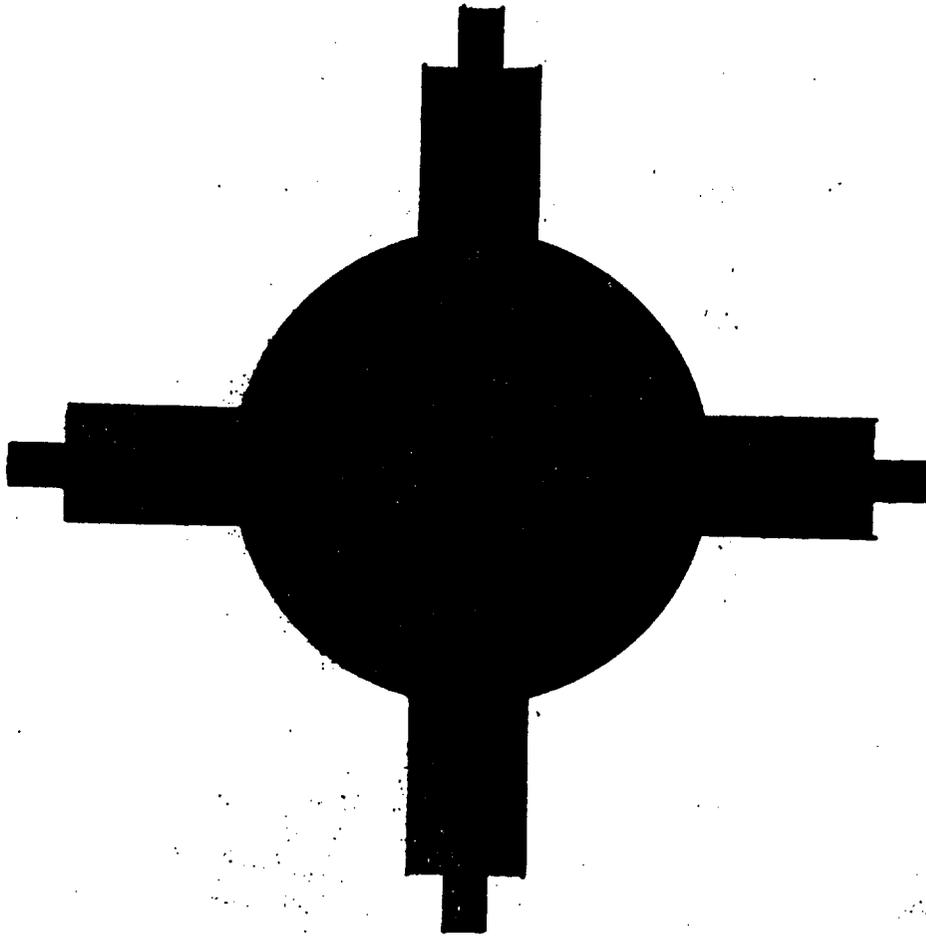


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NEW MEXICO GEOLOGICAL SOCIETY



Guidebook
OF THE
SAN JUAN BASIN
New Mexico and Colorado

FIRST FIELD CONFERENCE

November 3-4-5, 1950

NMOCD CASE #11996
PENDRAGON ENERGY
EXHIBIT

W-5

**CRETACEOUS ROCKS
OF THE SAN JUAN BASIN AREA**

By Paul H. Umbach
Stanolind Oil and Gas Company

The Cretaceous in the San Juan Basin consists mainly of interbedded sandstone and shale varying in general from approximately a 5, 250-foot predominantly shale series in the northeastern portion to approximately a 4, 000-foot predominantly sandstone series in the southwestern portion. The Cretaceous thickness over the San Juan Basin is relatively uniform, considering the rapid change in the type of sediments.

The Graneros shale, 20-150 feet thick, consists of a black, dense, heavy, "poker chip" shale which can be correlated over the entire basin.

The overlying Greenhorn limestone, 50-100 feet thick, is recognized as a very calcareous shale over most of the central and northern portion of the San Juan Basin. The Mancos, with a thickness of 700-2, 300 feet, thins and intertongues with the Mesaverde in the southern portion of the San Juan Basin. In the northeastern portion of the basin the Mancos consists of black, dense shale, which grades to a more silty shale in the southwestern portion.

Although the Carlile and Niobrara shale are recognizable in some areas, they are not in common use. Most geologists at the present time prefer to

DEFIANCE UPLIFT	SAN JUAN UPLIFT	NACIMIENTO UPLIFT	ZUNI UPLIFT
WEST	NORTH	EAST	SOUTH
Ojo Alamo	Animas / Ojo Alamo	Ojo Alamo	Ojo Alamo
	McDermott		
Kirtland	Kirtland	Kirtland	Kirtland
Fruitland	Fruitland	Fruitland	Fruitland
Pictured Cliffs	Pictured Cliffs	Pictured Cliffs	Pictured Cliffs
Lewis	Lewis	Lewis	Lewis
Cliff House			See Coal Reports for Detail
Menefee	Menefee	Menefee	
Point Lookout	Point Lookout	Point Lookout	
Mancos	Mancos	Mancos	Mancos
Dakota	Dakota	Dakota	Dakota

**CRETACEOUS FORMATIONS FLANKING THE MAJOR
UPLIFTS IN THE SAN JUAN BASIN**

The Dakota, with a thickness of 175-275 feet, varies from a fine-grained sandstone to a coarse conglomerate with intervening black shale and coal and is often divided into three zones commonly known as the upper, middle, and lower Dakota. Although these zones may be used in general as the upper, consisting of fine-grained sandstone, the middle, a shale and coal series, and the lower, a coarse conglomerate, such a division is difficult to correlate with any degree of accuracy.

obtain more control to determine the value of these members as correlative markers.

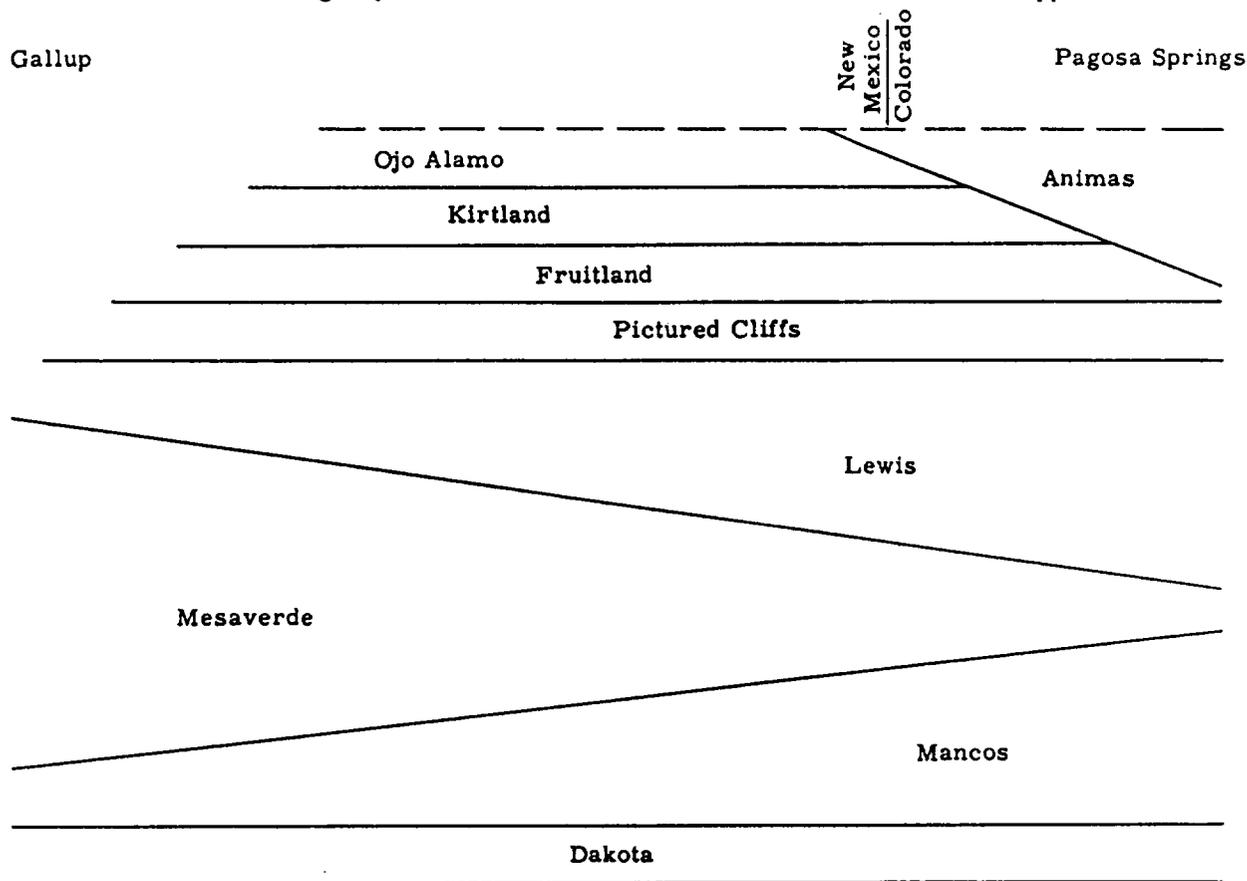
The Mesaverde Group

The Mesaverde group consists of the Point Lookout, Menefee, and Cliff House formations, with the exception of the southern portion of the San Juan Basin, where the group is further subdivided as a result of coal studies made by the U. S. Geological Survey.

The Point Lookout sandstone, 150-200 feet thick, consists of a medium- to fine-grained sandstone which extends over the central and northern portion of the basin. In the southern portion of the basin this sandstone is underlain by tongues of sandstone interbedded with shale and coal which are considered to be in the Mesaverde group.

The Fruitland formation 0-500 feet thick, consists of coal, clay, shale, and sandstone of brackish and fresh water origin.

The Kirtland formation 0-1,200 feet thick, contains green to gray shale with interbedded sandstone and is divided into an upper and a lower



HYPOTHETICAL SECTION SHOWING RELATIONSHIP OF BEDS IN THE SAN JUAN BASIN BETWEEN GALLUP, NEW MEXICO, AND PAGOSA SPRINGS, COLORADO

The Menefee formation, 0-1,600 feet thick, consisting of black shale, coal, and sandstone, is present in the northern three-fourths of the basin. In the southern portion the formation is subdivided into several coal members.

The Cliff House formation, 0-250 feet thick, contains medium- to fine-grained sandstone which thins northeastward in the San Juan Basin.

Overlying the Mesaverde is the Lewis formation, 150-2,500 feet thick, a gray, silty shale with a few thin sandstone layers. This formation thickens to the east at the expense of the Mesaverde.

The Pictured Cliffs sandstone, 50-500 feet thick, contains interbedded shale and thin coal streaks within the massive white marine sandstone. This sandstone thickens northeastward at the expense of the overlying Fruitland formation.

member with a middle sandstone tongue which has been called the Farmington sandstone member.

The McDermott formation, 0-300 feet thick, is composed of brown to purple shale with a small amount of sandstone. This formation has its greatest thickness in the northwestern portion of the basin.

The Ojo Alamo sandstone, 0-200 feet thick, consists mainly of coarse sandstone and pebbles lying unconformably upon the Kirtland series. Although this contact has been reported as being conformable, sufficient evidence has been presented to prove that it is unconformable.

The Animas formation, 0-2,000 feet thick, of late Cretaceous and Paleocene age, consists predominantly of arkosic sandstone and green to gray micaceous shale.

STRATIGRAPHY AND DEPOSITIONAL HISTORY OF UPPER CRETACEOUS ROCKS OF THE SAN JUAN BASIN AREA, NEW MEXICO AND COLORADO, WITH A NOTE ON ECONOMIC RESOURCES

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INTRODUCTION

During Late Cretaceous time, the San Juan Basin was part of the large western interior geosyncline that transected much of North America. The San Juan Basin, which is a 100- to 150-mile (160- to 240-km)-wide, near-circular, early Tertiary structural basin, was superposed on a small part of this larger Cretaceous depositional basin, thus preserving an almost complete Upper Cretaceous section. These rocks, which contain large reserves of gas, oil and coal in or flanking the basin, crop out almost entirely around the basin. The many fine outcrops, the large quantity of subsurface well control (about 10,000 wells), and the simple structure within the basin make this area ideal for academic as well as economic studies of these rocks. Consequently, the literature abounds with many fine papers on different aspects of Upper Cretaceous rocks. A list of these papers probably would fill a good part of this volume.

Although the stratigraphy and depositional history of Upper Cretaceous rocks of the San Juan Basin have been covered in many different publications, it seems necessary to review them in a guidebook dealing with the San Juan Basin. Hopefully, this paper presents a balanced summary, based on the literature and many observations of the writer, with possibly a few new facts or ideas plus some stratigraphic trivia that may be of interest.

TIME-STRATIGRAPHIC ILLUSTRATION

A time-stratigraphic illustration portrays stratigraphy and depositional history in a time sense without the confinements of stratigraphic thicknesses. Using this method, units are placed in proper paleogeographic position in relation to other time-equivalent strata or events. Figure 1 is an Upper Cretaceous time-stratigraphic section across the San Juan Basin and extending southwest into the Zuni basin across the depositional strike. This section was constructed from both outcrop and well data and shows the generalized relationships of three major fields: marine shale or siltstone, marine and coastal-barrier sandstones and nonmarine deposits. These varying lithologies are the basis for differentiating most Upper Cretaceous formational units in this area. Because time, rather than thickness, is represented on the vertical scale, thickness can be shown only by notation; however, the interpretation of facies and formational relationships and of depositional history is more readily apparent using this type of illustration.

Many absolute time scales are available. Each has some limitation in fitting the stratigraphy (and paleontology) to absolute time. As more precise radiometric age dates are tied to paleontologic zonations, undoubtedly more accurate time scales will become available. The time scale used for Figure 1, right or wrong, seemed to be the best fit for the Upper Cretaceous of the San Juan Basin at the time (1972). However, problems still exist. For instance, (1) was Greenhorn time as

long as that shown, and (2) was the rate of sedimentation of the Lewis Shale almost twice as fast as that of the upper Mancos Shale and six times that of the lower Mancos Shale, as depicted on the right side of Figure 1?

In constructing the cross section, some of the paleontological data were comprised in order to show the different time-stratigraphic units within the time scale that was used. This is especially true in the Mulatto Tongue through the lower part of the Point Lookout interval. More emphasis was placed on the physical relationships of the many marker beds, and a more-or-less uniform sedimentation rate was assumed within this interval. Recent fossil evidence indicates that the Mulatto and Satan tongues may be somewhat younger in their relation to the stages than is shown on the section. For a time correlation of the different units, strictly on the basis of the most recent macrofossil data, refer to the paper in this volume by Peterson and Kirk. Some of these data were unknown to this writer at the time of the construction of the time-stratigraphic section.

Needless to say, more refinements are necessary in tying paleontology to absolute time. However, the essence of a time-stratigraphic section is the portrayal of time-synchronous deposition (or erosion) and of how facies migrate through time—regardless of whether the time scale is absolutely correct.

DEPOSITIONAL SETTING

During Late Cretaceous time, the San Juan Basin area was a scene of interplay between a shallow seaway on the northeast and a clastic sediment supply coming across a low-relief area on the southwest. Or, as one geologist put it (Fassett, 1974), the area was in the SCI-SWO ("sea came in, sea went out") zone. Four or five major transgressions and regressions, as well as many minor ones, left a stratigraphic record similar to that shown in Figure 1. Most of the deposition took place during the regression, or when the shoreline was migrating seaward. During all this time, relative sea level was rising and/or the area was subsiding, at least episodically, so that at least 6,500 feet (2,000 m) of sedimentary rocks was deposited. Basin subsidence played a large part in this; during this same period of time, about half this thickness of strata was deposited in eastern Colorado and about twice as much was deposited in central Utah. Even within the San Juan Basin area, depositional thickening to the southwest can be demonstrated.

The regressive wedges consist of composited deltaic and interdeltic deposits. The delta fronts and the strandlines of the interdeltic areas were dominated by marine processes, dominantly longshore currents, which produced fairly straight shorelines and thick shoreface or coastal-barrier sands. The

time logs. It is an excellent time surface to which stratigraphy of underlying and overlying formations may be related.

Pictured Cliffs Sandstone

The Pictured Cliffs Sandstone is a regressive coastal-barrier sandstone that represents the final retreat of the western interior sea from the San Juan Basin area. The continued regression to the northeast is represented by the slightly younger Trinidad Sandstone of the Raton basin. Like the Point Lookout, the Pictured Cliffs prograded at different rates; and, as a result of still-stands or small transgressions and subsequent regressions, greater thicknesses were built up. Locally, it is as much as 400 feet (122 m) thick, but the average thickness is much less. On the southeast side of the basin, the Pictured Cliffs is very thin; it is absent for a considerable distance along the outcrop belt on the east side. This is due to removal by pre Ojo Alamo (Paleocene) erosion in the northeastern part, but in the southeast part, the Fruitland Formation directly overlies the Lewis Shale. Fassett and Hinds (1971, p. 12) suggested that either concomitant uplift in the area caused rapid retreat of the sea and prevented development of strandline sands, (Pictured Cliffs) or uplift resulted in erosion of the sands prior to Fruitland deposition.

The total stratigraphic rise of the Pictured Cliffs Sandstone across the San Juan Basin from outcrops on the southwest to outcrops on the northeast, a distance of about 80 miles (129 km), is about 1,100 feet (355 m) (Fassett and Hinds, 1971).

Fruitland Formation

~~The Fruitland Formation represents nonmarine, lower coastal-plain deposition behind the Pictured Cliffs shoreline. It consists of paludal carbonaceous shale and coal interbedded with siltstone and sandstone. It forms subdued topography, and the best outcrops usually are found in roadcuts. However, good outcrops of the Fruitland occur in the Bisti badlands just south of Bisti Trading Post on the Farmington-Crownpoint road. Some of the thickest coal beds in the basin occur in the Fruitland.~~

The upper contact of the Fruitland with the overlying Kirtland Shale is placed at the highest coal or carbonaceous shale bed. This is somewhat arbitrary, because different geologists may pick the contact very differently. The Fruitland ranges in thickness from zero on the east side of the basin, owing to truncation prior to Ojo Alamo (Paleocene) deposition (Fassett and Hinds, 1971), to about 500 feet (152 m), but averages about 300-350 feet (91-107 m).

Kirtland Shale

The Kirtland Shale conformably overlies the Fruitland Formation and represents upper coastal- or alluvial-plain deposition landward from the Fruitland coal swamps. It has been divided into three units called, in ascending order, the lower shale member, Farmington Sandstone Member, and upper shale member. The lower shale member is composed predominantly of gray shale containing a few thin interbeds of sandstone and siltstone. The Farmington Sandstone is composed of a number of fluvial sandstone beds interbedded with shale. The upper shale member also consists of sandstone and shale. The Farmington Sandstone and upper shale members are difficult to separate consistently, because of the presence of sandstone beds similar to the Farmington Sandstone throughout the upper shale member (Fassett and Hinds, 1971, p. 23).

The lower shale member ranges in thickness from zero on the east, owing to truncation prior to Ojo Alamo deposition, to about 450 feet (137 m) and averages about 200-250 feet (61-76 m). The undivided Farmington Sandstone and upper shale member ranges in thickness from zero on the east to about 1,500 feet (457 m) in the northwest part of the basin.

The total Kirtland Shale thins from northwest to southeast across the San Juan Basin owing to truncation prior to Ojo Alamo deposition. How much Upper Cretaceous strata have been removed is speculative, but certainly a considerable amount has been removed on the east side of the basin.

McDermott Member of the Animas Formation

The McDermott Member of the Animas Formation is a local unit present in outcrops along the northwest side of the San Juan Basin, primarily in the Colorado portion. It is composed of purple to brown nonmarine sandstone, conglomerate and shale of andesitic composition and is about 300 feet (91 m) thick in the Durango area. On the basis of dinosaur bones reported by Reeside (1924), the McDermott has been considered Late Cretaceous in age. It is now mapped as a basal member of the Animas Formation, which is considered Paleocene in age (Fassett and Hinds, 1971, p. 33). The McDermott (and the Animas) is thought to unconformably overlie the Kirtland.

The McDermott and probably the uppermost part of the Kirtland Shale represent a change in provenance from the distant southwesterly source for other Upper Cretaceous formations to a local north, northwest, or possibly even western source as igneous activity commenced in the Rico, La Plata, Ute and Carizzo Mountain areas. Late Cretaceous to earliest Tertiary radiometric age dates have been determined for intrusive rocks in those areas (Armstrong, 1969). Extrusive equivalents of intrusives could well have been the source for the volcanic detritus found in these uppermost Cretaceous units in the northwestern corner of the San Juan Basin.

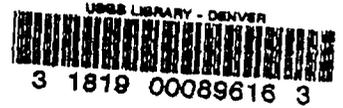
ECONOMIC RESOURCES

The purpose of this paper has been to summarize the Upper Cretaceous stratigraphy and depositional history. However, because the San Juan Basin contains the third largest gas field (Prudhoe Bay is considered second) and one of the largest coal mines in the country; and both are from Upper Cretaceous rocks, it seems fitting to briefly mention the economic resources of the Upper Cretaceous rocks and the respective formations in which they occur. Much of the statistical data on the oil and gas are from the 1975 International Oil and Gas Development Yearbook of the International Oil Scouts Association.

Oil and Gas

The Blanco gas field covers about 1,340,000 acres of the central San Juan Basin. The field is unique because the accumulation largely is hydrodynamically controlled in the structurally low part of the basin. The major production is from the Dakota, Point Lookout, Cliff House and Pictured Cliffs sandstones, with minor production from the Fruitland Formation and Farmington Sandstone. The ultimate recovery is estimated to be about 23 trillion cubic feet of gas, plus significant amounts of condensate (Pritchard, 1972, p. 284). Total gas production in 1974 was about 556 billion cubic feet,

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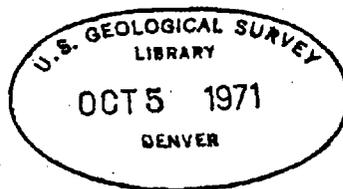


Geology and Fuel Resources of the Fruitland Formation and Kirtland Shale of the San Juan Basin, New Mexico and Colorado

By JAMES E. FASSETT and JIM S. HINDS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 676

A subsurface and surface study of the coal-bearing Fruitland Formation, the Kirtland Shale, and associated rocks, with emphasis on the relation between regional stratigraphy and the distribution, thickness, and quality of coal



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ductivity curve. The conductivity is much less, about 190 millimhos/m in contrast with 550 millimhos/m figure 3A. As in figure 3A, the response of the resistivity and the spontaneous-potential curves to the marker bed is slight. On the sonic-gamma ray log, the gamma ray curve shows the Huerfanito to be relatively more radioactive than it is in figure 3A. The interval transit time, however, is much less in figure 3B than in 3A.

To summarize: (1) The marker bed is more conductive than the rocks above and below it, particularly on the west side of the San Juan Basin. (2) The marker bed is more radioactive than the rocks above and below it, especially on the east side of the basin. (3) The marker bed transmits sound waves more slowly than the beds above and below it, particularly on the west side of the basin. The Huerfanito Bentonite Bed has been traced by the authors throughout the subsurface of the San Juan Basin on electric logs.

The bentonite composing the Huerfanito Bed represents an ancient volcanic ash fall into the Lewis Sea. The source of the ash was probably to the west because the relative response of both the conductivity curve and the interval-transit-time curve decreases from west to east across the basin, indicating a thicker bed of ash to the west. Unfortunately, the Huerfanito has never been cored in the San Juan Basin, so it has never been seen. Also, it has not been possible to correlate a specific Lewis bentonite bed on the outcrop with the Huerfanito. Hollenshead and Pritchard (1961, p. 106) stated: "The examination of cuttings demonstrated that the 'Green Marker Horizon' lies within a somewhat bentonitic zone, but did not conclusively prove that the marker is actually representative of a bentonite bed." Until the portion of the Lewis Shale containing the bentonite bed is cored and the cores are compared with electric logs, the precise composition of the bed will not be known; nevertheless, the Huerfanito Bed is an excellent time surface to which the stratigraphy of the Pictured Cliffs Sandstone, Fruitland Formation, Kirtland Shale, and Ojo Alamo Sandstone may be related.

PICTURED CLIFFS SANDSTONE
DEFINITION

The Pictured Cliffs Sandstone was named by Holmes (1877, p. 248) for outcrops along the north side of the San Juan River west of Fruitland, N. Mex., where Indian petroglyphs are numerous. Holmes described the Pictured Cliffs as consisting of 140 feet: "Forty feet of white sandstone; 60 to 80 feet yellowish-gray sandstone. Beneath these 30 to 40 feet of brownish laminated sandstones." Reeside (1924, p. 18) revised the original definition to include interbedded sandstones and shales beneath the massive sandstones referred to by Holmes.

LITHOLOGY

Throughout most of the San Juan Basin the Pictured Cliffs Sandstone can be divided into two parts: an upper part consisting of one or more massive sandstone beds interbedded with a few thin beds of shale; and a lower part, sometimes called the transition zone, composed of relatively thin interbeds of shale like the underlying shale of the Lewis, and sandstone like the overlying sandstone in the upper part of the Pictured Cliffs. The sandstone beds are medium to fine grained and well sorted and have an average composition of 86 percent quartz, 7 percent potassium feldspar, 6 percent plagioclase feldspar, and 4 percent coal (fragments), according to Burgener (1953, p. 19). Cementing material averages 60 percent calcite, 30 percent clay, and 10 percent silica. Iron oxide makes up less than 1 percent of the cementing materials. The shale beds are concentrated in the transition zone.

In some parts of the basin the Pictured Cliffs Sandstone is characteristically capped by a hard red-brown iron-cemented sandstone layer, which ranges in thickness from a few inches to approximately 1 foot. This hard zone is noticeable when penetrated by drilling because it causes the drill string to bounce and vibrate. The presence of the hard zone has aided in surface mapping of the Pictured Cliffs, particularly in the southeastern part of the basin where the Pictured Cliffs becomes thin and argillaceous and somewhat difficult to trace.

CONTACTS

The Pictured Cliffs Sandstone is conformable with both the underlying Lewis Shale and the overlying Fruitland Formation throughout most of the basin. The lower contact is gradational in most places; shale beds of the Lewis intertongue with sandstone beds of the Pictured Cliffs. The contact is arbitrarily placed to include predominantly sandstone in the Pictured Cliffs and predominantly shale in the Lewis.

The contact of the Pictured Cliffs and the overlying Fruitland is usually much more definite than the lower contact with the Lewis. On electric logs the Pictured Cliffs-Fruitland contact is placed at the top of the massive sandstone below the lowermost coal of the Fruitland except in those areas where the Fruitland and the Pictured Cliffs intertongue. On the surface, the contact is placed at the top of the highest *Ophiomorpha major*-bearing sandstone. This fossil is here used as a distinctive lithologic characteristic of the Pictured Cliffs in the sense referred to in Article 6(b) of the code of stratigraphic nomenclature (American Commission on Stratigraphic Nomenclature, 1961). Intertonguing of the Pictured Cliffs and the overlying Fruitland is common throughout the basin, and the tongues of Pictured Cliffs in the Fruitland are generally distinct

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STRATIGRAPHY

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ough in the subsurface and on the outcrop to be mapped or delineated as discrete units.

MODE OF DEPOSITION

The Upper Cretaceous rocks of the Western Interior of the United States were deposited in and near an epeiric sea that extended from the Gulf of Mexico to the Arctic Ocean. This seaway, which was 1,000 miles wide and 3,000 miles long, divided the North American continent into two landmasses as shown in figure 4. The San Juan Basin area lies on the west margin of the Cretaceous epeiric sea and was intermittently above and below sea level as the sea advanced and retreated during Late Cretaceous time. The final retreat of the * sea from the San Juan Basin area is represented by the shallow-water and beach-sand deposits of the Pictured Cliffs Sandstone.

The approximate westernmost advance of the sea just prior to the Pictured Cliffs regression is indicated by the westernmost extent of the Lewis Shale. The Lewis resulted from deeper water deposition of the finer grained fraction of the sediment that was carried to the sea in Pictured Cliffs and Lewis time. The Lewis is wedge shaped with the wedge pointing southwest. The maximum extent of the Pictured Cliffs Sea would parallel and be southwest of the Lewis wedge edge. Erosion has removed this edge in most of the basin area; however, about 8 miles east of Newcomb Trading Post in T. 24 N., R. 16 W. (projected), the Pictured Cliffs and the underlying Cliff House Sandstone merge, and the intervening Lewis Shale wedges out (Beaumont and others, 1956, p. 2159). The westernmost position of the Pictured Cliffs shoreline was, thus, probably only a few miles to a few tens of miles west of the Pictured Cliffs-Cliff House coalescence.

The problem of how and why the sea transgressed and regressed during Late Cretaceous time was thoroughly discussed by Sears, Hunt, and Hendricks (1941, p. 103-105). The salient point of their discussion regarding regressive deposition was that there are two probable explanations for regressing shorelines: (1) regression caused by rising of the trough containing the sea, and (2) regression caused by trough filling and the outward growth of the land by nearshore deposition. Sears, Hunt, and Hendricks were unequivocal in stating that "the regressive deposits of the Upper Cretaceous described in this paper resulted from a process of trough filling." Pike (1947, p. 15, 19) also discussed theories of transgressive and regressive deposition and concluded that "regression of the sea was brought about by silting-in along the margins of the trough." Both papers dealt with the Mesaverde Group and did not discuss the Pictured Cliffs Sandstone.

The authors' studies of the Pictured Cliffs Sandstone throughout the San Juan Basin indicate that the regression of the Pictured Cliffs Sea from the San Juan Basin area was primarily the result of trough filling along the west margin of the sea; however, locally, particularly on the east side of the present basin, uplift of the shoreline may have been a secondary factor in causing the sea to retreat.

Trough filling, the predominant cause for regression of the Pictured Cliffs Sea from the basin area, is shown in figure 5, which illustrates in cross section the relation among the various rock units involved in a shifting shoreline situation. The units here shown are generalized but could be labeled as follows: Marine shale, Lewis Shale; marine sandstone, Pictured Cliffs Sandstone; continental deposits and coal beds, Fruitland Formation and Kirtland Shale; and continental deposits and fluvial sandstone, Farmington Sandstone Member of the Kirtland. Time lines in these sections are obviously parallel to the subaerial-subaqueous paleoslope; thus, each of the rock units shown is younger in the northeast than in the southwest. It is assumed that throughout the time represented by these illustrations the area was continuously subsiding.

Figure 5A shows a section through a hypothetical strand-line environment. Sediment was transported to the sea by rivers that probably were eroding a highland somewhere to the southwest of the present San Juan Basin area. When these rivers reached the sea, they dropped their coarser sediment fraction close to the shoreline to be distributed along the coast by littoral drift; thus, at and close to the sea-land contact, beach and shallow-water marine sands were laid down. The finer fraction of the sediment brought to the sea was carried farther from shore and deposited below wave base as marine mud. As the shoreline continued to build outward, the sea was pushed back. However, if the sediment supply decreased slightly or the rate of subsidence of the sea trough increased slightly to the extent that sediment supply exactly balanced subsidence, the shoreline position would become geographically stable.

Figure 5B shows a section through a hypothetical strand line after a period of stability. The subsiding seaway, which itself would have caused the sea to transgress, was exactly balanced by the influx of sediments that were continuously being dumped into the sea by rivers. The word stable as used here refers to the relative geographic position of the shoreline. In all probability a stable or fixed shoreline seldom, if ever, existed. In figure 5B the shoreline was relatively stable in that, even though it was moving back and forth constantly through time, it crossed and recrossed the same geographic area, resulting in a vertical

GEOLOGY OF THE POINT LOOKOUT, CLIFF HOUSE AND PICTURED CLIFFS SANDSTONES OF THE SAN JUAN BASIN, NEW MEXICO AND COLORADO

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INTRODUCTION

The San Juan Basin is located in northwest New Mexico and southwest Colorado, near the common corner of New Mexico, Arizona, Utah and Colorado (fig. 1). The basin is a northwest-trending asymmetric structural depression; around the east, north and northwest parts of the basin; rocks dip steeply, whereas, along the west and southwest flanks of the basin, dips range from less than 1° to 3° .

The purpose of this paper is to discuss the subsurface geometry of the Upper Cretaceous Point Lookout and Cliff House sandstones (including several named and unnamed tongues) of the Mesaverde Group and the Pictured Cliffs Sandstone. The physical configuration of these rock units is related to their environments of deposition, and some of the nomenclature problems associated with the Cliff House Sandstone transgression are discussed. No attempt is made in this report to formally revise the nomenclature of the rock units.

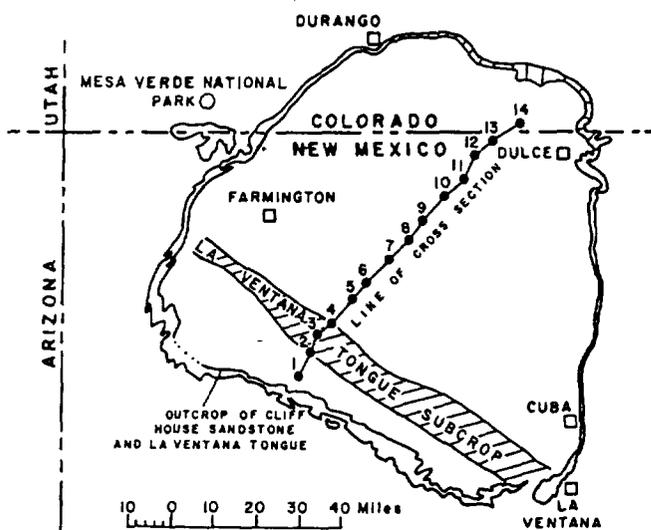


Figure 1. Index map showing the location of the San Juan Basin as defined by the outcrop of the Cliff House Sandstone (including the La Ventana Tongue). The hatched outcrop between Durango, Colorado, and Dulce, New Mexico, is the undivided Mesaverde Group. The dotted upper contact in the southwest part of the basin is where the Pictured Cliffs Sandstone and the Cliff House Sandstone have merged. Numbered wells along the line of cross section are wells, the logs of which are shown on Figure 2. The La Ventana Tongue subcrop band is that area underlain by the La Ventana Tongue of the Cliff House Sandstone.

GEOMETRY OF THE POINT LOOKOUT, CLIFF HOUSE AND PICTURED CLIFFS SANDSTONES

Figure 2, a northeast-trending, subsurface, stratigraphic cross section clearly illustrates the geometric configuration of the Point Lookout Sandstone, Cliff House Sandstone (and included tongues), and Pictured Cliffs Sandstone of the San Juan Basin. The Huerfanito Bentonite Bed of the Upper Cretaceous Lewis Shale (Fassett, 1971) is used as a datum. Because this bed was deposited as an instantaneous geologic event on a nearly flat surface, using it as a datum should portray the regressive and transgressive sandstones close to their original attitudes after deposition but before any deformation (with the exception of differential compaction). The geophysical logs used for control on this section are more or less evenly spaced across the basin and average about 6 miles (10 km) apart; these logs are listed in Table 1. The cross section is oriented at right angles to the average shoreline trend throughout the time that the rock units portrayed were being deposited.

At first glance, one notices that the configuration of the Point Lookout Sandstone and the Pictured Cliffs Sandstone on Figure 2 is remarkably similar. Both units rise to the northeast in a series of steps. The rise of the top of the Point Lookout Sandstone is 970 ft (296 m) between wells 1 and 14; the top of the Pictured Cliffs Sandstone rises 1,026 ft (313 m) between wells 2 and 14, representing a difference between the two of only 56 ft (17 m). Upon closer examination, however, it is seen that most of the stratigraphic rise of the Point Lookout occurs between wells 4 and 9, whereas the Pictured Cliffs has a more even rise across the basin, except for the abrupt rise between wells 9 and 12.

The geometry of the Cliff House Sandstone is quite different from that of the Point Lookout and Pictured Cliffs sandstones. The Cliff House consists of a few thick sandstone lenses at the base, irregularly dispersed along a surface that rises gently to the southwest. This surface, represented by the contact between the Lewis Shale and Upper Cretaceous Menefee Formation of the Mesaverde Group in those areas where the Cliff House is absent, rises only 38 ft (12 m) from well 14 to well 3. In this report, this part of the Cliff House Sandstone will be referred to as the basal Cliff House Sandstone.

In the southwest part of the basin, the thick, massive La Ventana Tongue of the Cliff House Sandstone occurs above the basal Cliff House Sandstone. At well 3 the La Ventana is 610 ft (186 m) thick, with a 70-ft (21-m) thick shale break separating it from the underlying basal Cliff House Sandstone. To the northeast the La Ventana interfingers with the Lewis

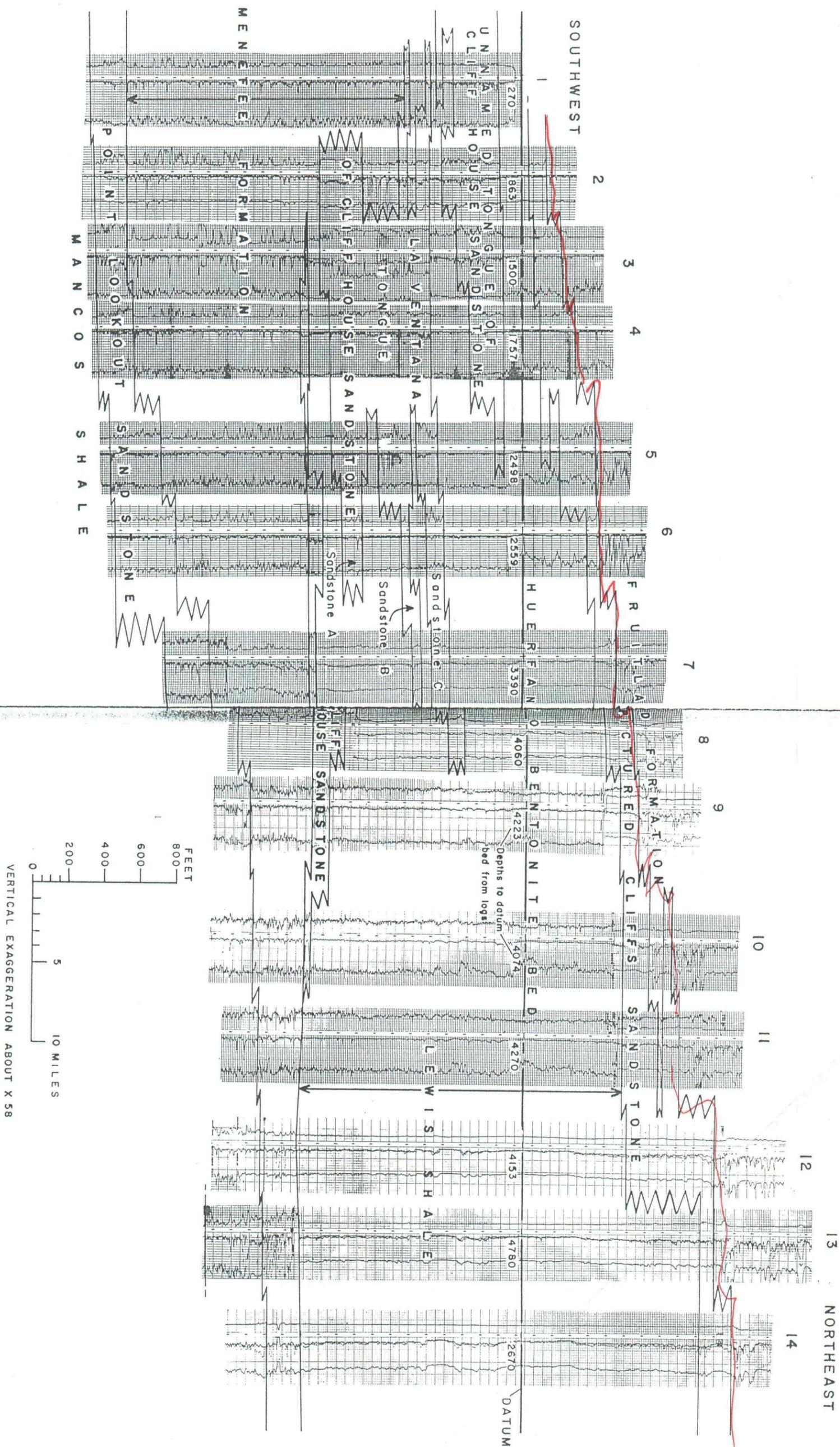


Figure 2. Stratigraphic, subsurface cross section across the San Juan Basin.

Line of section shown on Figure 1. The wells used for control are listed in Table 1.

Table 1. List of Wells on Southwest-Northeast Cross Section (fig. 2)
(Kind of log used: IE, induction-electric; E, electric. Elevation, in feet, at well (Kelly Bushing))

Well No.	Company	Well name	Location			Kind of log used	Elevation (feet)
			Sec.	T.N.	R.W.		
<i>New Mexico</i>							
1	Humble Oil and Refining Co	Tanner Unit Z . . . . .	.23	23	12	IE	6034
2	Magnolia Petroleum Co	Beamon Federal 1 . . . . .	.29	24	11	E	6251
3	Davis Oil Corp	Fannin Govt. 1 . . . . .	.3	24	11	IE	6590
4	Sun Oil Co	Heirs of Ith-Hal-E-Wood 1 . . . . .	.19	25	10	IE	6583
5	El Paso Natural Gas Co	Huerfano 120 . . . . .	.25	26	10	IE	6629
6	Turner and Webb	Huerfanito 60-4 . . . . .	.4	26	9	IE	6406
7	El Paso Natural Gas Co	Schwerdtfeger 13-A . . . . .	.8	27	8	E	6745
8	. . . do	San Juan 28-7'30 . . . . .	.18	28	7	E	6871
9	. . . do	San Juan 29-7 65 . . . . .	.22	29	7	E	6781
10	. . . do	Barron Kldd 7 . . . . .	.21	30	6	E	6457
11	. . . do	Rosa Unit 24 . . . . .	.32	31	5	E	6528
12	Stanolind Oil and Gas Co	San Juan 32-5 2 . . . . .	.35	32	5	E	6336
13	Phillips Petroleum Co	Mesa 32-4 2-16 . . . . .	.16	32	4	E	6808
<i>Colorado</i>							
14	Stanolind Oil and Gas Co	Southern Ute 1 . . . . .	.22	32	3	E	7188

Shale, and the last tongue, sandstone C, pinches out between wells 8 and 9. To the southwest the La Ventana fingers out into the Menefee Formation, and only a few thin tongues are left at well 1.

Above the La Ventana, but not physically connected to it on this section, occurs an upper unnamed tongue also of the Cliff House Sandstone. This unit extends northeastward as far as well 5 and southwestward beyond the limits of this section; it reaches a maximum thickness of 320 ft (98 m) at well 2. At this well, the upper unnamed tongue of the Cliff House is only 160 ft (49 m) beneath the base of the overlying Pictured Cliffs Sandstone. The total stratigraphic rise of the top of the Cliff House Sandstone between wells 10 and 1 is 1,065 ft (225 m).

Between the above described sandstone units are the Menefee Formation and the Lewis Shale. Each is wedge-shaped; the continental, coal-bearing Menefee thins northeastward from 1,550 ft (472 m) to 185 ft (56 m), whereas the marine Lewis Shale thins southwestward from 2,300 ft (701 m) to 160 ft (49 m).

NOMENCLATURE OF THE CLIFF HOUSE SANDSTONE

Of the three sandstone units discussed in this report, only the Cliff House Sandstone has been the object of any continuing nomenclatural controversy. The unit was first described by Holmes (1877), who defined the Mesaverde Group at its type locality in Mesa Verde National Park. Holmes divided the Mesaverde into three units called the Lower Escarpment Sandstone, Middle Coal Group and the Upper Escarpment Sandstone. Collier (1919, p. 297) later named these three units the Point Lookout Sandstone, the Menefee Formation and the Cliff House Sandstone, respectively. The Cliff House name of course, was derived from the many prehistoric cliff dwellings located on this unit in the Mesa Verde National Park area.

In 1936, Carle Dane described the geology and coal deposits of the southeastern part of the San Juan Basin. In his report, Dane defined the La Ventana Sandstone and the Chacra sandstone members of the Mesaverde Formation. Dane's original La Ventana sandstone member was named for the village of La

Ventana (fig. 1), in the southeast part of the basin, and is the outcrop equivalent of the massive sandstone unit of the same name shown in Figure 2. The Chacra sandstone member of Dane, named for Chacra Mesa, is the outcrop equivalent of the unnamed sandstone tongue of the Cliff House shown on Figure 2. Dane's report included a geologic map of the area from just east of La Ventana and Cuba northwestward along the Cliff House outcrop for a distance of about 50 miles (80 km) (fig. 1). Northwest of the break in the outcrop in the southeast part of the basin (fig. 1), the unit was mapped by Dane as the Chacra sandstone member; east of this break to just east of Cuba, the unit was mapped as the La Ventana sandstone member.

Over the next two decades, the entire outcrop band of the Cliff House Sandstone was mapped around the basin rim: From Mesa Verde National Park south and southeastward, and from Mesa Verde National Park northeastward to Durango, Colorado, it was mapped as Cliff House Sandstone; east from Durango to near Dulce, New Mexico, the Cliff House Sandstone was not mapped separately but was included in the undivided Mesaverde Group; and from Dulce to Cuba, New Mexico, the unit was mapped as La Ventana Sandstone Member of Mesaverde Formation. Later, Beaumont and others (1956) abandoned the name Chacra sandstone member in favor of Cliff House Sandstone and changed the name La Ventana sandstone member to La Ventana Tongue of the Cliff House Sandstone.

Over the following two decades, other new names were applied to various parts of the Cliff House. (As illustrated on Figure 2, many tongues of sandstone and shale are associated with the Cliff House, Lewis Shale and Menefee Formation, and the compulsive splitter of rock units could apply a name to each of them.) The most serious problem is the misuse of the name "Chacra" for sandstones B and C of Figure 2; this name was applied because these sandstone units were found to contain natural gas in parts of the San Juan Basin, and oil-and-gas company geologists informally labeled them "Chacra." Credit (or blame) for this naming remains vague. The New Mexico Oil Conservation Commission is considering the formal adoption of the term "Chacra producing interval"

for a zone that extends from 750 ft (229 m) below the Huerfanito Bentonite Bed to the Huerfanito.

The author and others had earlier suggested that Dane's original definition of the Chacra sandstone member be restored to those outcropping rocks in the southern San Juan Basin equivalent to the upper unnamed tongue of the Cliff House Sandstone of Figure 2; however, with the name "Chacra" now being used informally for the subsurface sandstones B and C of the La Ventana Tongue, a new name seems desirable for this overlying upper, unnamed tongue of the Cliff House Sandstone. The name Tsaya Canyon sandstone tongue of the Cliff House Sandstone should be considered for this unit, because it is particularly well exposed in Tsaya Canyon in the southwest part of the basin. (This name is not formally recommended here as guidebooks are not appropriate places to make formal nomenclature changes.)

The above discussion is far from a comprehensive treatment of the nomenclatural problems connected with the Cliff House Sandstone, but it will introduce field trip participants and other users of this guidebook to the problems.

ENVIRONMENTS OF DEPOSITION OF THE POINT LOOKOUT, CLIFF HOUSE AND PICTURED CLIFFS SANDSTONES

The littoral marine sandstone units discussed herein clearly represent three major cycles of regression-transgression-regression of part of the shoreline of the western interior seaway during Late Cretaceous (late Campanian) time. Both the Point Lookout and the Pictured Cliffs sandstones were deposited during regression of the Cretaceous sea, whereas the Cliff House represents—at least in an overall sense—a transgressive episode.

The strandline fluctuations which resulted in deposition of these units across the SCI-SWO ("sea-came-in, sea-went-out") zone (Fassett, 1974) on the west edge of the epicontinental seaway have been discussed frequently in papers over the past 36 years. The first paper, by Sears and others (1941), suggested that the transgressive-regressive deposits of the basin were created in a slowly subsiding trough and that the movements of the shoreline resulted from changes in the rate of sediment influx. Subsequent work confirmed this hypothesis. Thus, the Point Lookout and Pictured Cliffs regressions (fig. 2)

occurred when sediment influx exceeded the rate of subsidence.

During Cliff House time a series of three distinct events probably occurred, as indicated by the geometry of this unit shown on Figure 2: First, there was a fairly rapid transgression of the sea from the position of well 14 to well 3, as evidenced by the scarcity of sandstone on top of the Menefee Formation and by the small amount (38 ft or 12 m) of stratigraphic rise of this unit (basal Cliff House Sandstone) between these two points. This episode reflects a very low rate of sediment influx in to the sea at that time. Second, the geographic position of the shoreline stabilized near wells 2 through 5, when the rate of sediment influx increased until it nearly equaled the rate of basin subsidence. Minor regressions of the sea are reflected by sandstones A, B and C. Minor transgressive pulses are indicated by the sandstone tongues extending from the La Ventana into the Menefee Formation to the southwest. Third, a period of less sediment influx resulted in a rapid transgression to the southwest, as evidenced by the gap between the La Ventana and the unnamed tongue of the Cliff House, followed by a period of regression and stabilization of the shoreline over the area from wells 1 through 4; and then a final transgression that carried the shoreline to the southwest beyond the limits of this cross section. This third episode caused deposition of the unnamed sandstone tongue of the Cliff House Sandstone.

REFERENCES

- Collier, A. J., 1919, Coal south of Mancos, Montezuma County, Colorado: U.S. Geol. Survey Bull. 691-K, p. 293-310.
- Beaumont, E. C., Dane, C. H., and Sears, J. D., 1956, Revised nomenclature of Mesaverde group in San Juan Basin, New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 40, no. 9, p. 2149-2162.
- Dane, C. H., 1936, Geology and fuel resources of the southern part of the San Juan Basin, New Mexico, Pt. 3—The La Ventana-Chacra Mesa coal field: U.S. Geol. Survey Bull. 860-C, 166 p.
- Fassett, J. E., 1971, Geology and fuel resources of the Fruitland Formation and Kirtland Shale of the San Juan Basin, New Mexico and Colorado: U.S. Geol. Survey Prof. Paper 676, 76 p.
- Fassett, J. E., 1974, Cretaceous and Tertiary rocks of the eastern San Juan Basin: in New Mexico Geol. Soc. Guidebook, 25th Field Conf., p. 225-230.
- Holmes, W. H., 1877, Report (on the San Juan district, Colo.): U.S. Geol. and Geog. Survey Terr. 9th Ann. Rept. for 1875, p. 237-276.
- Sears, J. D., Hunt, C. B., and Hendricks, T. A., 1941, Transgressive and regressive Cretaceous deposits in southern San Juan Basin, New Mexico: U.S. Geol. Survey Prof. Paper 193-F, p. 101-121.

3. Geologic controls on coalbed methane occurrence and production in the Fruitland Formation, Cedar Hill field and the COAL site

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Abstract—The Cedar Hill field area contains some of the most productive coalbed methane wells in the San Juan Basin. To determine geologic controls on occurrence and producibility of coalbed methane at Cedar Hill field and the Completion Optimization and Assessment Laboratory (COAL) site, structure, coal occurrence, net sandstone thickness, and production were mapped.

The primary targets for coalbed methane production in Cedar Hill field are the thick lower Fruitland Formation coals (coal group A), which formed in a lower coastal-plain setting. Group A coal beds are the thickest, up to 35 ft (11 m), and most continuous coal beds at Cedar Hill field. In contrast, at the COAL site the thickest coal beds are more than 30 ft (>9 m) thick and occur in the middle Fruitland Formation (coal group C).

Fruitland coal seams form complex reservoirs at Cedar Hill field and the COAL site because of coalbed-sandstone relations and minor structural deformation. Compactional folding in coal beds is present where they underlie or override Fruitland channel-fill sandstones. Coal beds may be more intensely fractured, and thus more permeable, where folded. Northwest-trending (?) faults along the basin hingeline and a syncline that bisects Cedar Hill field also contribute to coal seam complexity. Faults at the hingeline offset coal beds and may hinder fluid flow, thus causing the boundary between overpressured and underpressured strata.

Introduction

Cedar Hill field, in the north-central San Juan Basin (Fig. 3.1), has the longest history of coalbed methane production in the basin. Developed by Amoco Production Company in 1977, Cedar Hill field produces from basal Fruitland Formation coal seams at a depth of approximately 2,800 ft (854 m). Coal seams there contain an estimated 313 million tons of coal and 89 billion cubic feet (Bcf) of gas in place (Decker and others, 1988). Approximately 17.2 Bcf of coalbed methane and 737,000 bbls of water were produced in Cedar Hill field from 1977 through 1989 (Petzet, 1990).

The COAL site, located approximately 2.5 mi (~4 km) northwest of Cedar Hill field (Fig. 3.1) in Colorado, has a coalbed methane field research laboratory operated jointly by Amoco Production Company and the Gas Research Institute (GRI). Research at the COAL site is designed to compare the effectiveness of open-hole cavity completions with cased-hole, hydraulically fractured completions, and to determine the parameters that favor open-hole cavity completions. At both Cedar Hill field and the COAL site, the Fruitland Formation is overpressured. Because overpressuring is due to artesian conditions, most coalbed methane wells in the area produce water.

Objectives

The objectives of this study were to (1) identify Fruitland coal groups and depositional subunits, (2) define geologic control on the thickness, continuity, and structural attitude of major coal seams (reservoirs) that occur in each coal group, and (3) characterize the boundary between overpressured and underpressured Fruitland strata. The geologic characteristics defined in this study will be compared with coalbed methane production trends to determine geologic and hydrologic controls on coalbed methane producibility (Kaiser and Ayers, this volume, Chapter 10). This area was selected because (1) Cedar Hill field has the longest history of coalbed methane production in the basin, and (2) geologic characterization of the COAL site provides an interpretation of coalbed methane research results by describing controls on coalbed reservoir complexity and productivity.

Methods

Data from 260 geophysical logs, including 22 from shallow (<600 ft [<183 m] deep) boreholes near the Fruitland outcrop, were used in this study. Outcrops were described to document relationships between Fruitland and Pictured Cliffs stratigraphic units, to evaluate coalbed continuity, and to support interpretations of depositional systems.

Stratigraphic units below, above, and in the Fruitland Formation were correlated on eight structural and stratigraphic cross sections to provide a framework for determining the lateral extent of Fruitland coal seams and sandstones. Marker beds that were correlated included the Huerfano Bentonite Bed, five shale marker beds in the Lewis Shale and Pictured Cliffs Sandstone, tonsteins (ash layers) in Fruitland coal seams, carbonaceous shales in the Fruitland Formation, and a high-conductivity shale at the Fruitland-Kirtland contact (Ayers and others, this volume, Chapter 2).

The Fruitland Formation was divided into three depositional subunits, each bounded by continuous coal beds or locally by shale and sandstone beds. Depositional models of subunits were based on a comparative analysis of net coal thickness, net sandstone thickness, isopach, and structure maps. Sandstone thickness was determined from resistivity and natural-gamma curves; coal identification was confirmed with bulk-density logs. We recorded coal seams thicker than 2 ft (>0.6 m); partings thinner than 2 ft (<0.6 m) were included as coal because of the limits of resolution of the geophysical logs. For logs without a density curve, natural-gamma, neutron, and resistivity curves were used; coal seams in these logs were identified by correlation with coal seams in nearby logs having bulk-density curves.

Stratigraphic and structural setting

At Cedar Hill field and the COAL site, the Fruitland Formation is 430 to 470 ft (131 to 143 m) thick; it thickens northwest toward the Fruitland outcrop, where it is more than 570 ft (>174 m) thick (Fig. 3.1). The Fruitland Formation was divided into three depositional subunits (lower, middle, and upper) that contain four coal groups in as-

Cedar Hill field but override LF2 sandstones northeast of the field (Fig. 3.3). Group C coal seams are thicker and more continuous than group D seams, which occur between thin channel-fill sandstones in the upper Fruitland subunit.

The Fruitland-Kirtland contact is a regionally extensive, high-conductivity shale (Fig. 3.2). This shale interval is inferred to be a marine condensed section deposited over older Fruitland coastal-plain deposits (Ayers and others, this volume, Chapter 2). Foraminifera have been reported in this shale (Dilworth, 1960), which has a geophysical-log response (high natural-gamma, high conductivity) and regional continuity similar to that described for other marine condensed sections in the Western Interior seaway (Leckie and others, 1990).

Cedar Hill field is bisected by an east-plunging syncline (Fig. 3.4). In the syncline, Fruitland strata are more tightly folded (Fig. 3.4a) than the underlying Huerfano Bentonite Bed (Fig. 3.4b). Structural relief on the base of Fruitland

coal group A across Cedar Hill field is 70 ft (21 m) (Fig. 3.4a). Up to 40 ft (12 m) of structural relief occurs across faults and where coal seams override sandstones (Fig. 3.3).

Depositional systems

Pictured Cliffs Sandstone

The Pictured Cliffs Sandstone, which forms a sandstone platform at the base of the Fruitland Formation, consists of northwest-trending, strike-elongate shoreline deposits of barrier-island and wave-dominated delta systems that prograded northeastward (Ayers and others, this volume, Chapter 2). North of the study area, the upper Pictured Cliffs Sandstone intertongues with the Fruitland Formation. The lower Pictured Cliffs Sandstone intertongues with the Lewis Shale and is 175 ft (53 m) thick, 2 mi (3.2 km) updip (southwest) of the basin hingeline (Fig. 3.3). However, it is 250 ft (76 m) thick in Cedar Hill field, and 4 mi (6.4 km)

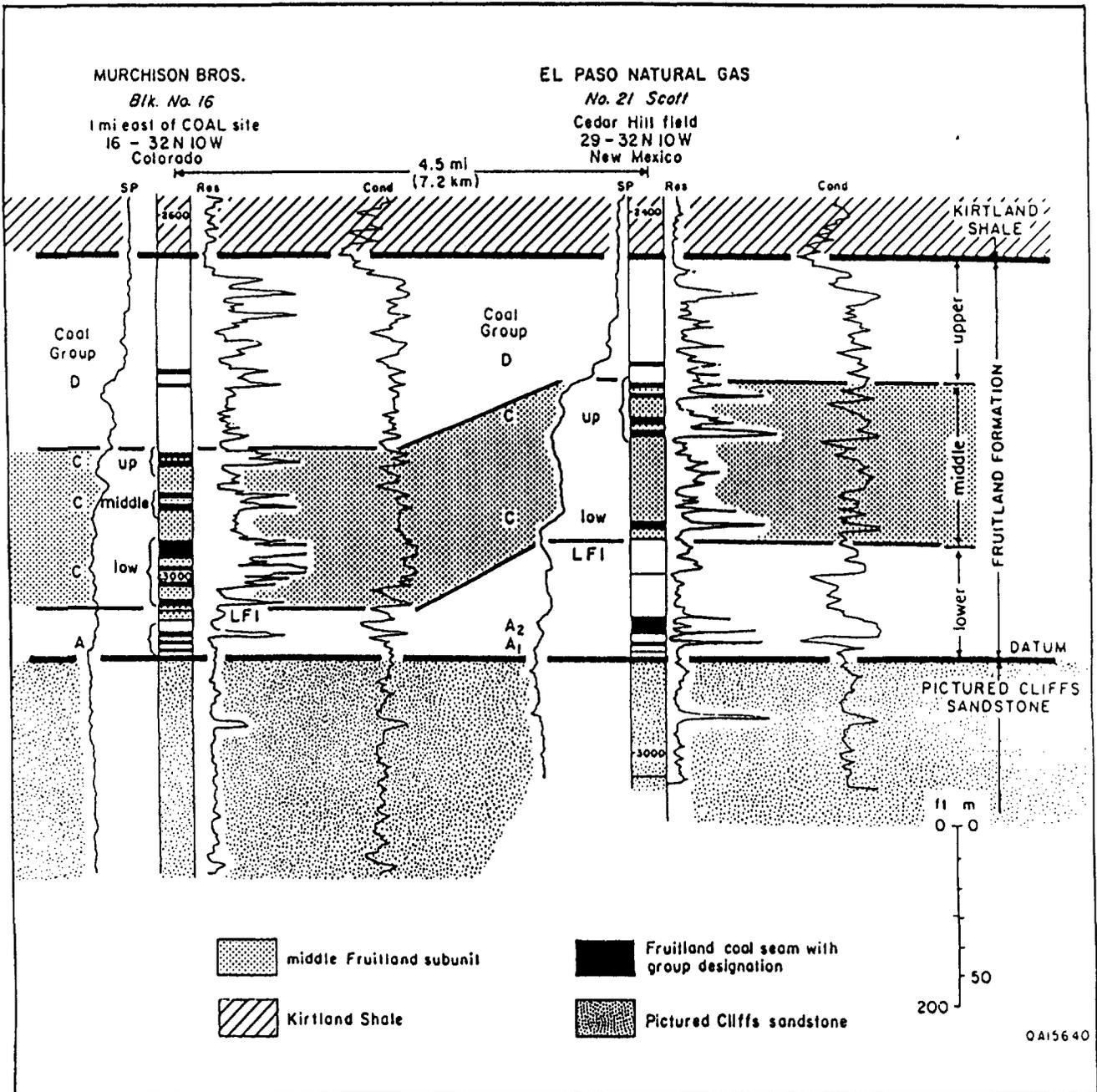


FIGURE 3.2—Type logs (located in Fig. 3.1) showing Fruitland stratigraphic units in Cedar Hill field and in the area of the COAL site Group B coal seams and the overlying LF2 sandstone (shown in Fig. 3.3) are absent in Cedar Hill field and the COAL site

northeast of the field it thickens basinward to more than 350 ft (>107 m). Marker beds in the Lewis Shale, used to correlate well logs in this study, represent isochronous surfaces across proximal-shelf and shoreface facies. These marker beds intersect and are unresolvable in Pictured Cliffs coastal sandstones (Ayers and others, this volume, Chapter 2). Similar stratigraphic marker beds have been described in progradational coastline deposits in the Upper Cretaceous Point Lookout Sandstone in the southern part of the San Juan Basin (Wright, 1986).

Fruitland Formation

The Fruitland Formation, the primary coal-bearing formation in the San Juan Basin, is the nonmarine facies tract consisting of interbedded sandstone, mudstone, and coal beds (Fig. 3.3) deposited landward of the marine (barrier-island and delta-front) facies tract of the Pictured Cliffs Sandstone. In the Fruitland Formation, dip-elongate (north-east-trending), fluvial and lower coastal-plain sandstone bodies form the depositional framework. Net sandstone thickness in the Fruitland Formation ranges from 110 to 230 ft (34 to 70 m) (Fig. 3.5).

Lower Fruitland subunit—Thin, northeast-trending sandstones associated with coal group A, below LF1 (Figs. 3.2 and 3.3), were mapped to determine depositional controls on occurrence of lower Fruitland coal beds. Sandstones in the lower Fruitland subunit are locally more than 40 ft (>12 m) thick at Cedar Hill field, but thin to only 10 ft (3 m) northeastward (Fig. 3.6a). They are interpreted to be distributary-channel and crevasse-splay complexes deposited in a lower delta-plain setting, on the basis of their stratigraphic position (directly overlying the Pictured Cliffs Sandstone) in the offlapping Fruitland-Pictured Cliffs facies tract. The Pictured Cliffs delta front, inferred from pinch-outs of associated distributary-channel sandstones, was 3 to 6 mi (4.8 to 9.6 km) northeast of Cedar Hill field and the COAL site.

Northeast-trending LF1 sandstones, locally more than 40 ft (>12 m) thick (Fig. 3.6b), are interpreted to have been deposited in upper delta-plain fluvial systems that were deposited over older, lower delta-plain deposits associated with coal group A. A major LF1 channel-belt system in the eastern half of Cedar Hill field is defined by sandstones more than 40 ft (>12 m) thick. In contrast, the COAL site is located between LF1 depositional axes, where net sandstone thickness is less than 10 ft (<3 m). LF2, a lenticular sandstone less than 20 ft (<6 m) thick, occurs above coal group B, but was not mapped because it is present only locally at the margin of the study area (Fig. 3.3).

Middle Fruitland subunit—The middle Fruitland subunit consists of strata from the base to the top of coal group C (Figs. 3.2 and 3.3). Sandstone bodies display a strongly dip-elongate geometry in the middle Fruitland subunit. Net sandstone thickness is 40 to 60 ft (12 to 18 m) in Cedar Hill field and more than 80 ft (24 m) near the northwestern margin of the basin (Fig. 3.7a). The inferred depositional setting of the middle Fruitland subunit is a transition between upper coastal plain and lower alluvial plain; as the Pictured Cliffs shoreline prograded northeastward, there was a corresponding seaward shift in depositional environments of overlying, younger Fruitland strata. During deposition of the middle Fruitland subunit, the Pictured Cliffs shoreline was located farther basinward than it was during deposition of the lower Fruitland subunit because of the seaward-stepping geometry caused by net shoreline progradation.

Upper Fruitland subunit—The upper Fruitland subunit consists of all Fruitland strata above coal group C (Fig. 3.2). Sandstones occur in dip-elongate (northeast-trending) belts; these belts are less than 2,000 ft (<610 m) wide at Cedar

Hill field (Fig. 3.7b). The upper Fruitland subunit contains the thickest Fruitland sandstones, with thickness of individual sandstone bodies up to 50 ft (15 m) and net sandstone thickness up to 130 ft (40 m). The upper Fruitland subunit is interpreted to be the most landward part of the Fruitland fluvial facies tract. At Cedar Hill field and the COAL site, sandstone belts are interpreted to be tributary-stream deposits that merge down the paleoslope (northeastward) to form alluvial trunk-stream deposits.

Fruitland coal groups

The four Fruitland coal groups (A, B, C, and D) consist of one or more individual coal seams (Figs. 3.2 and 3.3). Coal seams in these groups vary in thickness and continuity because of deposition of peat in different settings and presence of lenticular sandstones that locally replace coal seams. Coal group B occurs only locally and pinches out approximately 1 mi (~1.6 km) northeast of Cedar Hill field (Fig. 3.3); therefore, it was not evaluated in this study. In this section we describe coal groups A, C, and D, and relate coal characteristics to depositional setting.

Fruitland net coal thickness at Cedar Hill field and the COAL site ranges from less than 40 ft (<12 m) to as much as 100 ft (30 m) (Fig. 3.8a). Coal deposits commonly are parallel to depositional dip (northeast-trending) at Cedar Hill field and south of the COAL site. Dip-elongate bands of 60 to 80 ft (18 to 24 m) of coal merge toward depositional dip (northeastward) to form a strike-elongate (northwest-trending) sheet of more than 80 ft (>24 m) of net coal, approximately 3 mi (~4.8 km) northeast of Cedar Hill field. The dip-elongate coal deposits in the Fruitland Formation formed in floodplain and interdistributary environments, whereas the strike-elongate coal deposits accumulated in swamps landward (southwest) of Pictured Cliffs shoreline sandstones. Similar depositional controls on coalbed geometry have also been described in the Upper Cretaceous Ferron Sandstone in central Utah (Ryer, 1981).

Coal group A

Coal group A consists of as many as three coal seams. In the northwestern San Juan Basin, the greatest net coal thickness in group A (35 ft [11 m]) occurs in northeast-trending bands in Cedar Hill field (Fig. 3.8b), where this group is the main target for coalbed methane production. Coal seams in group A pinch out 1 to 3 mi (1.6 to 4.8 km) from the northwestern margin of the basin.

The thickest coal in group A in the study area coincides with a 3-mi-wide (4.8-km-wide) area centered on Cedar Hill field, where thickness of underlying and interbedded sandstones exceeds 20 ft (>6 m). This relation suggests that peat in coal group A accumulated on a sand-rich platform in a deltaic depocenter at Cedar Hill field (Fig. 3.6a). However, net coal thickness of group A in the Cedar Hill deltaic depocenter is locally greatest (>30 ft [>9 m] thick) in sand-poor, narrow (<1 mi [<1.6 km] wide) interdistributary deposits, where net sandstone thickness is less than 20 ft (<6 m) (Fig. 3.6a). The depositional setting of coal group A is similar to that described by Levey (1985) for lower delta-plain coal seams in the Upper Cretaceous Rock Springs Formation in southwestern Wyoming. Thick Rock Springs coal seams formed from peats that had overspread abandoned-delta lobes, and the greatest accumulation occurred between distributaries.

Coal group C

Coal group C occurs in the middle Fruitland subunit (Figs. 3.2 and 3.3). Net coal thickness in group C is greatest northwest of Cedar Hill field, where thickness exceeds 60 ft (>18 m) (Fig. 3.9). Coal occurs in dip-elongate deposits that merge