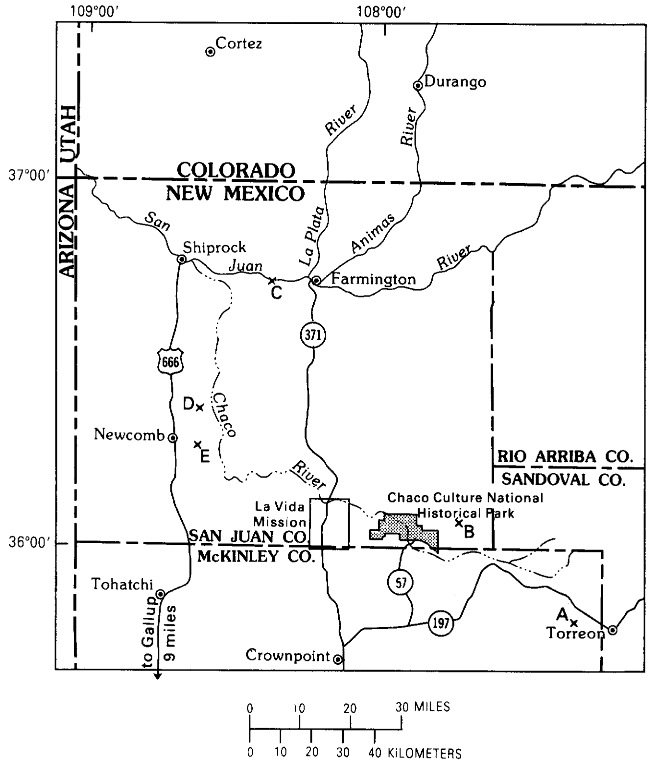


Figure 35. Location of core holes A–E from which analyses of coal samples from the upper part of the Menefee Formation have been published.

coal beds in the upper part of the Menefee outside the quadrangle but in this part of the San Juan Basin. Locations of these core holes with respect to the location of the La Vida Mission quadrangle are shown in figure 35. Analyses of the samples from these core holes have been published by the New Mexico Bureau of Mines (Shomaker and others, 1971, table 3; Shomaker and Whyte, 1977, table 2). The New Mexico publications record the coal by its heating value, in Btu's in three categories: the samples as received, moisture free, and ash free. In contrast, the classification of coal by the American Society for Testing and Materials, which is used by the USGS and U.S. Bureau of Mines (Averitt, 1975, table 4) to determine the rank, is on the basis of the moist, ash-free values. The heating values of the samples given in the published tables have, therefore, been recalculated, and are listed in table 7.

Analyses of all the samples from the core holes show fixed carbon well below 69 percent. Hence, the heating value of the coal becomes the factor for determining rank. Of the five analyses in table 7, the two to the east (core holes A and B, fig. 35) show heating values of 12,260 and 12,250 Btu's on a moist, ash-free basis, which would indicate coal of high-volatile C bituminous rank (Averitt, 1975, table 4). Core hole C, to the north of the quadrangle, has a value of 13,700 Btu's, which is in the high-volatile B range. The two samples from the Newcomb area to the west (core holes D and E) show heating values of 11,180 Btu's, which is in the high-volatile C rank if agglomerating, and 10,210 Btu's, which falls in the subbituminous A-B ranges. Core holes B, to the east, and D and E, to the west, are about equidistant from the La Vida Mission coal-bearing area, but the heating values of the three are quite different. Because core holes A-B and D-E, which are on opposite sides of the La Vida Mission quadrangle, are more likely than locality C to the north to be along the trend of similar facies, they may more closely approximate the rank of La Vida Mission coal beds. The A and B samples fall within the range of high-volatile C bituminous coal, whereas the D and E samples are in the ranges of subbituminous A and B coal, respectively, if D is not agglomerating. Menefee coal beds in the La Vida Mission quadrangle, therefore, are probably of high-volatile bituminous or low-volatile subbituminous rank.

Grade of Coal

The quality, or grade, of coal is largely dependent on the content of ash and sulfur. Other minor or trace constituents are present in all coals and may be deleterious for industrial or specialized uses of the coal. Presence of partings of noncoaly material within the coal beds is not considered serious in evaluating the grade of coal because this waste material can be removed in the processing of the coal. The criteria used by the U.S. Geological Survey

Table 7. Data from analyses of samples of coal beds in the upper part of the Menefee Formation, from core holes near La Vida Mission quadrangle

[Data recalculated to moist, ash-free basis from published analyses of Shomaker and others, 1971, table 3, and Shomaker and Whyte, 1977, table 2. Location of core holes shown in fig. 35]

Core hole	Location			Proximate analysis (as received percent)					Heating value (Btu)		Remarks
	Sec.	T.N.	R.W.	Moisture	Volatile matter	Fixed carbon	Ash	Sulfur	As received	Moist, ash free	
A	11	18	5	12.0	34.4	36.3	17.3	0.3	9,920	12,260	Average of 3 analyses; 3 coal beds?
B	7	21	8	12.0	33.6	44.9	9.5	1.0	10,950	12,250	
C	9	29	15	5.6	40.4	47.7	6.3	0.8	12,740	13,700	
D	36	25	17	15.8	31.5	40.0	11.8	1.3	9,720	11,180	Average of 2 analyses; 2 coal beds?
E	2	23	17	18.5	27.7	31.1	22.7	0.5	7,660	10,210	

(Wood and others, 1983) for determining the grade of coal on an as-received basis are as follows:

	Percent of ash	*Percent of sulfur*	
Low ash	−8	Low	−1
High ash	+15	High	+3
Non-coal	+33		

It is clear from the analyses in table 7 that there is no consistency in the quality of coal with respect to content of ash and sulfur. One of the analyses shows low-ash coal, two high-ash coal, and two in between. All but one of the analyses show low sulfur content. More analyses from unweathered samples within or near the La Vida Mission quadrangle will be needed before any generalizations about the quality of the coal in the La Vida Beds are justified.

Coal beds in the La Vida Mission quadrangle are remarkably free of visible detrital material. Partings within the coal beds are rare, be they carbonaceous shale, mudstone, or other material. "Bone coal" and sandy coal are likewise rare.

OIL AND GAS

Oil was first discovered in the New Mexico part of the San Juan Basin near Seven Lakes, McKinley County, in 1911. Oil and gas were found in six wells, but production was small and by 1913 the field was practically abandoned (Gregory, 1917). Later, in 1921, gas was discovered near Aztec, N. Mex., in the northern part of the San Juan Basin. This was followed in 1922 by discovery of oil near the Hogback monocline in the northwestern part of the basin (Bates, 1942). These early successes have been followed by many discoveries of both gas and oil fields, especially but not exclusively in the northern part of the basin. Two dry holes have been drilled in the La Vida Mission quadrangle, one that bottomed in the Morrison Formation (Jurassic) and another that bottomed in the Mancos Shale (Late Cretaceous). Other wells have been drilled to the west near the La Vida Mission quadrangle. Of those for which well records have been kept, only two reached the Dakota Sandstone. In 1986, a small oil field, named the "Nose Rock Field," was discovered 2 mi (3.2 km) south-southwest of the southeast corner of the La Vida Mission quadrangle. It produces from the Gallup Sandstone (section on Gallup Sandstone). In 1988, 15,000 barrels of oil were produced from five wells. As of May 1989, it was still producing (Ronald F. Broadhead, written commun., 1989). Large areas of the central and southern parts of the San Juan Basin remain untested. The Gallup and Dakota Sandstones appear to be the most favorable targets.

The earlier of the two wells within the quadrangle, located in the northeast corner of sec. 19, T. 21 N., R. 12 W. (pl. 1), was drilled by Sinclair Oil and Gas Company in 1957. It started about in the middle of the Juans Lake Beds of the Allison Member of the Menefee and bottomed at a depth of 2,875 ft (876 m) in the Mancos Shale. The tops of formations recorded on the driller's log are at the following depths: Point Lookout Sandstone 1,493 ft (455 m), Mancos Shale 1,630 ft (497 m), and Hospah-Gallup Sandstone [sic] 2,532 ft (772 m). No shows were reported. The second well was drilled by the same company in 1958, 2,500 ft (762 m) to the north. It is located in the east-central part of sec. 18, T. 21 N., R. 12 W. (pl. 1). Total depth was 3,852 ft (1,174 m). Like its predecessor, it was dry and no shows were recorded. Tops of formations were identified on the electric log and listed on the well record. It is difficult to reconcile some of the names used on this well log with the revised nomenclature for the Mancos-Mesaverde sequence of formations advanced by Beaumont, Dane, and Sears (1956). The thick sandstone units in the log are, however, believed to be correctly identified, and the tops are probably a close approximation. These tops are as follows: Point Lookout Sandstone 1,500 ft (457 m), Gallup Sandstone 2,736 ft (834 m), Dakota Sandstone 3,658 ft (1,115 m), and Morrison Formation 3,800 ft (1,158 m).

Although both of these wells in the La Vida Mission quadrangle were dry, small production was obtained from the Dakota Sandstone in a well 1.4 mi (2.3 km) west of the quadrangle close to the White Rock Trading Post in The Pillar 3 SE quadrangle. This well was drilled in 1950 on an anticlinal structure. It produced nearly 8,000 barrels of oil. The well was deepened to basement in 1952, and then abandoned. Seven additional Dakota wells, all dry, were drilled along the structural trend. Data on this tiny oil field, named the "Stoney Butte Field," were recorded by R.E. Lauth (1978, p. 503–504). Three additional shallow wells in The Pillar 3 SE quadrangle northward along the same structural trend each produced a few barrels of oil (less than 12 barrels per day) from a sandstone lens in the Allison Member (Juans Lake Beds) of the Menefee Formation at depths of about 900 ft (274 m) (Lauth, 1978, p. 505–506). Cumulative production over a 5-year interval (1953–1957) was nearly 16,000 barrels.

Prospects for oil or gas in the La Vida Mission quadrangle are little tested and virtually unknown. The uniform, very gentle dips (1/2 to 1 1/2° to the north-northeast) and the absence of faults provide no promise of structural traps. Stratigraphic traps involving the Dakota Sandstone, Gallup Sandstone, Point Lookout Sandstone, and (or) thinner sandstone units in the marine Mancos Shale and equivalents are possible. Regional subsurface studies and geophysical surveys, of which some may already have been made by industry, will be needed to establish favorability or otherwise of the La Vida Mission area.

OTHER RESOURCES

Hard red clinker from baked shale overlying a burned coal bed was used for road fill in construction of new State

Highway 371. The rock was quarried from a site near White Rock Trading Post in The Pillar 3 SE quadrangle 1 mi (1.6 km) west of the La Vida Mission quadrangle, and trucked to a stockpile near Tsaya Trading Post (topographic map) in the La Vida Mission quadrangle. Abundant clinker is present in the La Vida Mission quadrangle, some of which may be in favorable location and position for quarrying for future road building.

Dusky-brown, organic-rich mudstone (humate) is abundant in the quadrangle. Elsewhere, this rock has been quarried on a small scale and used as a soil conditioner.

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