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

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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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By JAMES E. FASSETT and JIM S. HINDS

ABSTRACT

The San Juan Basin is an asymmetric structural basin in northwestern New Mexico and southwestern Colorado containing sedimentary rocks that range from Cambrian to Holocene in age and are as much as 15,000 feet thick. Upper Cretaceous rocks, which are more than 6,000 feet thick, are composed of intertonguing marine and nonmarine sedimentary rocks deposited during three basin-wide cycles of transgression and regression of an epicontinental sea. The final regression of the sea is represented by the marine Pictured Cliffs Sandstone. Subsurface studies of this unit, based primarily on well-log interpretation, and surface evidence indicate that the Pictured Cliffs regression was interrupted frequently by relatively minor transgressive episodes that resulted in vertical buildups and intertonguing of the Pictured Cliffs Sandstone with the overlying Fruitland Formation. The strand lines of the Pictured Cliffs Sea had northwest alinements, and the Pictured Cliffs Sandstone and the overlying Fruitland Formation and Kirtland Shale are younger in the northeastern part of the basin than in the southwestern part. Concomitant with the Pictured Cliffs regression, an area southeast of the basin was uplifted, resulting in either lack of deposition or possible erosion of the Pictured Cliffs; there the Fruitland Formation now rests on the Lewis Shale.

After deposition of the Fruitland and Kirtland, the Upper Cretaceous McDermott Member of the Animas Formation was deposited in the northwestern part of the basin area. Next, the basin area was tilted toward the northwest, and as much as 2,100 feet of rocks was eroded in the east. Following this erosion cycle, the fluvial Ojo Alamo Sandstone of Paleocene age was deposited. The source of the Ojo Alamo was primarily from the west, as indicated by a decrease in pebble size in the Ojo Alamo conglomerates toward the east, although renewed uplift to the east may have furnished some Ojo Alamo sediment. In the northeastern part of the basin, the Ojo Alamo rests on Lewis Shale. After deposition of the Ojo Alamo, the Paleocene Nacimiento Formation and upper shale member of the Animas Formation were deposited, followed by deposition of the Eocene San Jose Formation. These units seemingly rest unconformably on older rocks near the edge of the basin and rest conformably on older rocks in the central part of the basin.

Fuel resources of the Fruitland Formation and the Kirtland Shale include uranium, oil, gas, and coal. The uranium occurs in channel sandstone in the Fruitland Formation. Oil and gas occur mostly in small scattered stratigraphic traps. The thickest coal beds occur in the lower part of the Fruitland Formation. Deposition of the coal was controlled by the position and the relative stability of the strand lines of the Pictured Cliffs Sea. The thickest coal occurs adjacent to and southwest of major stratigraphic rises of the Pictured Cliffs Sandstone. The coal occurs in elongate tabular bodies whose long axes trend northwest parallel to the strand lines. The coal beds intertongue with and pinch out into marine rocks to the northeast and grade southwestward into flood-plain deposits.

The wells selected for detailed study of coal beds are generally about 6 miles apart. Because of stratigraphic complexities, this spacing did not permit reliable correlation of individual coal beds, although many of the beds are continuous for more than 10 miles and a coal zone generally overlies the Pictured Cliffs Sandstone.

Analyses of Fruitland coal samples from rotary-drill cuttings show that the highest quality coal on an as-received basis underlies the northwestern part of the San Juan Basin. As-received Btu values in this area range from about 12,000 to more than 13,000 compared with values elsewhere of about 9,000–12,000. The coal from the washed drill cuttings is low in moisture content, ranging generally between 2–6 percent. The ash content of the coal is unusually high and erratic, ranging from 10 to more than 30 percent. The lowest ash contents are in the west-central part of the basin; the highest ash contents are in the middle and eastern parts of the basin. The moisture and ash-free Btu values and fixed-carbon ratios of the samples show a well-defined zonation across the basin paralleling the trends of deposition and the basin axis.

The statistical method of analysis used in this report indicates that the Fruitland Formation in the San Juan Basin contains approximately 200 billion tons of coal in beds more than 2 feet thick at depths of as much as 4,500 feet.

INTRODUCTION

PURPOSE AND SCOPE

The purpose of this report is to illustrate and describe the occurrence and extent of the Fruitland Formation and Kirtland Shale in the San Juan Basin, N. Mex. and Colo., and to present in detail the distribution of the fuel resources, principally coal, of these units. Analyses of coal samples collected from cuttings during drilling of oil and gas test wells provided coal Btu values at selected locations throughout the basin. Reconnaissance surface geological mapping was conducted as needed, particularly on the east side of the basin, to clarify the relationship between the subsurface and outcrop occurrence of Fruitland and Kirtland rocks. The reconnaissance mapping resulted in some revision of formation boundaries shown on previously published geologic maps.

LOCATION AND EXTENT OF AREA

The San Juan Basin is in northwestern New Mexico and southwestern Colorado (fig. 1). The part of the basin discussed in this report is shown on plate 1 and is the area inside the outcrop of the Pictured Cliffs Sandstone. This area includes parts of San Juan, Rio Arriba, Sandoval, and McKinley Counties in New Mexico and La Plata and Archuleta Counties in Colorado. It also includes parts of the Navajo, Southern Ute, and Jicarilla Apache Indian Reservations. The basin is elliptical; it is about 100 miles long (north-south) and 90 miles wide (east-west) and extends over an area of about 7,500 square miles.

EARLIER INVESTIGATIONS

SURFACE GEOLOGY

The Kirtland Shale and the Fruitland Formation were defined and named by Bauer (1916) in a paper on the stratigraphy of the western San Juan Basin; Bauer divided the Kirtland Shale into an upper and a lower shale member separated by the Farmington Sandstone Member. The Ojo Alamo Sandstone was named by Brown (1910), was redefined by Sinclair and Granger (1914), and was redefined again by Bauer (1916) and by Baltz, Ash, and Anderson (1966). The Pictured Cliffs Sandstone was named by Holmes (1877) and was redefined by Reeside (1924).

Other early workers in the San Juan Basin area included Gardner (1909a, b; 1910) who mapped the "Laramie formation" in parts of the northern and

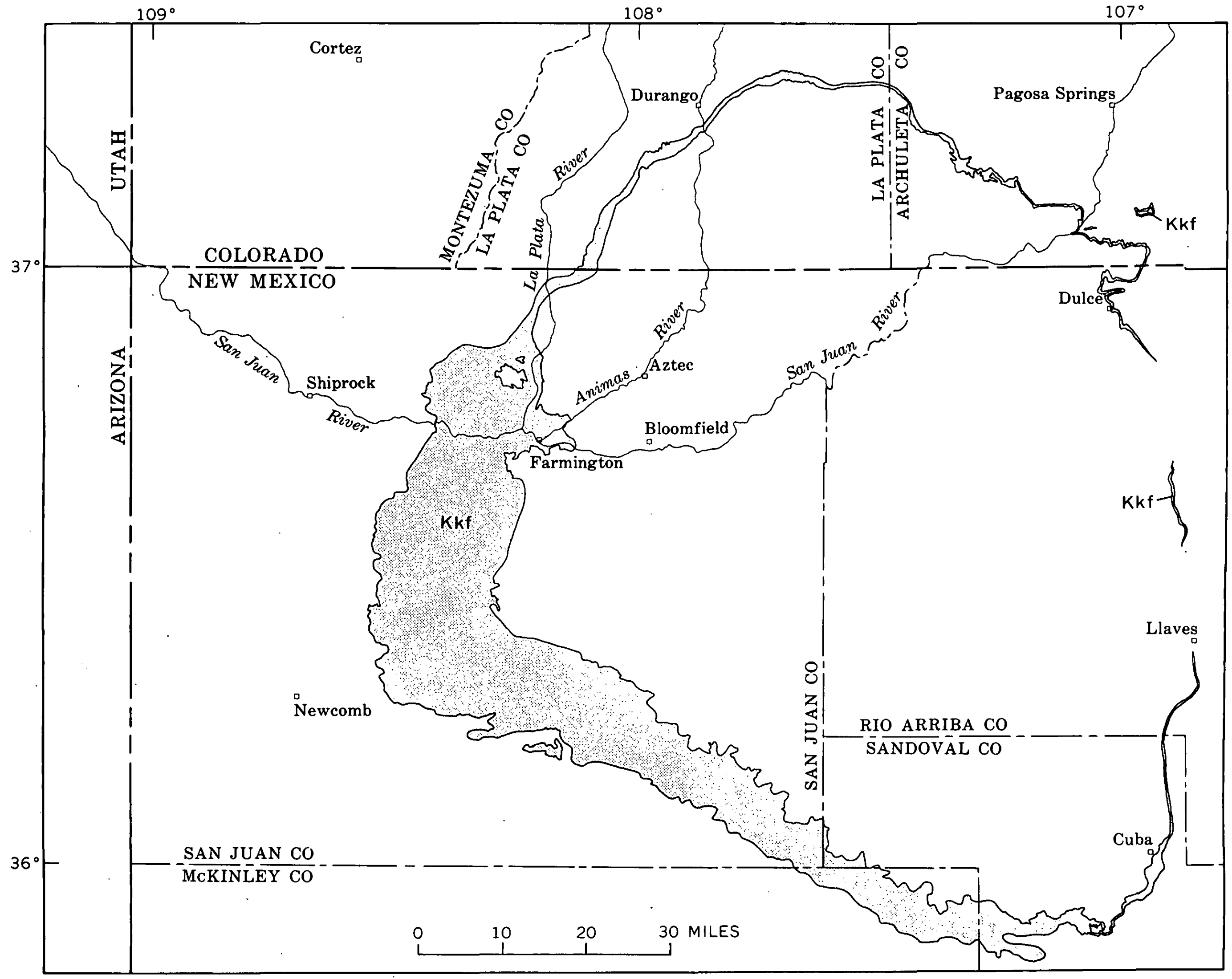


FIGURE 1.—Index map showing the location of the San Juan Basin. Kkf, Fruitland Formation and Kirtland Shale; outcrop is shaded.

southern San Juan Basin; Bauer and Reeside (1921) who described the occurrence of coal in the Fruitland Formation in the western and southwestern parts of the basin; Reeside (1924) whose paper on the western part of the San Juan Basin summarized earlier data and offered new conclusions as to the stratigraphic relations between the Kirtland Shale and the Fruitland Formation; and Dane (1936) who mapped the southeastern part of the basin and noted that Kirtland, Fruitland, and Pictured Cliffs rocks were not present on the east side of the basin.

In more recent years, the following geologists mapped the outcropping Kirtland Shale and Fruitland Formation in other parts of the San Juan Basin: Dane (1946, 1948), Wood, Kelley, and MacAlpin (1948), Zapp (1949), Barnes (1953), Barnes, Baltz, and Hayes (1954), Hayes and Zapp (1955), Beaumont and O'Sullivan (1955), O'Sullivan and Beaumont (1957), Baltz, Ash, and Anderson (1966), Fassett (1966), Hinds (1966), and Baltz (1967).

SUBSURFACE GEOLOGY

Many of the early subsurface geologic studies of the Kirtland Shale and the Fruitland Formation were done by oil-company geologists and consulting geologists, most of whose work has never been published. Nearly all the material on the subsurface occurrence of the Kirtland and Fruitland rocks that has been published is in Guidebooks of the New Mexico Geological Society and the Four Corners Geological Society.

Silver (1950, 1951) illustrated and described the subsurface attitude of the Kirtland and Fruitland rocks of the basin and speculated on their source. Bozanic (1955) and Kilgore (1955) briefly discussed the Fruitland and Kirtland rocks and illustrated their subsurface occurrence in cross sections. Dilworth (1960) discussed the subsurface occurrence of the Farmington Sandstone Member of the Kirtland Shale. Baltz (1962, 1967) described the Fruitland and Kirtland rocks in the southeastern part of the basin. Fassett (1964) illustrated with electric-log sections the subsurface relation of the Kirtland and Fruitland rocks throughout the basin and discussed their source, mode of deposition, and tectonic history. Hinds (1964) discussed the sampling of Fruitland coals from wells in the San Juan Basin and illustrated the distribution of heating values based on analyses of these samples.

PRESENT STUDY

This report resulted from a study of the coal deposits of the Fruitland Formation throughout the San Juan Basin. The study was started by the U.S. Geological Survey in 1961 to provide a basis for classification of public lands in outstanding coal-land withdrawals. The Fruitland Formation and the Kirtland Shale were studied in the subsurface by using well logs, sample descriptions, cores, and drilling time records, and by the authors "sitting on wells" being drilled through the Fruitland and Kirtland rocks. During the study more than 2,000 electric logs were examined to determine the thickness and distribution of coal beds in the Fruitland Formation. Coal samples were collected from well cuttings at 64 selected sites throughout the basin and at a few localities from outcropping Fruitland coal beds. These coal samples were analyzed by the U.S. Bureau of Mines to determine the heating value and the moisture, volatile matter, fixed-carbon, ash, and sulfur content. The surface geology of a stratigraphically complex area in the southeastern part of the San Juan Basin was mapped in detail by the authors (Fassett, 1966; Hinds, 1966). In addition, reconnaissance geological mapping was done in several other areas around the margin of the basin. The results of this and previous mapping are synthesized on plate 1.

GEOGRAPHY

DRAINAGE

The north-trending Continental Divide lies along the east side of the San Juan Basin. The streams west of the divide are in the San Juan River drainage area, whereas the streams east of the divide are in the Rio Grande drainage area. The major stream in the basin is the San Juan River, which flows southwestward through the Colorado part of the basin and into northern New Mexico to the town of Blanco; from Blanco it flows westward across the basin and joins the Colorado River in Utah. The Animas River flows south through Durango, Colo., into New Mexico and joins the San Juan River at Farmington, N. Mex. The La Plata River flows south near the west rim of the basin and joins the San Juan River in Farmington, about 2 miles below the Animas–San Juan junction. In addition to these three perennial streams, many intermittent streams, of which the largest are the Chaco River and Canyon Largo, drain the area. The Chaco River drains the southern and western parts of the basin and enters the San Juan from the south near the town of Shiprock. Canyon Largo drains the south-central part of the basin and joins the San Juan at the town of Blanco.

LANDFORMS

The San Juan Basin lies in the Navajo physiographic section of the Colorado Plateaus province (U.S. Geol. Survey, 1946). The topographic relief in the basin is nearly 3,000 feet. Altitudes range from slightly more than 8,000 feet in the northern part of the basin to about 5,100 feet on the west side where the San Juan River crosses the basin rim. The most prominent physiographic feature in the area is Hogback monocline (fig. 14), which rims the basin on the northwest, north, and east sides and rises as much as 700 feet above the adjoining country on the west side of the basin. The central part of the basin is a dissected plateau, the surface of which slopes gently to the west. The principal streams have cut into the plateau to form deep steep-walled canyons. On the upland plains between the canyons, stabilized sand dunes are numerous. Along the San Juan and Animas Rivers several stream-terrace levels can be distinguished.

The climate throughout most of the San Juan Basin is arid to semiarid. The rainfall in the basin ranges from as low as 3 or 4 inches a year at lower altitudes to nearly 20 inches a year at higher altitudes, and the annual average is less than 15 inches. Precipitation is generally rare in early and middle summer and is more frequent in late summer and spring. The temperature ranges from below 0°F in the winter to above 100°F in the summer. The mean annual temperature at Farmington, N. Mex., is 52.6°, and the annual range is about 115°. The daily variation in temperature often exceeds 30°.

At lower altitudes short grass, sagebrush, and many varieties of cactus are common. The mesas of the basin generally support a growth of pinyon and juniper, scattered sagebrush, and sparse scrub oak. Ponderosa pine grows on the higher areas, mostly around the north and east rims of the basin. Cottonwood trees grow in the valleys of many of the streams.

ACCESS

The three main roads in the San Juan Basin are New Mexico State Highways 44 and 17 and U.S. Highway 550. Other State highways and a myriad of oil and gas well access roads furnish entry to almost every part of the basin. The Denver and Rio Grande Western Railroad narrow-gage line crosses the northern part of the basin from Durango eastward through Dulce and southward from Durango through Aztec to Farmington.

GEOLOGY OF THE SAN JUAN BASIN

GEOLOGIC SETTING

The San Juan Basin is an asymmetric structural depression which contains Cambrian, Devonian, Mississippian, Pennsylvanian, Permian, Triassic, Jurassic, Upper Cretaceous, Tertiary, and Quaternary rocks. The maximum known thickness of sedimentary rocks in the basin was penetrated by the El Paso Natural Gas Co. San Juan 29–5 Unit 50 in the SE¼ sec. 7, T. 29 N., R. 5 W., New Mexico principal meridian. This well was drilled to a total depth of 14,423 feet and penetrated Precambrian rocks at 14,030 feet. The Upper Cretaceous rocks of the basin are 6,000 or more feet thick and consist of intertonguing marine and nonmarine units that represent three basin-wide transgressive-regressive cycles of deposition. The final regression of the sea resulted in deposition of the marine Pictured Cliffs Sandstone.

The Pictured Cliffs is overlain by three Cretaceous units of continental origin: the Fruitland Formation, the Kirtland Shale, and the McDermott Member of the Animas Formation. These units are composed of interbedded sandstone, siltstone, shale, and coal and attain an aggregate thickness exceeding 2,100 feet in the northwestern part of the basin. The Tertiary rocks of the basin consist of part (locally) of the Kirtland Shale, the Ojo Alamo Sandstone, part of the Animas Formation, and the Nacimiento Formation of Paleocene age, the San Jose Formation of Eocene age, and intrusive rocks of possible Miocene age. Quaternary deposits consist of Pleistocene and Holocene terrace gravels and alluvium. The Tertiary and Quaternary rocks attain a maximum total thickness of more than 3,900 feet.

ELECTRIC-LOG INTERPRETATION

Several different kinds of geophysical devices are lowered and raised through drill holes to determine various properties of the rocks penetrated. Each of these devices measures a different physical characteristic or group of characteristics. The log of a well or borehole is the graphic record of the characteristics of the rocks penetrated as determined by a given borehole device. Three major classes of devices used to measure rock characteristics in a borehole are: electric, radioactivity, and sonic.

The electric log shows the conductivity, resistivity, and spontaneous potential of the formations penetrated. The radioactivity log shows both the natural and the induced radioactivity of the material penetrated. The sonic log shows the rate at which sound travels through the rocks adjacent to the borehole. Other devices are used to measure the size of the borehole, temperature in the hole, and inclination of the hole.

Approximately 9,500 wells have been drilled in the San Juan Basin, and the majority of these have had some sort of logging device run in them. In preparing this report the authors examined more than 2,000 logs, most of which were electric logs. Radioactivity and sonic logs were used wherever possible to supplement and confirm electric-log interpretation. Electric and induction-electric logs were used primarily because they form the bulk of the log file for the San Juan Basin.

Figure 2 shows a typical induction-electric log through the Lewis Shale, Pictured Cliffs Sandstone, Fruitland Formation, Kirtland Shale, and Ojo Alamo Sandstone. The contacts between the various units composing this sequence and a graphic representation

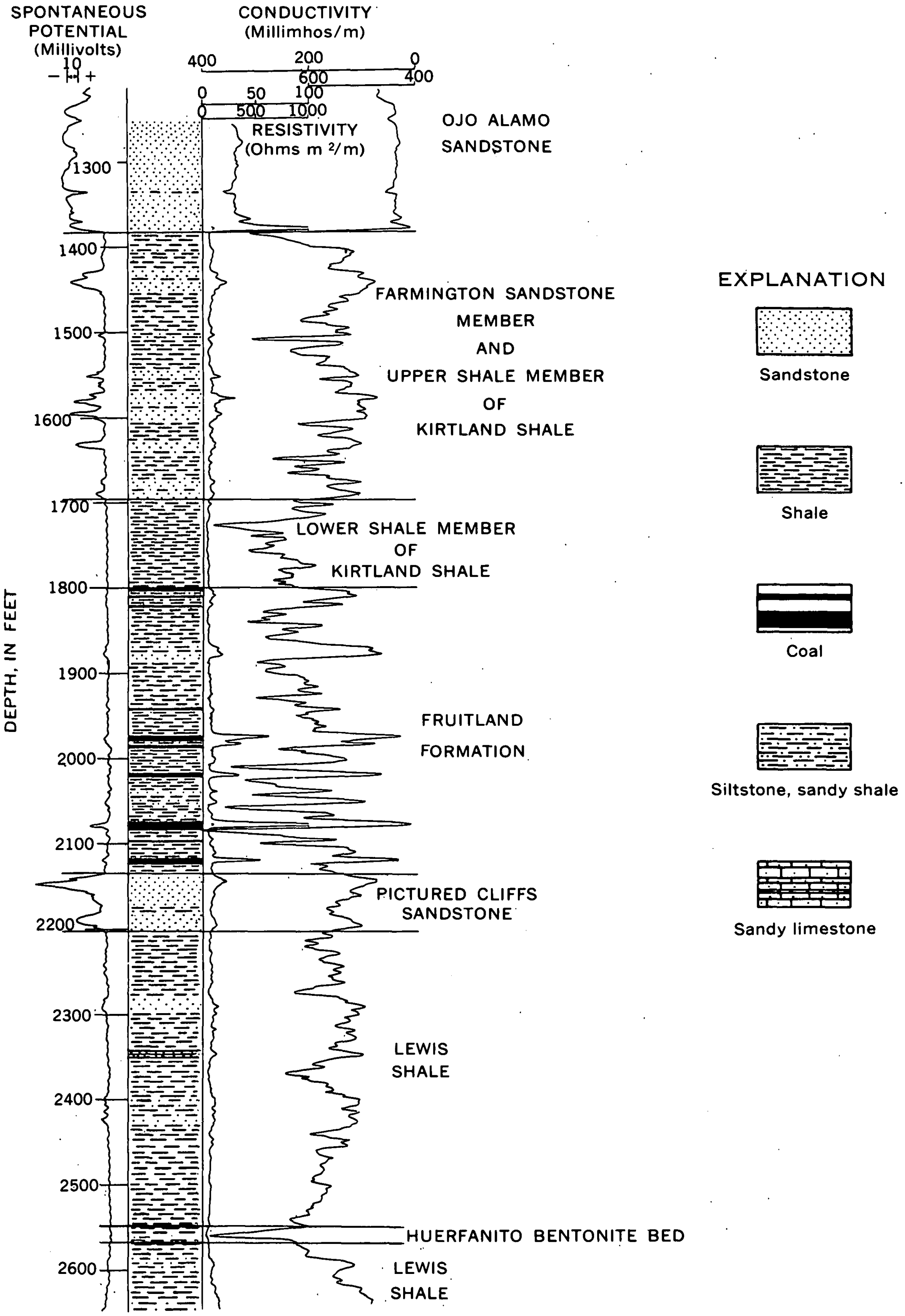


FIGURE 2.—Induction-electric log and lithologic column of the type well of the Huerfanito Bentonite Bed of the Lewis Shale showing the interval from below the Huerfanito through the lower part of the Ojo Alamo Sandstone. Lithologies are based on an interpretation of the three curves shown. The curves were traced from an induction-electric log of well 5 in cross section B–B′ (pl. 2). The induction curve was deleted to avoid masking the resistivity curve.

of the lithology based on interpretation of the log curves are also shown. Imaginary reference lines called shale lines are useful in interpreting rock types from electric logs. These are imaginary vertical lines connecting the points furthest to the right on the spontaneous-potential (S.P.) curve and the points furthest to the left on the resistivity curve. In areas where both curves move outward, away from the shale lines, sandstone or siltstone is indicated; in areas where the resistivity curve moves to the right and the spontaneous-potential curve stays on or close to the shale line, coal or limestone is indicated. This is an oversimplification, but it will serve for a general interpretation of the log in figure 2.

Figure 2 shows that the Lewis Shale is predominantly shale that contains some thin limestone and sandstone stringers. The Huerfanito Bentonite Bed is conspicuous on the conductivity curve. The lithology and response of the Huerfanito on various types of logs is discussed at length in the section "Stratigraphy." The Pictured Cliffs Sandstone, which directly overlies the Lewis Shale, has a distinct contact with both the underlying Lewis and the overlying Fruitland. The contact of the Fruitland Formation with the lower shale member of the Kirtland Shale is picked at the highest coal or carbonaceous shale bed (1,800-ft depth, fig. 2) above the base of the Fruitland. The contact of the lower shale member of the Kirtland Shale with the overlying Farmington Sandstone Member of the Kirtland is picked at the base of the first relatively thick sandstone above the lower shale member. The contact of the upper shale member of the Kirtland with the base of the Ojo Alamo Sandstone is picked at the base of the first thick massive sandstone above the upper shale member. The base of the Ojo Alamo is characterized throughout much of the San Juan Basin by high resistivity on the electric log.

STRATIGRAPHY

UPPER CRETACEOUS ROCKS

LEWIS SHALE

A detailed discussion of the Lewis Shale is beyond the scope of this report; however, the Lewis is briefly described because the Huerfanito Bentonite Bed, a new name in this report and used as a datum in several illustrations, is in the upper part of the Lewis.

The Lewis Shale is the stratigraphically highest unit of marine shale in the San Juan Basin. It is a light- to dark-gray and black shale that contains interbeds of light-brown sandstone, sandy to silty limestone, calcareous concretions, and bentonite. The Lewis ranges in thickness from 0 feet in the southwestern part of the basin to about 2,400 feet in the northeastern part. It was named by Cross, Spencer, and Purington (1899) for exposures near the former Fort Lewis army post, about 15 miles southwest of Durango, Colo.

HUERFANITO BENTONITE BED

Oil-company geologists who have studied the subsurface Upper Cretaceous rocks of the San Juan Basin have long been aware of the existence of several marker beds in the Lewis Shale that show as distinctive responses on electric logs. One of these markers was used as a datum by Hollenshead and Pritchard (1961) and was given the name "Green Marker Horizon." The "Green Marker Horizon" is near the base of the Lewis Shale and is characterized by low resistivity on electric logs.

Another marker bed, here named the Huerfanito Bentonite Bed, is in the upper part of the Lewis Shale. The Huerfanito Bentonite Bed is named for the type well, Huerfanito Unit 60, drilled by Turner and Webb, and completed in November 1960. The well is in the SW¼SW¼ sec. 4, T. 26 N., R. 9 W. (pl. 2). The surface altitude of the well is 6,396 feet; the kelly-bushing altitude from which the log depths were measured is 6,403 feet; total depth of the well is 6,760 feet. This well is in the Huerfanito Unit operated by El Paso Natural Gas Co. The unit name is derived from Huerfanito Peak, about 2 miles northeast of the well.

The induction-electric log of the type well, the Huerfanito Unit 60, is shown in figure 2. On this log the Huerfanito Bentonite Bed exhibits typical high conductivity at the drilled depths of 2,550–2,562 feet. This bed, which is 12 feet thick in this well, exhibits a characteristic response on several types of well logs. Figure 3 shows the response to the Huerfanito Bentonite Bed on induction-electric and sonic–gamma ray logs run in two wells 78 miles apart in the San Juan Basin.

In the left-hand log of figure 3*A*, spontaneous-potential, resistivity, and conductivity curves are shown. It is apparent that the conductivity curve responds markedly to the Huerfanito Bed. The Huerfanito has a conductivity value of about 550 millimhos/m (millimhos per meter) on this log. The resistivity curve and the spontaneous-potential curve respond only slightly to the marker bed on this log. In the right-hand log, the gamma ray and the interval-transit-time curves are shown. The response of the interval-transit-time curve to the Huerfanito in this well is pronounced, giving a reading of about 140 microseconds per foot. The gamma ray curve also responds to the Huerfanito, but this curve alone would not serve to identify the marker bed.

The logs shown in figure 3*B* exhibit similar but more subdued responses to the Huerfanito Bed; nevertheless, the bed is the most conductive unit shown on the con-

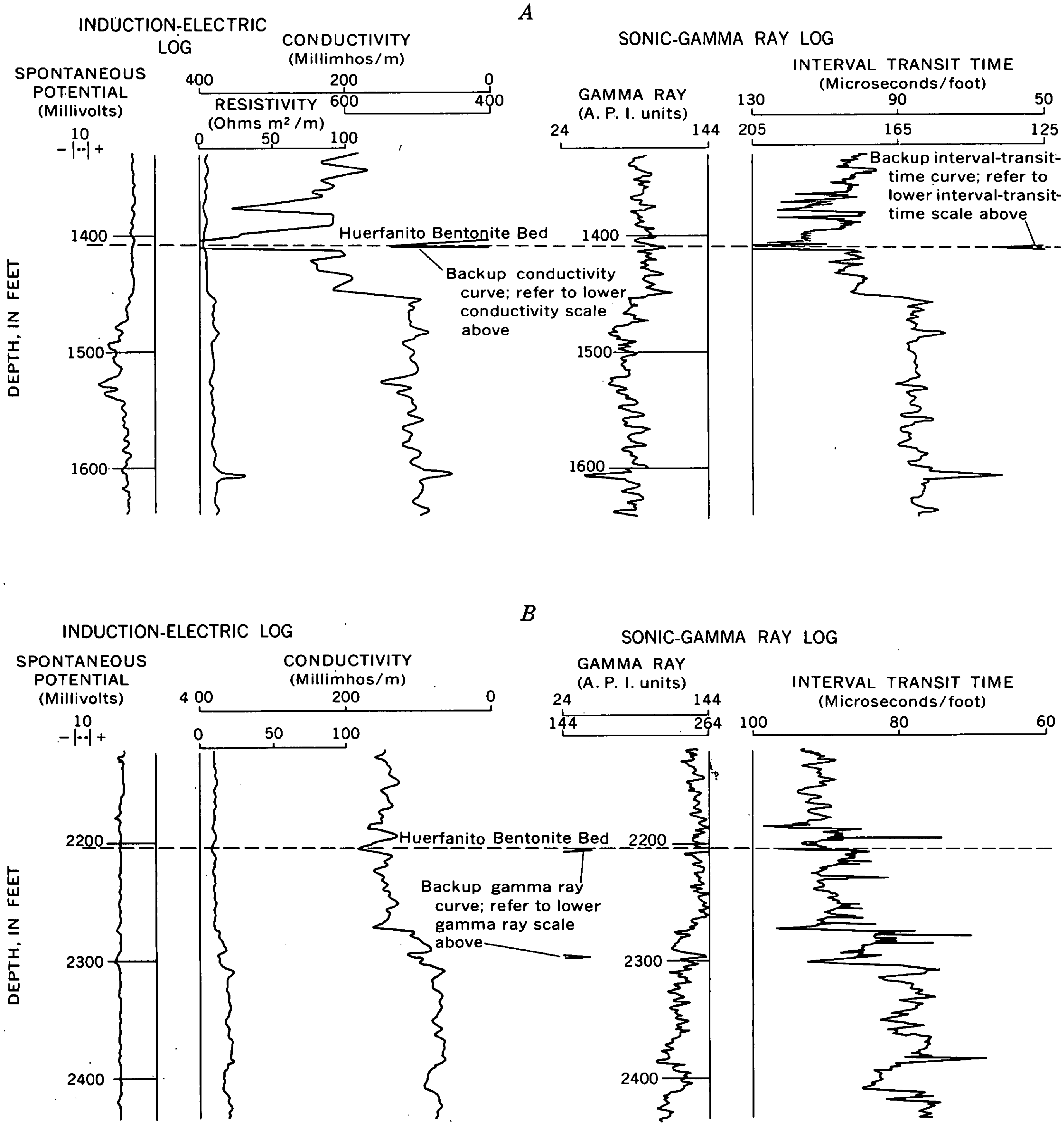


FIGURE 3.—Induction-electric and sonic-gamma ray logs from two wells 78 miles apart, showing the response of the curves to the Huerfanito Bentonite Bed. *A*, Logs from a well on the west side of the San Juan Basin (NE¼ sec. 4, T. 27 N., R. 14 W.; well 2 in section *F–F′* on pl. 2). *B*, Logs from a well on the east side of the basin (NE¼ sec. 36, T. 31 N., R. 2 W.).

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

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 enough 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 5*A* 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 5*B* 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 5*B* 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

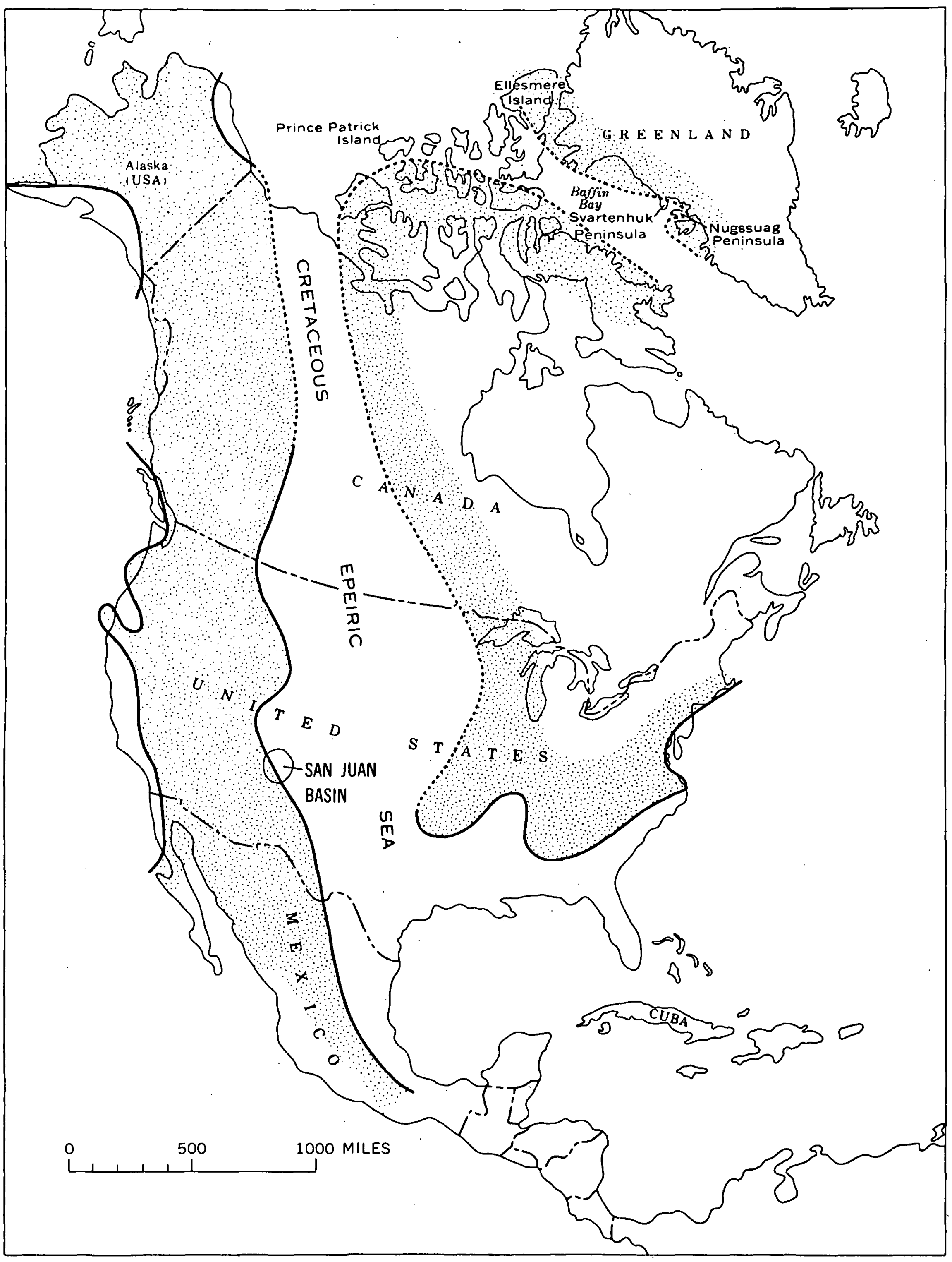


FIGURE 4.—Probable configuration of the North American epeiric seaway at the time that the Upper Cretaceous rocks of the San Juan Basin were being deposited. After Gill and Cobban (1966, fig. 15).

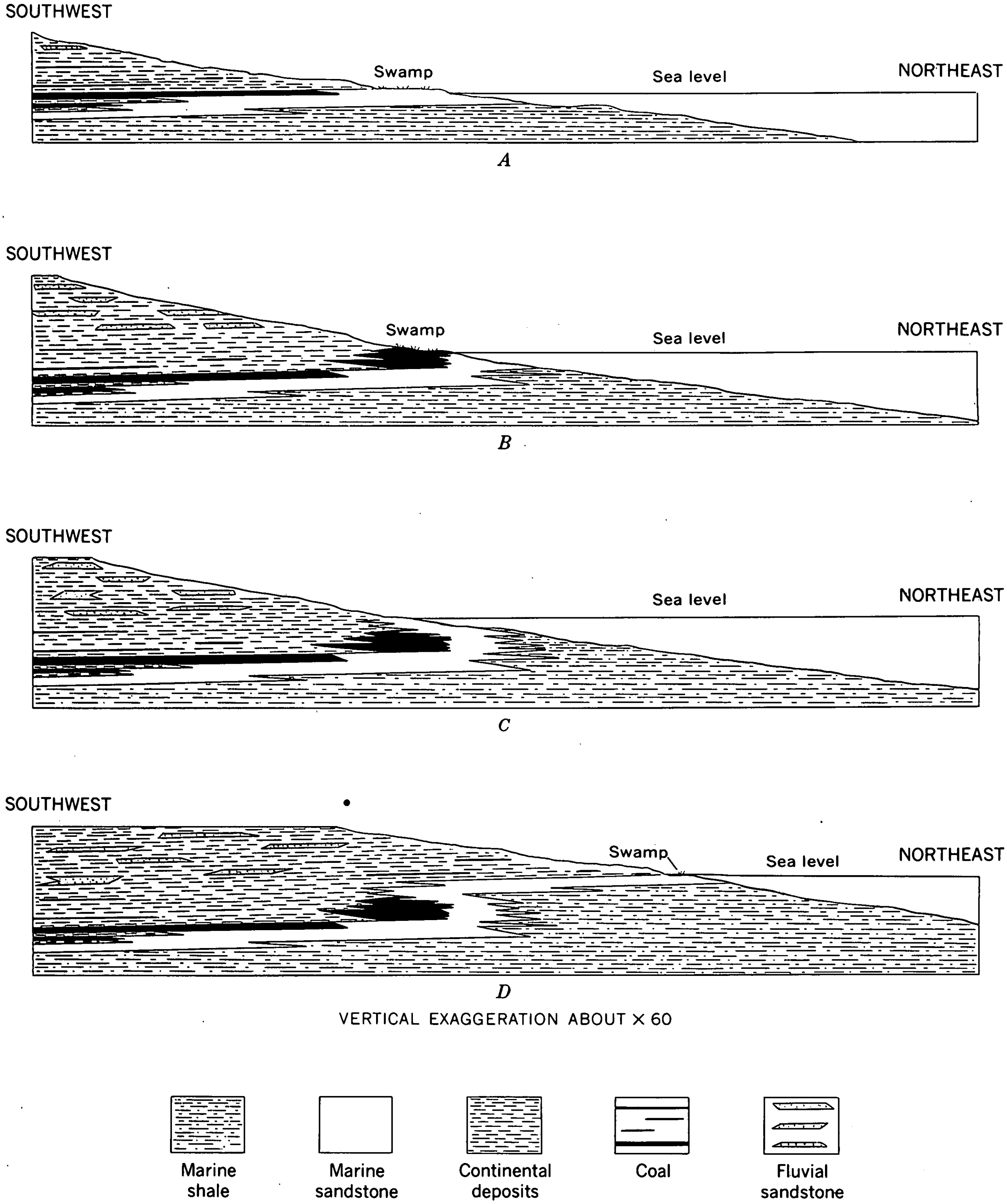


FIGURE 5.—Diagrammatic cross sections showing the relations of the continental, beach, and marine deposits of Pictured Cliffs time after (*A*) shoreline regression, (*B*) shoreline stability, (*C*) shoreline transgression, and (*D*) shoreline regression.

buildup of sand. The stable shoreline situation also allowed for the maximum amount of vegetal-matter buildup in coastal swamps (discussed in detail in the section "Fuel Resources").

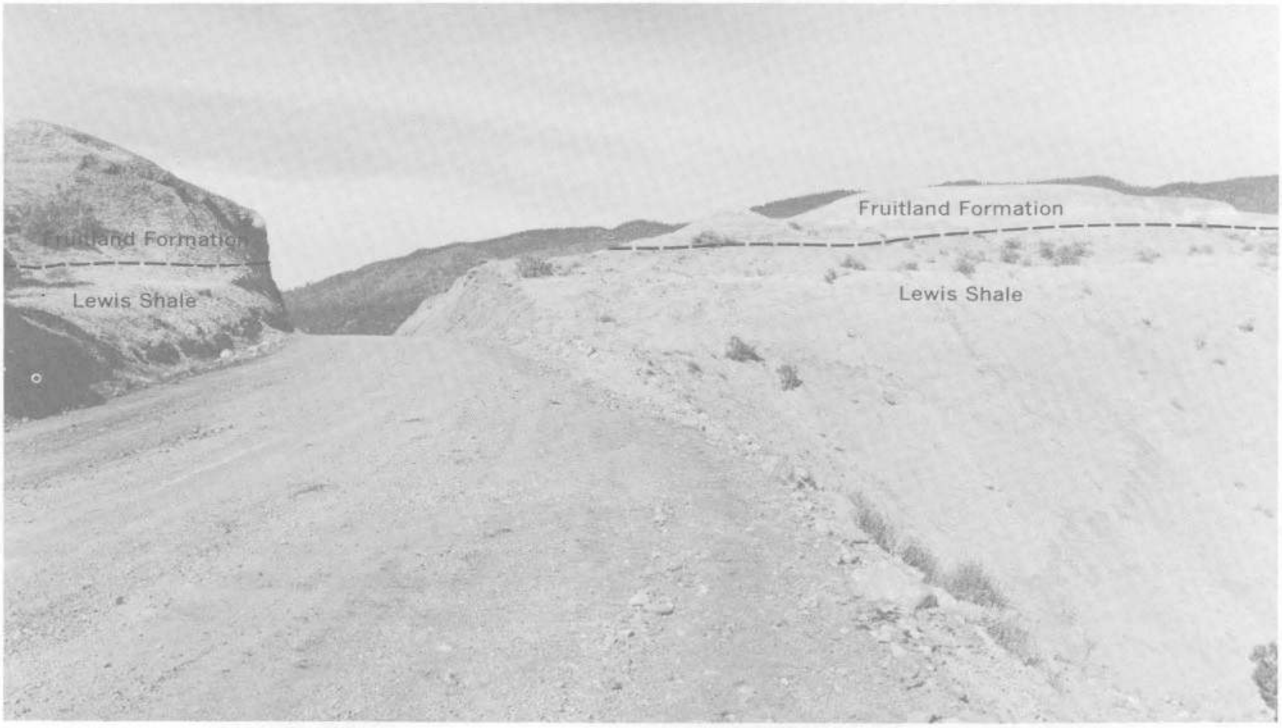
Figure 5*C* illustrates a shoreline that has transgressed, which resulted either when the sediment supply decreased while the rate of subsidence remained constant, or when the rate of subsidence of the sea floor increased and the sediment supply remained constant. The sea moved overland, depositing beach and shallow-water marine sand deposits on top of continental deposits. As shown in panel *C*, the new deposits formed on top of vegetal matter that had been accumulating in a coastal swamp. Figure 5*D* shows a shoreline that has regressed, where again the sediment supply exceeded the rate of subsidence of the sea floor, resulting in a shift of the shoreline to the northeast. As shown in panel *D*, the past history of the regression (and associated minor transgressions) of the sea from the basin area is faithfully recorded in the sediments deposited during that time.

The Pictured Cliffs Sandstone is absent in two areas on the east side of the San Juan Basin (pl. 1). In the northeastern area the Lewis Shale is overlain by the Ojo Alamo Sandstone; in the southeastern area the Lewis is overlain by the Fruitland Formation. The absence of the Pictured Cliffs in the northeastern area is explained by post-Lewis and pre-Ojo Alamo erosion. The absence of the Pictured Cliffs in the southeastern area is not so easily explained. Here, the carbonaceous silicified-wood-bearing rocks of the Fruitland overlie the marine rocks of the Lewis. Figure 6 shows a roadcut in the SW¼NW¼ sec. 23, T. 21 N., R. 1 W., about 3 miles northeast of Cuba, N. Mex., where the contact of the Fruitland and the Lewis is well exposed. The contact seems to be disconformable, but the irregularity may be the result of slumping of the overlying Fruitland rocks. The Lewis here contains thin sandstone stringers that might be of Pictured Cliffs lithology. However, the Lewis is known to be sandy throughout most of its thickness in this area (Dane, 1936, p. 109; Fassett, 1966), and the authors believe that there is no substantial reason to call these sand stringers Pictured Cliffs Sandstone. Furthermore, at this locality there is more shale than sandstone in the rocks underlying the Fruitland; thus, the majority of the geologists working in the San Juan Basin would probably assign these rocks to the Lewis Shale rather than to the Pictured Cliffs Sandstone.

Possible explanations for the absence of Pictured Cliffs Sandstone in the southeastern San Juan Basin are: (1) No sand was available to be deposited in this area, (2) a relatively sudden increase in sediment influx caused the sea to regress rapidly and allowed insufficient time for the beach and shallow marine sands to be developed, (3) uplift in the area resulted in the rapid retreat of the sea which prevented development of strand-line sands, and (4) uplift resulted in erosion of the sand prior to Fruitland deposition. The authors believe the last two explanations best explain the absence of Pictured Cliffs Sandstone in this area. Uplift, in addition to causing the sea to regress rapidly, probably resulted in subaerial erosion of some marine sediments prior to deposition of the Fruitland rocks. A local disconformity between the Fruitland and the Pictured Cliffs is indicated by channels at the base of the Fruitland, which have cut as much as 50 feet into the underlying Pictured Cliffs in T. 19 N., R. 2 W., near Mesa Portales (Fassett, 1966). The exposures in the roadcut shown in figure 6 indicate a hiatus between the Fruitland and the Lewis. The absence or scarcity of coal deposits in a narrow band along the east edge of the San Juan Basin (fig. 21) also indicates that there was uplift in this area either contemporaneous with or slightly later than the retreat of the Pictured Cliffs Sea. Uplift may have been centered southeast of the present basin area in the Nacimiento Mountains, which may have been an island or a peninsula in the Pictured Cliffs Sea.

If the Huerfanito Bentonite Bed is an ancient volcanic ash fall laid down in the Lewis Sea, then the bed is a time surface which reflects the configuration of the sea floor at the time it was laid down. What the configuration or gradient of the sea floor was at the time the Huerfanito was deposited in the basin area is not known; however, it is highly probable that the sea floor was relatively smooth and even and the gradient was extremely low. For the purpose of discussing past orientations of the Pictured Cliffs shoreline, it is assumed that the Huerfanito was a horizontal surface. Presuming that there was no basin-area tilting between the time the Huerfanito was deposited and the time the Pictured Cliffs Sandstone was deposited, lines drawn on top of the Pictured Cliffs Sandstone which parallel the Huerfanito should represent both time lines and the configuration of the Pictured Cliffs Sea shoreline. Figure 7 is an isopach map of the interval between the Huerfanito and the top of the Pictured Cliffs Sandstone, and the isopachs, in effect, should approximately represent past shoreline orientations of the Pictured Cliffs Sea.

The minimum thickness of the interval between the top of the Pictured Cliffs Sandstone and the Huerfanito Bentonite Bed is 150 feet in the southwestern part of the basin. Note that the 150-foot isopach nearly parallels the present outcrop of the top of the Pictured Cliffs Sandstone. The 200- and 250-foot isopachs parallel the 150-foot line and are roughly an equal distance apart.



A

B

FIGURE 6.—Outcrop of Fruitland Formation on Lewis Shale. *A*, In roadcut in the SW¼NW¼ sec. 23, T. 21 N., R. 1.W., about 3 miles northeast of Cuba, N. Mex. *B*, Closeup of contact, at left of road shown in *A*; contact appears to be disconformable. Note reverse fault.

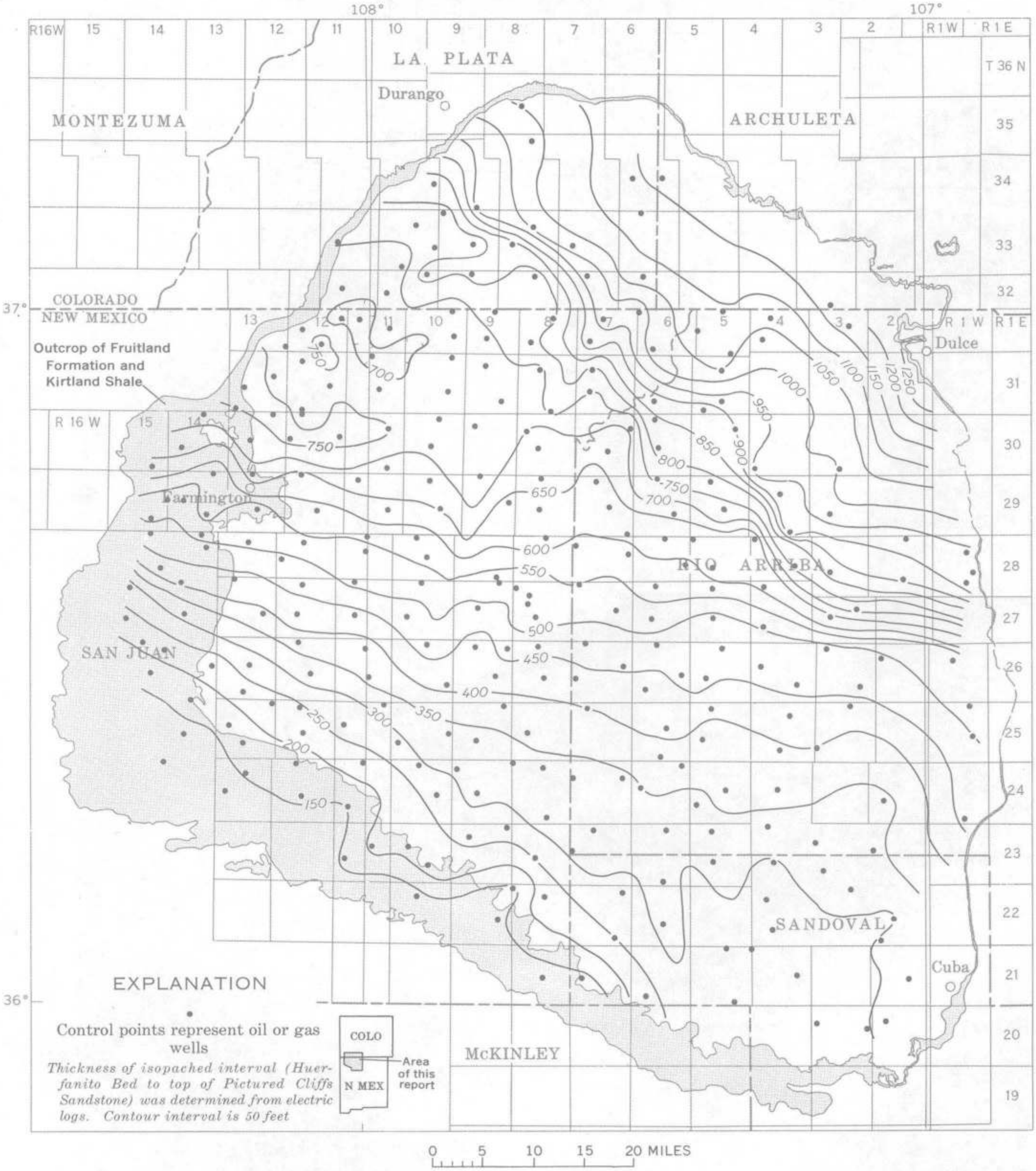


FIGURE 7.—Isopach map of the interval between the Huerfanito Bentonite Bed of the Lewis Shale and the top of the Pictured Cliffs Sandstone.

Thus, when the Pictured Cliffs was being deposited in this part of the basin, the shoreline trended northwest and the sea regressed northeast.

A change in configuration of the Pictured Cliffs shoreline is indicated in the basin area between the 300-foot and the 500- to 550-foot isopachs, particularly in the southeastern part of the basin. The shoreline apparently shifted from a northwest trend at the 300-foot isopach to nearly an east trend at the 500-foot isopach. This shift in shoreline orientation may have resulted from a more rapid regression of the sea in the southeast than in the west. The rapidity of the regression could have been caused by (1) a greater influx of sediments into the southeastern part of the basin while the sediment supply being brought in to the west remained constant or perhaps even decreased; (2) local uplift in the southeastern part of the basin area; or (3) the fact that the slope of the sea floor in the southeast was gentler than the slope of the sea floor to the northwest with the result that, given equal sediment influx, the shoreline would regress faster in this area.

During the time that the Pictured Cliffs Sandstone was being deposited in the area between the 500- and 650-foot isopachs, the shoreline was again relatively straight, trending nearly east, and the sea was regressing to the north. However, between the 650- and 750-foot isopachs, the alinement again swung around to a northwest trend, probably in response to an increased sediment supply from the west or northwest and decreased sediment influx in the east, local uplift in the northwest, or a more gently sloping sea floor in the northwest.

The 700-foot depression isopach in the northwestern part of the basin and the two 750-foot isopachs southwest of this line are anomalous and may represent irregularities of the sea floor present at the time of deposition of the Huerfanito Bentonite Bed rather than highs and lows in the top of the Pictured Cliffs. The shoreline of the Pictured Cliffs Sea continued to maintain the northwest trend as the sea retreated out of the present basin area. The total rise of the top of the Pictured Cliffs Sandstone across the basin is 1,100 feet, ranging from 150 feet above the Huerfanito in the southwest to 1,250 feet above the marker bed in the northeast.

This stratigraphic rise is best shown in the six cross sections which were constructed across the basin area (pl. 2). The sections are based on data obtained from electric logs of wells drilled for oil or gas in the San Juan Basin, and the datum is the Huerfanito Bentonite Bed. The three northeast sections, *A–A′*, *B–B′*, and *C–C′*, best show the stratigraphic rise of the Pictured Cliffs because these sections are in general normal to the ancient Pictured Cliffs shoreline. There are a large number of steplike rises in the stratigraphic position of the Pictured Cliffs Sandstone. Many of the rises are inferred between control wells, but some are shown at the control wells. Each step represents either a regression or a temporary stabilization or minor transgression of the Pictured Cliffs shoreline. In particular, two prominent areas of abruptly rising Pictured Cliffs can be seen in the sections, one on the southwest edge of the basin and one in the northeastern part. The southwest rise is between wells 1 and 5 in section *A–A′*, between wells 1 and 4 in section *B–B′*, and between wells 1 and 3 in section *C–C′*. The same rise was mapped by the authors on the outcrop in T. 19 N., Rs. 3 and 4 W. The northeast rise is between wells 8 and 9 in section *A–A′*, wells 9 and 11 in section *B–B′*, and between well 8 and the outcrop in section *C–C′*. The northeast rise is much more apparent and continuous than the one to the southwest and is clearly shown in figure 7, the isopach map of the interval between the Huerfanito Bed and the top of the Pictured Cliffs. The northeast rise was noted by the authors on the outcrop in sec. 7, T. 27 N., R. 1 E. It is probably the same stratigraphic rise mapped by Zapp (1949) in the Durango, Colo., area.

The west-east section, *F–F′* (pl. 2), also illustrates the two major stratigraphic rises of the Pictured Cliffs. The southwest rise occurs between the outcrop and well 3, and the northeast rise occurs between wells 12 and 15. The south-north section, *D–D′*, shows the two major rises but not as distinctly as does the west-east section. In the south-north section, the southwest rise occurs between wells 1 and 4, and the northeast rise occurs between wells 13 and 15. The northwest-southeast section, *E–E′*, does not show either of the two major rises because it is about parallel to and between them.

The large stratigraphic rise in the northeastern part of the basin is not time-equivalent along its extent but, rather, is older in the southeast than in the northwest. As shown in figure 7, this rise or vertical upbuilding of the Pictured Cliffs is between the 550-foot and the 800-foot isopachs in the southeast and between the 800-foot and 950-foot isopachs in the northwest. Thus, at the same time that the Pictured Cliffs shoreline was relatively stable in the southeast, the sea was regressing relatively more rapidly in the northwest.

Fossils and Age

The most abundant and widespread fossil in the Pictured Cliffs Sandstone consists of molds and casts of *Ophiomorpha major* (crustacean burrows; compare Weimer and Hoyt, 1964). This fossil is of little use as an age indicator; however, its presence indicates a shallow marine environment and can be used in most instances to differentiate nonmarine sandstone beds of the Fruitland from lithologically similar marine sandstone beds of the Pictured Cliffs, especially where the two formations intertongue. Reeside (1924, p. 19) listed fossils collected from the Pictured Cliffs at four localities in the north-central and northwestern parts of the San Juan Basin. He concluded that these fossils indicate a littoral marine environment of deposition and are of Montana age. In the southern part of the basin, Dane (1936, p. 112) collected Pictured Cliffs fossils, to which Reeside assigned a Montana age.

The authors collected fossils from a thin limestone bed in the Pictured Cliffs in the SW¼SW¼ sec. 10, T. 19 N., R. 2 W., on the southeast end of Mesa Portales about 10 miles southwest of Cuba, N. Mex. (Fassett, 1966, fossil loc. 29200). The fossils were identified by D. H. Dunkle of the U.S. National Museum (written commun., January 8, 1965) as follows:

Sharks:

Lamna appendiculata (Agassiz)—Cosmopolitan, Cenomanian to Maestrichtian and ?Danian.

Oxyrhina angustidens Reuss—Cosmopolitan, range combined with that of *Odontaspis cuspidata*, with which it is often identified, Campanian to Sarmatian.

Scapanorhynchus raphiodon (Agassiz)—Cosmopolitan, Cenomanian to top of Maestrichtian.

Squalicorax pristodontus (Agassiz)—Cosmopolitan, Campanian to Ludian.

Ischyrhiza mira Leidy—North and South America, Campanian to top of Maestrichtian.

Teleost:

Enchodus sp.—Cosmopolitan, upper Albian to top of Maestrichtian.

Reptiles:

Indeterminate turtle and ?dinosaur scrap.

Dunkle stated that the widest Cretaceous age range of the above fossils is Campanian to Maestrichtian. This age range is compatible with the Montana age determined by Reeside for fossils found in the Pictured Cliffs at other localities in the basin.

The Pictured Cliffs Sandstone rises stratigraphically northeastward across the basin (pl. 2); thus, it must be younger in the northeastern part than in the southwestern part. The exact difference in age has not yet been determined, but preliminary fossil evidence affords an indication of what the age difference may be. The authors collected fossils from the upper part of the Lewis Shale at USGS Mesozoic locality D4834 in the SW¼SW¼ sec. 29, T. 25 N., R. 1 E. Unfortunately, the exposures at this locality were not good enough to establish the thickness of the interval between the fossil horizon and the base of the Fruitland Formation; the Pictured Cliffs is apparently not present in this area. The collection included *Didymoceras nebrascense* (Meek and Hayden), according to W. A. Cobban of the U.S. Geological Survey (written commun., 1965). If the isopachs in figure 7 are equivalent to time lines, as hypothesized on page 12, then they should also be equivalent to faunal zones. Theoretically, the 500-foot isopach, which would intersect the Lewis Shale outcrop at the point where *Didymoceras nebrascense* was collected, represents the *Didymoceras nebrascense* faunal zone across the basin. By the same reasoning, because *Didymoceras cheyennense* was inferred to occur in the Pictured Cliffs in the Durango, Colo., area (Gill and Cobban, 1966, pl. 4), this faunal zone is probably equivalent to the 950-foot isopach, which would intersect the Pictured Cliffs outcrop near Durango.

Gill and Cobban (1966, table 2) showed the *Didymoceras nebrascense* zone to be about 1.5 million years older than the *Didymoceras cheyennense* zone. Applying this figure to the corresponding isopachs gives a value of 300,000 years for each 100 feet of rise of the Pictured Cliffs Sandstone. Extrapolating across the basin from the 150-foot isopach to the 1,250-foot isopach yields an age difference of about 3 million years for the Pictured Cliffs between the southwestern and the northeastern parts of the basin.

Extent and Thickness

The Pictured Cliffs Sandstone crops out around the north, west, and south sides of the San Juan Basin but is absent along parts of the east side (pl. 1). It is present throughout the subsurface of the basin except in a narrow band along the east side. In the areas in the southeastern part of the basin, where the Pictured Cliffs is not present, the Lewis Shale is overlain by the undivided Fruitland Formation and Kirtland Shale. In a small area in the northeastern part of the basin, the Pictured Cliffs, the Fruitland, and the Kirtland are absent, and the Lewis Shale is overlain directly by the Ojo Alamo Sandstone. In this area scattered thin stringers of sandstone occur in the uppermost Lewis. The Pictured Cliffs is present in a small area near the center of the east side of the San Juan Basin in T. 27 N., R. 1 E., and T. 28 N., R. 1 W. In the southern part of this exposure, the Pictured Cliffs apparently intertongues with the Fruitland. In another area to the south, in T. 25 N., R. 1 E., there is an outcrop that is believed to be Pictured Cliffs.

Baltz (1967, p. 19) stated that the Pictured Cliffs is not present along the east-central margin of the San Juan Basin. Baltz wrote:

> In this area the stratigraphic interval of the Pictured Cliffs is occupied by silty, sandy upper beds of the Lewis Shale. Subsurface data from other parts of the basin indicate that the silty,

sandy upper part of the Lewis Shale that is equivalent to the Pictured Cliffs persists northwestward across the structurally deepest part of the Central basin nearly to the northwestern edge in Colorado. This body of shale divides the Pictured Cliffs into southwest and northeast lobes which merge in the northwestern part of the Central basin near the outcrops on the Hogback monocline southwest of Durango, Colo. Thus, the Pictured Cliffs is a horseshoe-shaped body of sand that is open to the southeast (fig. 7).

In his figure 7, which is a paleogeographic map, Baltz showed an interpretation of the subsurface distribution of the Pictured Cliffs. The figure shows the Pictured Cliffs absent in a northwest-trending area in the northern part of the basin.

The authors believe that the Pictured Cliffs Sandstone is present throughout nearly all the area where Baltz showed it missing in the northern part of the basin. Sections *A–A′* through *D–D′* and *F–F′* (pl. 2) all intersect the area, and the Pictured Cliffs was found to be present in all the wells in these cross sections. Indeed, the zone of thickest Pictured Cliffs in the San Juan Basin trends northwestward directly through the area in which Baltz showed the Pictured Cliffs to be absent. A core log (Fassett, 1968a, b) from a well in sec. 36, T. 29 N., R. 4 W., near the center of that area, described the Pictured Cliffs between the drilled depths of 3,913 and 4,200 feet, a total thickness of 287 feet. The lithology of this interval is predominantly fairly well sorted fine-grained glauconitic sandstone that contains abundant *Ophiomorpha*. Figure 8 shows the electric log and lithologic column of the cored portion of this well. The core was from one of the test holes, GB–1, for Project Gasbuggy (Holzer, 1967, 1968), an experimental project to evaluate stimulation of natural gas production from the Pictured Cliffs Sandstone by the use of nuclear explosives.

The Pictured Cliffs Sandstone ranges in thickness from 0 feet on the east side of the basin to about 400 feet in the north-central part. Sections *A–A′* to *E–E′* (pl. 2) illustrate the variability of thickness of the Pictured Cliffs and show that there are two belts of relatively thick sandstone in the basin. Both belts trend northwest and coincide with the two areas of prominent stratigraphic rise of the Pictured Cliffs discussed on page 15. The Pictured Cliffs was not recognized outside the San Juan Basin until Dickinson (1965) mapped a white to yellow fine-grained sandstone, 200–250 feet thick, that cropped out in a small area in the southeastern part of the Cerro Summit quadrangle in Montrose County, Colo. He called this unit the Pictured Cliffs Sandstone on the basis of lithic evidence.

FRUITLAND FORMATION

Definition

The Fruitland Formation was first defined by Bauer (1916). The name was derived from the town of Fruitland, N. Mex., on the San Juan River where outcrops of the formation are well exposed. Earlier, the rocks comprising the Fruitland had been included by Holmes (1877) in the Laramie Formation, which was equivalent to the sequence from the base of the Pictured Cliffs Sandstone to the top of the Ojo Alamo Sandstone (pl. 1). Bauer (1916, p. 274) gave the thickness of the Fruitland as ranging from 194 to 292 feet. He wrote that both its upper and lower contacts were conformable, with "interfingering" with the Pictured Cliffs at the base and a "gradational" contact with the Kirtland at the top. Bauer suggested that the top of the Fruitland was marked by "a gradational zone containing in many places sandstone lenses that are apparently of fluviatile origin."

Lithology

The Fruitland is composed of interbedded sandstone, siltstone, shale, carbonaceous shale, carbonaceous sandstone and siltstone, coal, and, at places in the lower part, thin limestone beds composed almost entirely of shells of brackish-water pelecypods. Nearly all the rock units composing the Fruitland are discontinuous. Most individual beds pinch out laterally, usually within a few hundreds of feet. The coal beds are the most continuous rock units in the Fruitland and, in places, are traceable for several miles. The average composition of Fruitland sandstone beds in the northern part of the San Juan Basin, as determined by Burgener (1953), is 85 percent quartz, 6.5 percent orthoclase feldspar, 5.5 percent plagioclase feldspar, and 2.7 percent coal. Burgener stated that calcite is the most common cement, especially toward the top of the formation, and clay cement is somewhat less abundant. Locally, thin iron-cemented sandstone beds and sporadic thin barite concretion zones and calcite concretion zones are conspicuous markers in the Fruitland. The lithology of the Fruitland changes vertically in a generally consistent way: the thicker coal beds are invariably confined to the lower one-third or even to the lower one-fifth of the formation, the limestone beds are found only in the lowermost part of the formation, sandstone is usually more abundant in the lower part than in the upper part, and predominantly siltstone and shale is found in the upper part.

In the southeastern part of the basin, the Fruitland contains sandstone beds that seem to be lithologically different from sandstone beds in the Fruitland throughout the rest of the basin. These beds are conspicuous in surface exposures and on electric logs. In surface exposures they consist of scattered lenses of white fine- to coarse-grained sandstone which contain numerous silicified wood fragments and flattened clay balls as much as 1 foot across. The clay balls readily weather

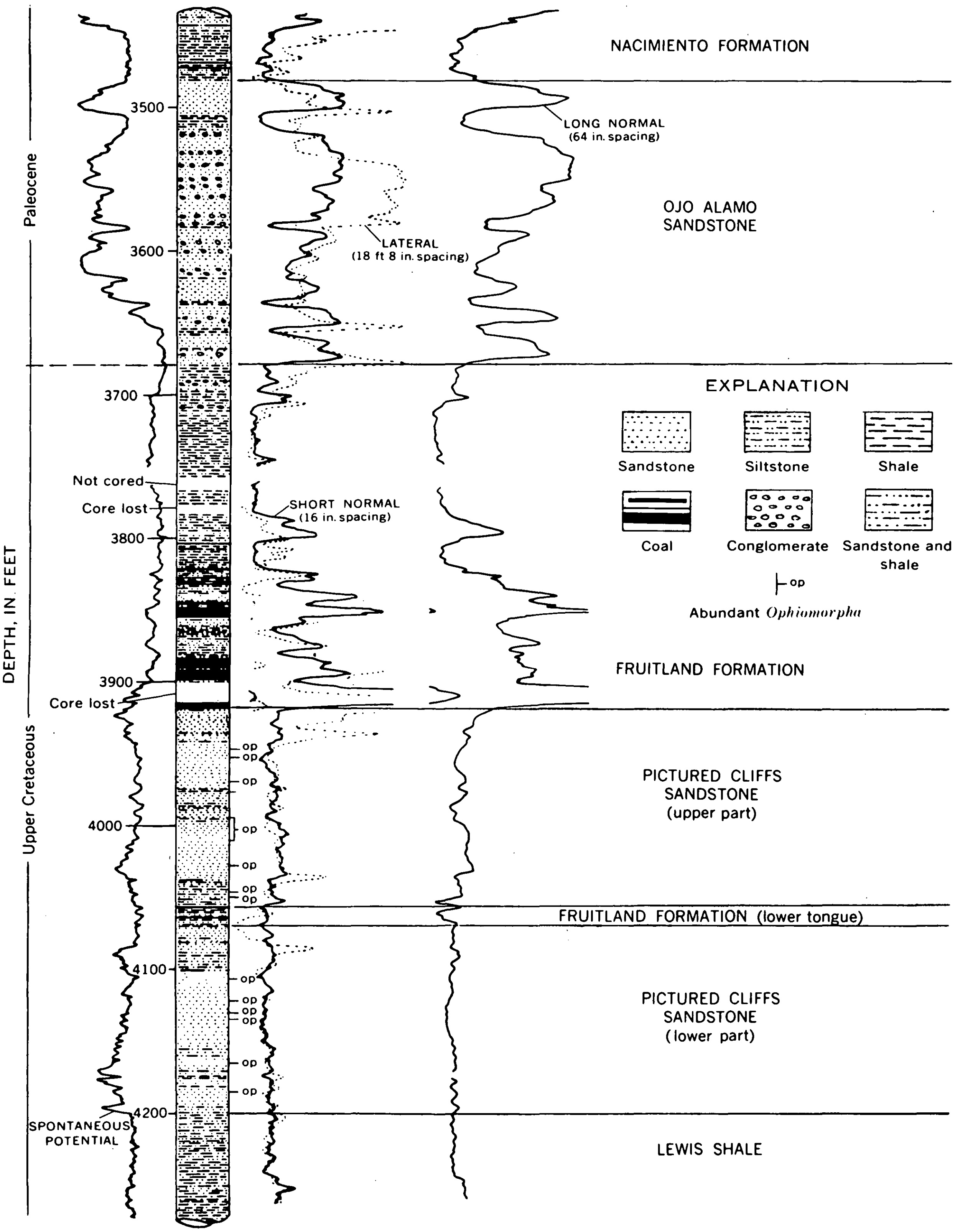


FIGURE 8.—Electric log and lithologic column of the cored portion of borehole GB-1, Project Gasbuggy (after Fassett, 1968b, fig. 2).

out, giving the sandstone a vuggy appearance on the outcrop. The beds represent channel sands that may have had a source southeast of the present basin area. The age of the sandstone beds is not definitely known. Some beds were obviously deposited contemporaneously with other sedimentary rocks composing the Fruitland Formation and Kirtland Shale because they are enclosed by typical Fruitland and Kirtland rocks. Other beds, however, seem to represent post-Fruitland deposition and may have been laid down in channels formed during the last phases of basin-wide erosion that preceded deposition of the Ojo Alamo Sandstone. Good exposures of these sandstone beds can be observed on the southwest and east-central edges of Mesa Portales in the S½ sec. 7, T. 19 N., R. 2 W., and the NW¼ sec. 25, T. 20 N., R. 2 W.

Contacts

The lower contact of the Fruitland has been discussed in the section on the Pictured Cliffs Sandstone. Early geologists used several criteria to separate the Kirtland and the Fruitland. Reeside (1924, p. 20) stated that "the highest of the sandstones has been taken as the top of the Fruitland formation and the overlying softer rocks have been assigned to the Kirtland shale." Dane (1936, p. 113) stated that the upper boundary of the Fruitland should be drawn "at the top of the stratigraphically highest brown sandstone." Barnes (1953) suggested that the top be picked to "include within the Fruitland formation all thick persistent coal beds and all prominent sandstone beds." Nearly all oil-company geologists and geologic consultants in the Four Corners area now place the top of the Fruitland at the top of the highest coal bed or carbonaceous shale bed, and the authors use this criterion.

On the east side of the San Juan Basin, the Fruitland is overlain by the Ojo Alamo Sandstone, and the Kirtland Shale is absent (fig. 9). Sections C–C′, F–F′, and E–E′ of plate 2 show areas where the base of the Ojo Alamo lies directly on top of the Fruitland. The nature of the basal Ojo Alamo contact is discussed in the section on the Ojo Alamo Sandstone.

Mode of Deposition

The Pictured Cliffs Sandstone was laid down during the final retreat of the Upper Cretaceous sea from the San Juan Basin area. As the sea regressed, coastal-swamp, river, flood-plain, and lake deposits were laid down shoreward on top of the Pictured Cliffs. These deposits compose the Fruitland Formation. Figure 5 shows the environment of deposition of the Fruitland. As the Pictured Cliffs Sea retreated, coastal swamps formed, and vegetal matter accumulated in the swamps. While the shoreline was regressing at a relatively steady rate, the vertical thickness of vegetal material that could accumulate was relatively small; also, swamps were probably unconnected and of rather small size along the shoreline. However, when the shoreline became geographically stable (fig. 5*B*), vegetal matter built up vertically to greater thicknesses, and swamps probably became more widespread behind and parallel to the shoreline. As the sea continued to regress, swamps continued to form close to the shoreline, and older swamps were covered by silt and sand laid down as river and flood-plain deposits. Some smaller swamps formed some distance landward of the retreating shoreline, but these swamps were usually ephemeral and accumulation of vegetal material in them was small.

Fossils and Age

Fossils are numerous in the Fruitland, and they have been described by Gilmore (1916), Knowlton (1916), Stanton (1916), and Osborn (1923). Since 1961, Dr. W. A. Clemens of the University of Kansas Museum of Natural History has collected mammalian fossils from the upper part of the Fruitland and the lower part of the Kirtland at about a dozen localities in the San Juan Basin. The best collections were made from the Fruitland in Hunters Wash in the southwestern part of the basin. Clemens (written commun., 1967) reported:

Preliminary analysis suggests the collections made at these different sites are samples of one faunal unit, and all have been considered in preparing the following provisional lists:

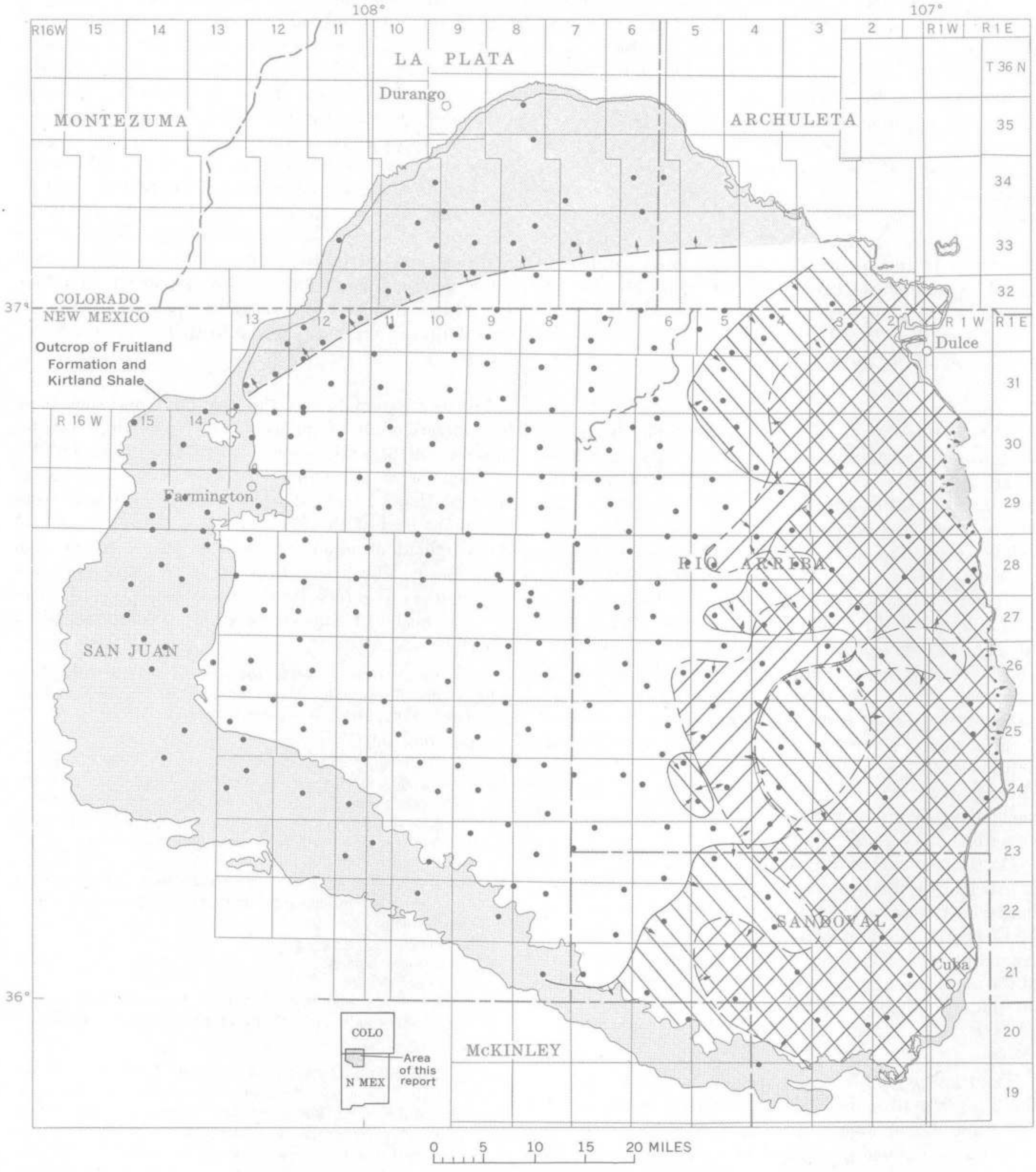
Multituberculata
- *Mesodma*, possibly *M. formosa*.
- *Cimolodon*, two species, one resembling *C. nitidus*, the other including animals of smaller individual size.
- A new species with a low, eucosmodontidlike P_4.
- A new species with high, trenchant P_4^4.

Marsupialia
- *Alphadon marshi* or a closely related species and at least one other, as yet undescribed species.
- *Pediomys* sp.

Eutheria
- *Gypsonictops* sp.
- *Cimolestes* sp.
- A therian mammal that cannot be referred to the Marsupialia or Eutheria on the available evidence.

* * * * *

Comparison of this faunal unit with the Lance local fauna from the Late Cretaceous of eastern Wyoming points out some interesting differences. For example, *Meniscoessus* (a multituberculate) and *Pediomys* (a marsupial) have high relative abundances in the Lance local fauna. The former is unknown and the latter very rare in New Mexico. Our collections are now large enough to warrant suggesting that their absence or low frequency of occurrence are not a product of bias in collecting technique or small sample size. Whether these faunal differences reflect differences in age, ecology, or combinations of these and other factors, remains to be determined.


108°
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LA PLATA
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ARCHULETA
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NEW MEXICO
37°
Dulce
Outcrop of Fruitland Formation and Kirtland Shale
R 16 W
Farmington
RIO ARRIBA
SAN JUAN
SANDOVAL
Cuba
36°
COLO
N MEX
Area of this report
McKINLEY
0 5 10 15 20 MILES

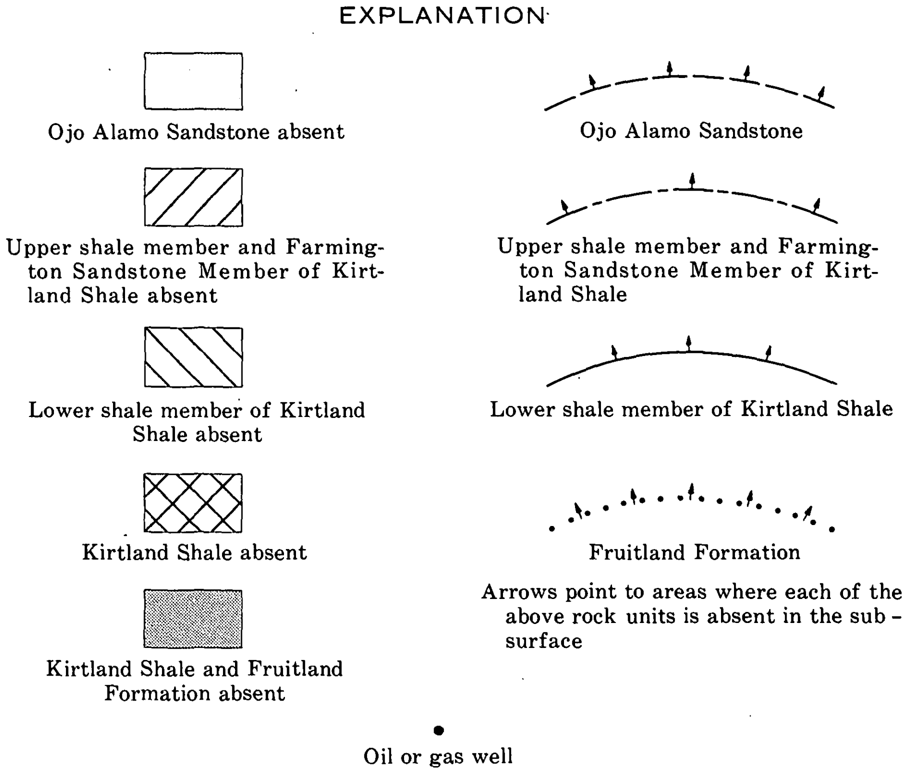

FIGURE 9.—Subsurface extent of the rock units composing the Fruitland Formation, the Kirtland Shale, and the Ojo Alamo Sandstone, and locations of all wells used for stratigraphic subsurface control in this report.

R. H. Tschudy of the U.S. Geological Survey examined rock samples collected by the authors from USGS paleobotany localities D4017–A, –B, and –C and D3738–C in the SE¼SE¼SW¼ sec. 9, T. 19 N., R. 2 W., on the south edge of Mesa Portales, Sandoval County, N. Mex., and D4149 near the center of sec. 32, T. 33 N., R. 2 W., New Mexico principal meridian, Archuleta County, Colo. The sample from locality D4149 was from a coal bed resting directly on top of the Pictured Cliffs Sandstone. The samples from localities D4017–A, –B, and –C were from a coal bed 100 feet above the top of the Pictured Cliffs, a green-gray shale 14 feet above the top of the coal bed, and a dark-gray shale 103 feet above the top of the coal bed, respectively; sample D3738–C was from a dark-green shale bed 165 feet above the top of the coal bed and about 40 feet below the base of the Ojo Alamo Sandstone (fig. 10). Locality D4149 is about 750 feet stratigraphically higher than locality D4017–A.

Table 1 shows the palynomorphs identified by Tschudy (written commun., 1968) from these localities. Of the samples from the Mesa Portales area, Tschudy reported:

> All the productive samples yielded specimens of the genus *Proteacidites*. The presence of this genus indicates a Cretaceous age. Sample D4017–A was from a coal and yielded an assemblage different from the assemblages from the shale samples. This is common, as the coals are deposited under different ecological conditions than are most shales.

In his report on the sample from the northeastern part of the basin, D4149, Tschudy stated:

> Sample D4149 I believe to be Cretaceous. The coal yielded a poor corroded assemblage. I was able to find only two specimens of the marker genus *Proteacidites*. This assemblage appears to have a closer resemblance to the Trinidad and Vermejo of the Raton Basin than to the assemblage reported by Anderson from the southern San Juan Basin.

The most abundant fossil of the Fruitland is *Ostrea*, which in parts of the basin locally forms coquina beds several feet thick. Fossil wood is abundant throughout the Fruitland, and some silicified logs are 4–5 feet in diameter. Fossil evidence indicates that the Fruitland is of Montana age. Most fossils are of fresh-water origin, but a few, notably *Ostrea*, are of brackish-water origin.

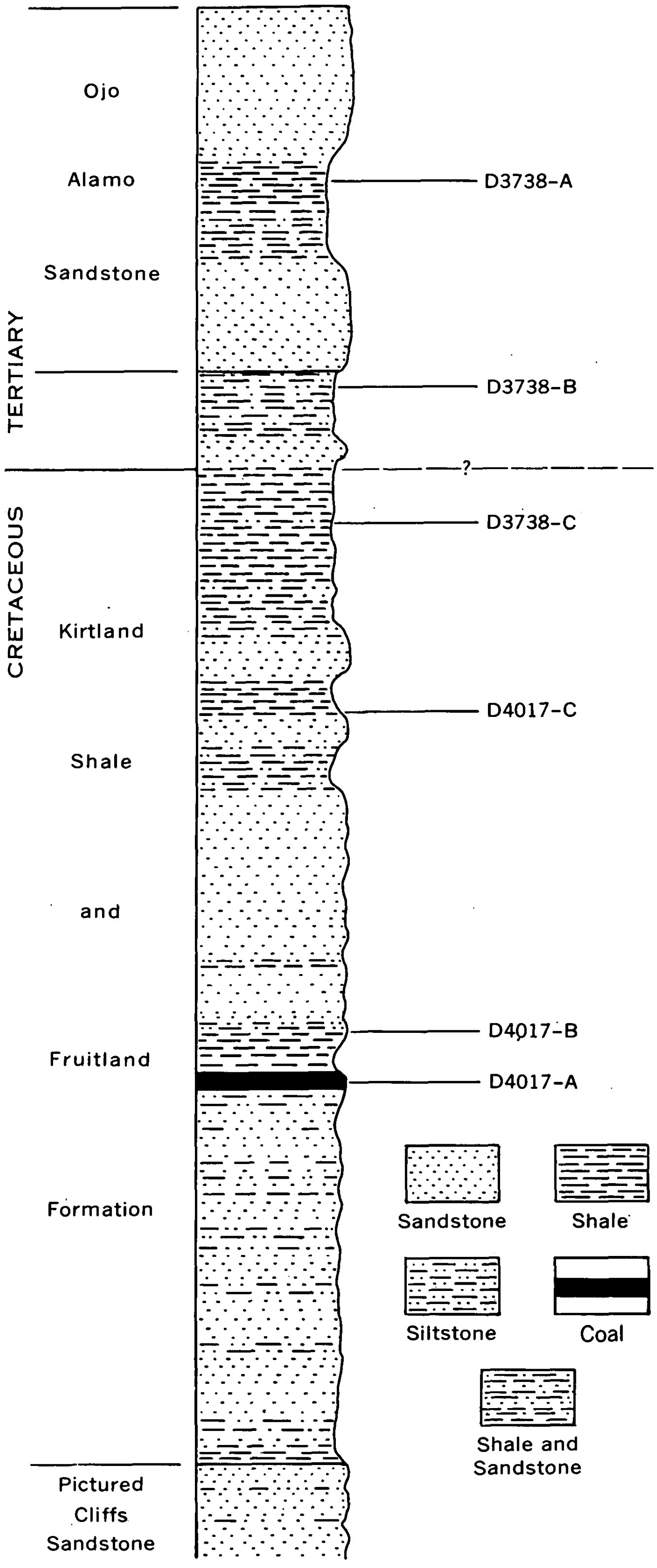

FIGURE 10.—Generalized geologic section showing the relative stratigraphic positions of samples collected for pollen and spore analysis on Mesa Portales. Vertical scale, 1 inch=50 feet.

EXTENT AND THICKNESS

The Fruitland Formation crops out around the north, west, and south sides of the San Juan Basin but is missing in two areas on the east side (fig. 9). It is also present throughout the subsurface of the basin except in the two areas on the east side. In both areas where the Fruitland is absent, the Pictured Cliffs Sandstone is also absent, and the Lewis Shale is overlain by the Ojo Alamo Sandstone. The Fruitland was not recognized outside the San Juan Basin area until Dickinson (1965) mapped a poorly exposed 50-foot-thick rock sequence consisting of white to yellow sandstone interbedded with coal, carbonaceous shale, and green shale in Montrose County, Colo. Dickinson assigned this rock unit to the Fruitland on the basis of lithic evidence.

In the southwestern part of the San Juan Basin, the Fruitland Formation and Kirtland Shale were mapped undivided by Zieglar (1955) near Newcomb, N. Mex. (pl. 1), outside the Pictured Cliffs Sandstone outcrop. Zieglar showed the undivided Kirtland and Fruitland resting on the Menefee Formation. This area is west of the coalescence of the Pictured Cliffs Sandstone and the underlying Cliff House Sandstone. Allen and Balk (1954, p, 96, 97) discussed these outcrops and applied the name Tohatchi Formation (spelled as Tohachi by some authors) to rocks correlative with tongues of the Cliff House and Pictured Cliffs, and to the Fruitland and possibly part of the Kirtland in this area. They stated:

> The stratigraphic position, lithology, thickness, and distribution of carbonaceous material suggest a tentative correlation of the lower member of the Tohatchi formation with the combined tongues of the Cliff House and Pictured Cliffs Sandstone * * *. The upper bentonitic unit may prove to be the equivalent of the Fruitland formation, and possibly part of the Kirtland formation, since similar vertebrates also occur in these units.

O'Sullivan, Beaumont, and Knapp (1957, p. 189) stated that this rock sequence is

> shown on map OM 190 (O'Sullivan and Beaumont, 1957) to be a part of the Menefee formation, although it is recognized to contain equivalents of the Tohatchi formation as used by Allen and Balk and the Kirtland-Fruitland formations undivided as used by Zieglar (1955) in the Toadlena quadrangle.

They further stated:

> In the Chuska Mountains the absence of the Pictured Cliffs–Cliff House tongue and the lack of suitable stratigraphic horizons in the associated nonmarine strata, virtually eliminates placing the position of the change from transgressive to regressive deposition which would correspond to the change from Menefee to Fruitland-Kirtland.

Whatever they are called, it is clear that rocks equivalent to the Fruitland and possibly to the Kirtland are present southwest of the Pictured Cliffs Sandstone outcrop in the Newcomb area.

TABLE 1.—*Selected palynomorphs from samples from the San Juan Basin*

[Identifications by R. H. Tschudy, U.S. Geological Survey. Age: P, recorded from the Paleocene only; K, recorded from the Cretaceous only; P, K, known from both the Paleocene and the Cretaceous; no prefix indicates a longer ranging species. Names in parentheses are those used by Anderson (1960)]

Age	Palynomorph	U.S. Geological Survey paleobotany locality number							
		Paleocene			Cretaceous				
		D3738-A	D3738-B	D3803	D3738-C	D4017-A	D4017-B	D4017-C	D4149
P	*Momipites* sp. (*Momipites inaequalis* And.)	X		X					
P	*Monosulcites* sp. (*Rectosulcites latus* And.)	X		X					
P	*Triatriopollenites* sp. A	X							
P	*Triatriopollenites* sp. B	X							
P, K?	*Cupaneidites* sp. (*Cupaneidites* aff. *C. major* And.)	X	X			X			
	Laevigatosporites sp. (*Polypodiidites* sp. And.)	X		X					
P	*Tricolporites* sp. (*Tricolporites angulolum inosus* And.)	X		X					
P, K	*Tricolpopollenites* sp. (*Quercus explanata* And.)	X				X		X	
	Abietineaepollenites sp. (*Podocarpus sellowiformis* And.)	X	X		X				
	Classopollis sp.		X				X	X	
	Abietineaepollenites sp. (*Podocarpus northropi* And.)		X						
P, K	*Zlivisporis* sp.		X						
P, K	*Ulmipollenites* sp. (*Ulmoidepites tricostatus* And.)		X		X	X		X	
P, K	*Liliacidites* sp.		X		X				X
P	*Polyporopollenites* sp.		X						
P	*Tricolporites* sp. (*Tricolporites rhomboides* And.)			X					
P	*Tricolporites* sp.			X					
	Tricolporites sp. [?*Eleagnaceae*]			X					
	Osmundacidites sp.			X					
P	*Tricolporites* sp.			X					
K	*Proteacidites* (*Proteacidites thalmanni* And.)				X	X	X	X	X
K	*Proteacidites* (*Proteacidites retusus* And.)				X				
K	*Monoporopollenites* sp.				X				
K	*Araucariacites* sp.				X	X	X		
	Erdtmannipollis sp.				X				
K	*Granabivesiculites* sp.				X				
P, K	*Liliacidites* sp. (*Liliacidites leei* And.)				X	X		X	
P, K	*Liliacidites* sp. (*Liliacidites hyalacinatus* And.)				X				
	Liquidambarpollenites sp.				X				
K	*Tricolpites interangulus* Newman					X			
	Tricolpopollenites sp.					X	X	X	
	Eucommiidites sp.					X	X	X	
	Foveosporites sp. cf. *F. canalis* Balme						X		
	Inaperturopollenites cf. *I. hiatus* (R. Pot.) Th. & Pf.						X		
K	*Ephedra* sp. cf. *E. voluta* Stanley						X	X	
K	*Zonalapollenites* sp.						X		
K	*Neoraistrickia* sp.							X	
K	*Tricolpopollenites* sp. A								X
K	*Monosulcites* sp.								X
K	*Tricolporites* sp.								X
K	*Tricolpopollenites* sp. B								X
K	*Tiliaepollenites* sp. (*Tilia wodehousei* And.)								X
P, K	*Tricolpopollenites* sp. C								X

The thickness of the Fruitland ranges from 0 to about 500 feet and is variable locally owing to the rather indefinite upper contact. Intertonguing of the Fruitland and the underlying Pictured Cliffs also results in abrupt local variation in the Fruitland thickness. The average thickness is about 300–350 feet with a very general depositional thickening from the southeast to the northwest of about 100–150 feet. Sections *A–A′* through *F–F′* (pl. 2) show the variations in thickness of the Fruitland in the basin. In the eastern part of the basin where the Kirtland Shale is absent, the Fruitland is overlain by the Ojo Alamo Sandstone. There the Fruitland thins to the east from about 300 feet to 0 feet. This thinning is partly the result of erosion or beveling of the Fruitland prior to deposition of the overlying Ojo Alamo and partly the result of the stratigraphic rise of the Pictured Cliffs Sandstone in this area. Sections *C–C′*, *F–F′*, and *E–E′* (pl. 2) show the thinning of the Fruitland on the east side of the basin.

KIRTLAND SHALE

DEFINITION

The Kirtland Shale was defined by Bauer (1916, p. 274) and was named for the town of Kirtland, N. Mex., on the San Juan River. Bauer stated that the Kirtland could be divided into three parts, "a lower shale 271 feet thick, a sandy part, here named the Farmington sandstone member * * *, and an upper shale 110 feet thick." Bauer further stated that the Farmington Sandstone Member was 455 feet thick along the San Juan River and that it there consisted of a series of discontinuous crossbedded overlapping sandstone lenses separated by shale interbeds.

In this report a twofold division of the Kirtland Shale is used: the lower shale member of Bauer and the undivided Farmington Sandstone Member and upper shale member of Bauer. The reasons for combining the Farmington and the upper shale are: (1) Well logs throughout most of the basin indicate that sandstone beds are present throughout the interval between the top of the lower shale member of the Kirtland Shale and the base of the Ojo Alamo Sandstone. Thus, on the basis of subsurface evidence, no upper shale member of the Kirtland can be differentiated. (2) A reconnaissance examination of the outcropping Kirtland rocks indicates that in some places a shale zone does exist between the stratigraphically highest sandstone lens of the Farmington and the base of the overlying Ojo Alamo Sandstone, but in other places, notably in the bluffs just south of Farmington, N. Mex., Farmington lenses crop out directly under the Ojo Alamo. Thus, even though an upper shale member is in some places locally differentiable, it can not be traced continuously any great distance on the outcrop. Hayes and Zapp (1955), in their discussion of the Kirtland in the area between the San Juan River and the Colorado border, stated: "The upper boundary of the Farmington member is even less distinct, for the overlying upper member of the Kirtland shale contains a large proportion of sandstone * * *."

It is the authors' opinion that the upper shale member as used by Bauer and as subsequently mapped by other geologists is not a continuous unit throughout most of the basin, but, rather, consists of the random shale interbeds that exist at any given outcrop immediately beneath the Ojo Alamo Sandstone. It will be shown in the discussion of the basal Ojo Alamo contact that these shale interbeds, which have been collectively called the upper shale member, are actually a series of shale lenses which are progressively older and stratigraphically lower toward the southeastern part of the basin.

Lithology

The lower shale member of the Kirtland Shale is composed predominantly of gray shale that contains a few thin interbeds of siltstone and sandstone. The Farmington Sandstone Member and upper shale member of the Kirtland are composed of a series of interbedded sandstone lenses and shale. The shale interbeds in the lower part of the Farmington are lithologically similar to the lower shale member of the Kirtland. The shale interbeds at the top of the Kirtland, however, are much more colorful than in the lower shale member and are purple, green, white, and gray. In the northwestern part of the basin, north of Pinyon Mesa near the La Plata River, channel deposits of quartz and jasper pebble conglomerate in a matrix of very fine grained to silt-size red to reddish-brown and yellow limonite and hematite occur in the upper part of the Farmington Sandstone Member and upper shale member. In the western and southwestern parts of the basin, local conglomeratic beds and purple shale beds occur in the Farmington and upper shale. In the Pinyon Mesa area, beds of tuff ranging in thickness from thin laminae to beds several feet thick and thicker sandstone beds which contain abundant andesitic debris occur in the uppermost Kirtland; these beds are in what Reeside (1924) originally called the McDermott Formation.

The Farmington Sandstone Member and the upper shale member of the Kirtland Shale contain a higher percentage of sandstone in the northern part of the basin than in the southern part. Electric logs indicate that the individual sandstone lenses composing the Farmington Sandstone Member become thinner and fewer in the southern part of the basin. The sandstone is fine to medium grained, the largest fraction being fine grained. According to Dilworth (1960), the average mineralogic composition of the Farmington based on petrographic examination of 11 thin sections from samples collected near the San Juan River is: 21 percent quartz, a trace to 5 percent chert, 12 percent potash feldspar, 33 percent plagioclase feldspar, 9 percent biotite, and 20 percent clay cement. Minor amounts of muscovite, chlorite, heavy minerals, limonite, and hematite are present. Mineral grains are angular and poorly sorted.

Contacts

The lower contact of the Kirtland Shale has been described on page 19. The contact between the lower shale member and the Farmington Sandstone Member of the Kirtland is transitional and is placed at the base of the lowest sandstone lens of the Farmington. In figure 2, the base of the Farmington is just above 1,700 feet. Because of lateral discontinuity of sandstone lenses in the Farmington, the base of the Farmington is erratically variable; the contact must be moved up or down to other sandstone lenses where a particular basal sand lens wedges out laterally.

In general, the contact at the base of the Farmington becomes stratigraphically higher toward the northeast. In section *D–D′* (pl.2), it is clear that from south to north, except at well 5, the base of the Farmington rises regularly. This stratigraphic rise is also shown in the southwest-northeast sections *A–A′*, *B–B′*, and *C–C′* (pl. 2), although the rise is irregular in these sections.

The Kirtland is overlain by the Ojo Alamo Sandstone throughout most of the San Juan Basin; however, in the northern part of the basin it is possibly overlain by the Nacimiento Formation, by the Animas Formation, and in at least one area by the San Jose Formation. Figure 9 shows the subsurface extent of the Ojo Alamo. North of the Ojo Alamo limit line in figure 9, the Ojo Alamo ceases to be a distinguishable unit, and in this area it is practically impossible to differentiate the Kirtland from the overlying Nacimiento and Animas Formations on electric logs. The subsurface contact between the Animas and the underlying Kirtland is inferred in sections *A–A′* and *D–D′* (pl. 2). The position of this contact between well 7 and the outcrop in section *A–A′* and between well 13 and the outcrop in section *D–D′* is based on interpolation.

On the surface, north of the Ojo Alamo Sandstone termination, between Pinyon Mesa in the southwestern part of T. 31 N., R. 13 W., and the New Mexico–Colorado border, it is extremely difficult to distinguish the contact between the Kirtland and the overlying Animas Formation or the Nacimiento Formation. At Pinyon Mesa, a quartz and jasper pebble conglomerate zone at the base of the Ojo Alamo rests on the Kirtland; north of the New Mexico–Colorado border, a purple shale and andesite pebble conglomerate zone at the base of the McDermott Member of the Animas rests on the Kirtland. Hayes and Zapp (1955) mapped the geology in the Pinyon Mesa area and stated:

> Considerable effort was expended during this investigation in an attempt to establish and trace a precise upper contact of the Kirtland shale, to be drawn at the lowest occurrence of pebbles, or megascopically identifiable andesitic detritus. Careful tracing of beds in areas of continuous exposures revealed that the stratigraphic horizon at which these materials appear is not constant, that the beds are lenticular, and that lithologies common in the Kirtland shale recur above the lowest coarse clastics. The upper contact of the Kirtland shale is therefore transitional and arbitrary.

The contact between the Kirtland and the Ojo Alamo Sandstone seems to be disconformable on the basis of subsurface evidence; however, evidence for a disconformity based on surface exposures is inconclusive. The nature of the basal Ojo Alamo Sandstone contact is discussed at length in the section on the Ojo Alamo Sandstone.

Mode of Deposition

The lower shale member of the Kirtland Shale was deposited in an environment similar but not identical to the depositional environment of the upper part of the Fruitland Formation. As stated earlier, the best criterion for differentiating the Kirtland from the Fruitland is the presence or absence of carbonaceous shale or coal beds. Because the lower shale member of the Kirtland contains little coal or carbonaceous shale, it must have been deposited in an environment that was not conducive to the accumulation and preservation of organic material. This change in depositional environment was probably gradual because nearly everywhere in the San Juan Basin the coal and carbonaceous shale become progressively less abundant stratigraphically upward in the Fruitland. Figure 2 clearly shows this gradual upward decrease in coal content of the Fruitland. The most obvious explanation for the scarcity of coal in the lower shale member of the Kirtland is the lack of sites for accumulation of organic material at the time of its deposition. Because organic material can be preserved in quantity only in a reducing environment, usually under swamp waters, it is probable that swamps were practically nonexistent at the places where the lower shale member was being deposited. The absence of swamps suggests relatively good drainage, which, in turn, might indicate greater stream gradients in these areas.

In all probability, the sandstone beds of the Farmington Sandstone Member were laid down in aggrading stream channels. Between the channels, silt and mud were laid down as flood-plain deposits during periods of rapid runoff when the rivers spilled over their banks. As the streams overflowed, natural levees were built up, causing the streams to build their channels above the surrounding flood plain in unstable positions. Ultimately, the streams broke through the levees and sought lower and more stable channels. Old channels were ultimately covered by flood-plain deposits as other streams continued to aggrade the area.

Figure 5 is a diagrammatic reconstruction of the depositional relation of the Kirtland Shale and the Fruitland Formation. Figure 5*A* shows sand lenses being deposited at the extreme left, shale being deposited toward the shoreline, coal and shale being deposited even further toward the shoreline, and marine sand being deposited at and somewhat seaward of the shoreline. The rock units here represented are the Farmington Sandstone Member and the lower shale member of the Kirtland Shale, the Fruitland Formation, and the Pictured Cliffs Sandstone. Figures 5*B*, *C*, and *D* show the same general relations between the rock units comprising the Kirtland and the Fruitland at later times; each unit transgresses to the right following the regressive Pictured Cliffs shoreline. The paleoslope looks relatively steep in these cross sections, but the vertical exaggeration is about 60:1.

Fossils and Age

Fossils collected from the Kirtland Shale are listed by Reeside (1924, p. 23). They include vertebrates described by Gilmore (1919, p. 8), invertebrates described by Stanton (1916, p. 310), and plant remains described by Knowlton (1916, p. 330). Reeside stated that all these fossils indicate a fluviatile origin and a late Montana age for the Kirtland.

Dilworth (1960, p. 25) and Baltz (1967) indicated that marine fossils had been collected from the Kirtland and Fruitland sequence. Dilworth listed the following Foraminifera from the Farmington Sandstone Member southwest of the town of Farmington: *Bathysiphon* sp., *Haplophromoides* sp., and Ostracoda (fragments). In describing these fossils, Dilworth stated: "All of these fossils have been replaced by iron compounds and are of too poor quality to photograph. It cannot be said with certainty that these foraminifera do not represent a reworked fauna * * *." Dilworth concluded, however, that these fossils were in place and that they were indicative of a marine origin for the Farmington Sandstone Member. It is the authors' opinion that the fossils described by Dilworth were reworked because (1) the total physical character of the Farmington clearly indicates a fluviatile origin, and (2) all the earlier fossil collections indicate a fluviatile origin for the Farmington.

Baltz (1962, p. 88) stated that he found *Halymenites* (now *Ophiomorpha*) and *Inoceramus* sp. in the undivided Fruitland and Kirtland in the eastern part of the San Juan Basin. In a later report, Baltz (1967, p. 18, ff.) reaffirmed the presence of marine fossils in "unit A" of the undivided Kirtland and Fruitland on the east side of the basin. Because the Fruitland and the Kirtland were defined as nonmarine units, it seems more logical to conclude that the presence of these marine fossils indicates that the rocks are not Kirtland and Fruitland. The authors' reconnaissance mapping on the east side of the San Juan Basin indicates that the rocks in which Baltz found *Halymenites* and *Inoceramus* are probably tongues of the underlying Pictured Cliffs Sandstone and Lewis Shale rather than a marine facies of the undivided Kirtland and Fruitland.

Pollen and spore identification by R. H. Tschudy from samples collected by the authors from the undivided Kirtland Shale and Fruitland Formation on Mesa Portales indicates that there the uppermost part of the Kirtland is Paleocene in age (table 1; fig. 10). The details of the fossils and age of the Ojo Alamo Sandstone are given on pages 31–33.

Extent and Thickness

The Kirtland Shale crops out around the north, west, and south sides of the San Juan Basin. The subsurface extent of the Kirtland is indicated in figure 9, which shows the Kirtland missing in the subsurface in the eastern part of the basin. Figure 9 also shows the subsurface limit of the lower shale member and the undivided Farmington Sandstone Member and upper shale member of the Kirtland. The crisscrossing of the lower shale member limit line and the undivided Farmington and upper shale limit line indicates that in some areas the lower shale is absent and the Farmington and upper shale is present, whereas in other areas the lower shale is present and the Farmington and upper shale is absent. This rather complicated pattern is believed to be the result of the interaction of two factors: (1) The Farmington Sandstone Member and upper shale member of the Kirtland Shale are missing on the east side of the San Juan Basin because they were removed by erosion prior to deposition of overlying rocks; nowhere are these rocks missing because of depositional thinning or wedging out. (2) The lower shale member is missing on the east side of the basin in some places owing to lack of deposition and in other places owing to erosion prior to deposition of overlying rocks.

All the cross sections of plate 2, except sections *A–A′* and *D–D′*, show the way in which the Kirtland thins and pinches out on the east side of the San Juan Basin. In section *B–B′* the lower shale member pinches out between wells 9 and 10; east of this pinchout, the Fruitland Formation is overlain by the Farmington Sandstone Member of the Kirtland. In section *C–C′* the Farmington and upper shale are absent in a narrow interval between wells 4 and 5, in a wider interval between wells 6 and 8, and between well 8 and the outcrop; the lower shale member pinches out between wells 4 and 5. Section *E–E′* shows the truncation of both the lower shale member and the Farmington and upper shale member prior to deposition of the Ojo Alamo Sandstone. The Farmington and upper shale are cut out between wells 10 and 11, and the lower shale is cut out between wells 13 and 14. In section *F–F′* the lower shale member pinches out between wells 11 and 12, and the Farmington Member and upper shale member of the Kirtland are cut out between wells 12 and 13.

The thickness of the lower shale member of the Kirtland is variable because of the arbitrary and erratic contacts at its base and top. The thickness ranges from 0 feet along the subsurface limit line (fig. 9) on the east side of the basin to 450 feet in the subsurface in the vicinity of the town of Farmington in the western part. In general, the lower shale thins to the east as a result of lenses of the Farmington Sandstone Member occurring at successively lower stratigraphic positions to the east. The lower shale has an average thickness of about 200–250 feet.

The thickness of the undivided Farmington and upper shale member of the Kirtland ranges from 0 feet on the east side of the basin (fig. 9) to about 1,500 feet in the northwestern part. In figure 11 the area of thickest Kirtland and Fruitland, shown by the 2,000-foot isopach line, more or less coincides with the area of greatest thickness of the undivided Farmington and upper shale. The Farmington and upper shale thin regularly southeastward (pl. 2, section *E–E′*). This thinning is primarily the result of the consistently lower stratigraphic position of the Ojo Alamo Sandstone from northwest to southeast across the basin.

In the northern part of the basin in the area where the Ojo Alamo Sandstone is absent (fig. 9), the Farmington Member and upper shale member thin northward and northeastward, as illustrated in sections *A–A′* and

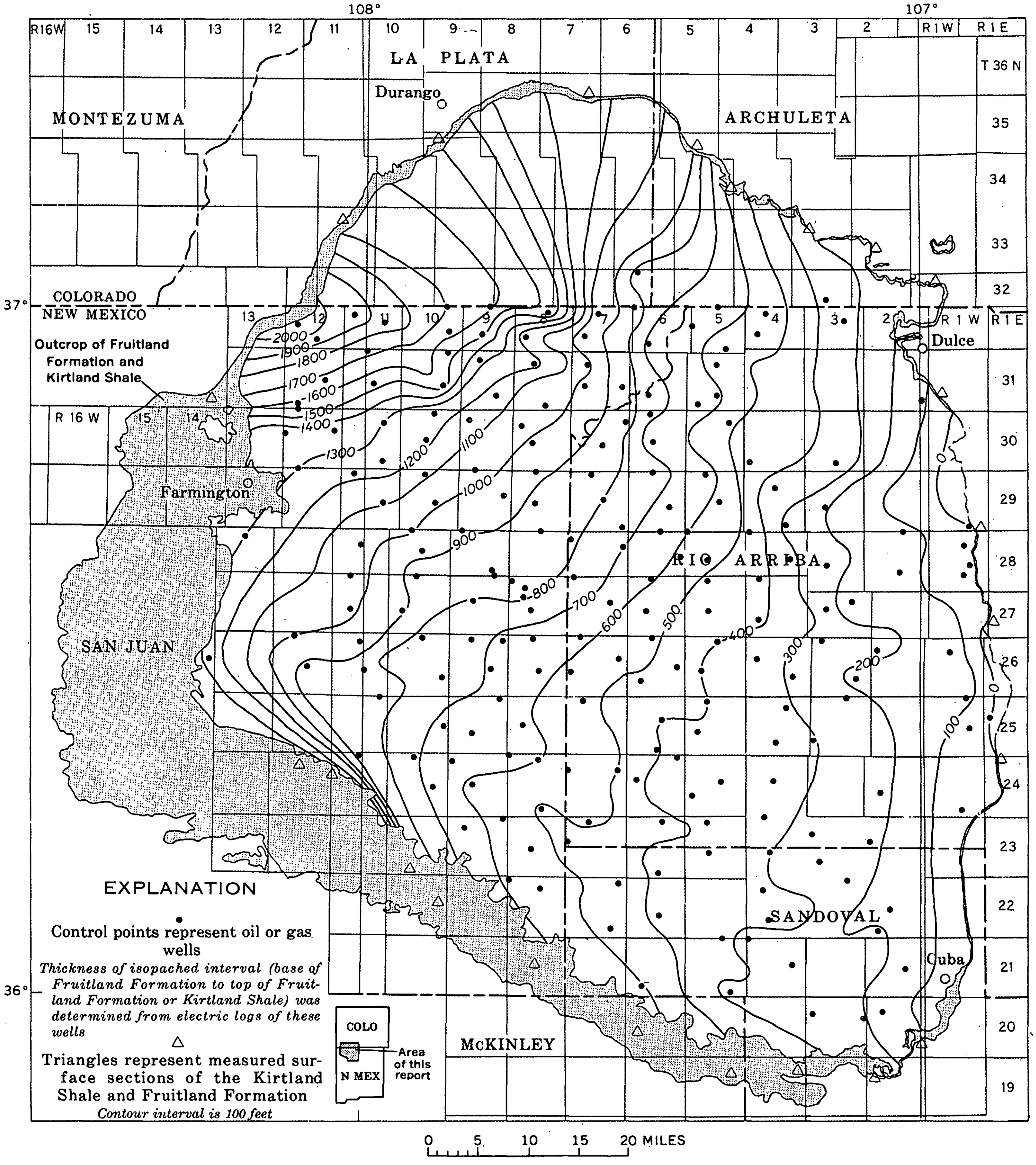

FIGURE 11.—Isopach map of the Fruitland Formation and Kirtland Shale.

D–D' (pl. 2). These sections show the rather abrupt change in the nature of the upper contact of the Farmington and upper shale in the northern part of the basin. Between well 13 and the outcrop to the north in section *D–D'*, the contact of the Animas and the upper shale and the contacts of the underlying rock units converge. South of well 13 the contact of the Ojo Alamo and the upper shale and the contacts of the underlying rock units converge in the opposite direction. Section *A–A'* also crosses this area and illustrates the same relations—the convergence of the base of the Animas and the underlying contacts northeast of well 7, and the convergence of the base of the Ojo Alamo and the underlying contacts southwest of well 8.

PALEOCENE ROCKS

OJO ALAMO SANDSTONE

DEFINITION

The "Ojo Alamo Beds" were named by Brown (1910, p. 268) for exposures south of the store at Ojo Alamo Arroyo. Brown said that the Ojo Alamo was a dinosaur-bearing shale unit overlain unconformably by a conglomerate bed. Brown put no lower boundary on the Ojo Alamo. Sinclair and Granger (1914, p. 301–304) raised the upper contact of the Ojo Alamo to include the overlying conglomerate because they found "the centrum of a dinosaurian caudal vertebra * * * loose on the surface * * *" of the "conglomeratic sandstone with much fossil wood." They also located a lower conglomerate, 6–8 feet thick, 58 feet below the upper conglomerate. Sinclair and Granger, also, did not place a lower boundary on the Ojo Alamo.

Bauer (1916, p. 275–276) redefined the Ojo Alamo as "a sandstone including lenses of shale and conglomerate." He agreed with Sinclair and Granger that the top of the OjoA lamo was the top of the conglomeratic sandstone, but he placed the base of the Ojo Alamo at the base of the lower conglomerate of Sinclair and Granger. Reeside (1924, p. 28) accepted Bauer's redefinition and mapped the Ojo Alamo as a conglomeratic sandstone throughout the western San Juan Basin. Reeside, however, designated the Ojo Alamo as Tertiary(?). Dane (1936, p. 116–121) discussed the Ojo Alamo, also agreed with Bauer's definition of it, but suggested that it "should be classified as Cretaceous." Dane mapped the Ojo Alamo throughout the southeastern San Juan Basin as a coarse-grained, in places conglomeratic, sandstone.

Baltz, Ash, and Anderson (1966, p. D13) suggested that "the name Ojo Alamo Sandstone be restricted to apply only to the upper conglomerate of Bauer's (1916, p. 276) type Ojo Alamo Sandstone on Ojo Alamo Arroyo." This redefinition of the Ojo Alamo eliminated the last remnant of Brown's original "Ojo Alamo Beds" on Ojo Alamo Arroyo from the "restricted Ojo Alamo Sandstone" of Baltz, Ash, and Anderson.

During the time that the definition of the Ojo Alamo was evolving, as briefly outlined above, the vertebrate remains collected by Barnum Brown, C. W. Gilmore, and others in the Ojo Alamo Arroyo area were being referred to in paleontological papers in publications throughout the world. Nearly all these publications referred to the Ojo Alamo as a dinosaur-bearing shale unit in much the same sense as the original definition of Brown. Thus, today the name Ojo Alamo has two distinct meanings: to rock stratigraphers, it is a conglomeratic sandstone of Paleocene age; to biostratigraphers, it is a shale unit containing a distinctive dinosaur fauna of Late Cretaceous age. The first meaning is the one used by the authors in this report.

GENERAL FEATURES

The Ojo Alamo Sandstone overlies the Kirtland Shale and the Fruitland Formation throughout a large part of the San Juan Basin. It is composed of interbedded sandstone, conglomeratic sandstone, and shale. The sandstone is arkosic, ranges from light brown to rusty brown, and contains abundant silicified wood and a few large sandstone blocks and clay balls as much as a a few feet in diameter. The conglomerate is typically near the base of the Ojo Alamo. Conglomerate pebbles range widely in composition; siliceous pebbles of quartzite, jasper, and chalcedony are most common; pebbles of granite, andesite, and clay are less common. The pebbles generally decrease in size from west to east across the basin. Ojo Alamo conglomerates on the west side of the basin contain pebbles several inches in diameter, whereas on the east side in the vicinity of Cuba, pebbles are scarce and small.

The Ojo Alamo throughout most of the basin consists of overlapping massive sandstone beds interbedded with shale. The sandstone beds are sheetlike and discontinuous. Sheets terminate by merging with underlying or overlying sandstone sheets or by wedging out into overlying or underlying shale beds. Sandstone sheets are, for the most part, parallel; intervening shale beds maintain a relatively constant thickness. Large-scale channeling at the base of the sandstone beds is common. Channels of 50 or more feet cut into the underlying Kirtland or the Fruitland have been measured by Fassett (1966) and Hinds (1966). In some areas, channels at the base of an upper sandstone sheet have cut through the intervening shale bed and into an underlying sandstone sheet.

The thickness of the Ojo Alamo varies according to the number of sandstone beds that constitute it at any given locality. Thicknesses range from less than 20 feet to more than 400 feet throughout the basin;

thicknesses of about 50–150 feet are the most common. The Ojo Alamo crops out around the west, south, and east sides of the basin. It does not crop out in the northern part, and in the subsurface it cannot be distinguished on electric logs north of the limit of the Ojo Alamo shown in figure 9. In an area along the east rim of the basin from slightly north of Llaves in T. 25 N., R. 1 E., to the northern part of T. 23 N., R. 1 E., the Ojo Alamo is not exposed. Whether this is due to thinning or nonexistence of the Ojo Alamo or to relatively recent erosion and cover by alluvium is not known.

CONTACTS

The upper contact of the Ojo Alamo Sandstone and the overlying Nacimiento Formation is conformable throughout most of the basin, and intertonguing of Ojo Alamo sandstone beds and Nacimiento shale beds is common and widespread. This intertonguing has been mapped by Fassett (1966). The nature of the basal contact of the Ojo Alamo, however, is not clear cut. Subsurface evidence very strongly indicates that an angular unconformity is present everywhere in the basin at the base of the Ojo Alamo. Surface information, however, does not everywhere support this conclusion. On Mesa Portales, for example, which is 11 miles southwest of Cuba, basal sandstone beds of the Ojo Alamo thin and pinch out into shales. Figure 12 shows one of these basal sandstone pinchouts. On the left (west) side of figure 12*A*, the Ojo Alamo consists of two sandstone sheets separated by a shale bed. In the middle of the figure, the lowermost sandstone sheet abruptly thins, pinches out, and is replaced laterally by shales to the east. A careful examination by the authors of the shales east of the termination of the lower sandstone failed to indicate any sign of a shale-on-shale unconformity at the level of the lower sandstone pinchout. In other words, the basal contact of the Ojo Alamo seems to be gradational with the underlying undivided Kirtland Shale and Fruitland Formation on Mesa Portales and not unconformable as subsurface evidence seems to indicate. Figure 12*B* is a closer view of the lower sandstone pinchout.

The subsurface evidence of an unconformity at the base of the Ojo Alamo is clearly indicated in stratigraphic cross sections *F–F′*, *D–D′*, and *E–E′* (pl. 2). Section *F–F′* crosses the San Juan Basin from west to east. The uppermost correlation line in this section represents the base of the Ojo Alamo. Notice that this line does not parallel the underlying formation boundary lines but, rather, it and the underlying formation contacts converge on the east side of the basin. From west to east the Fruitland and the Kirtland thin from a maximum thickness of 1,325 feet at well 3 to a minimum thickness of less than 20 feet on the outcrop just east of well 16. This thinning is the result of two separate and independent causes: (1) The Pictured Cliffs Sandstone rises 850 feet stratigraphically from the west to the east side of the basin; from well 3 to the east edge of the basin the stratigraphic rise is 500 feet. (2) The base of the Ojo Alamo becomes stratigraphically lower from west to east across the basin; this lowering accounts for a decrease in thickness of the underlying Fruitland and Kirtland of slightly more than 800 feet between well 3 and the east edge of the basin. The loss of uppermost Fruitland and Kirtland rocks that places progressively older rocks in contact with the base of the Ojo Alamo from west to east indicates that the Fruitland and Kirtland were beveled by erosion prior to deposition of the Ojo Alamo.

In section *D–D′* (pl. 2) the Fruitland and the Kirtland thin from 1,730 feet at well 13 in the northern part of the basin to 530 feet near well 2 in the southern part. As in section *F–F′*, the basal contact of the Ojo Alamo does not parallel underlying formation boundary lines but is at a distinct angle to them. As a result, progressively older rocks underlie the Ojo Alamo from north to south across the San Juan Basin, which indicates beveling of the Kirtland prior to deposition of the Ojo Alamo.

Section *E–E′* (pl. 2) trends northwest. At the outcrop northwest of well 1, the thickness of the Fruitland and the Kirtland is 1,900 feet. At the outcrop southeast of well 16, the thickness of the Fruitland and Kirtland rocks is 180 feet; thus, the Fruitland and the Kirtland are more than 1,700 feet thinner in the southeastern part of the basin than in the northwestern part. This thinning, with progressively older rocks in contact with the Ojo Alamo southeastward, again indicates beveling by erosion of the Fruitland and Kirtland rocks prior to Ojo Alamo deposition.

Sections *A–A′*, *B–B′*, and *C–C′* (pl. 2) do not individually indicate the presence of an unconformity at the base of the Ojo Alamo because their alinement is approximately parallel to the isopachs in figure 13. The thinning of the Fruitland and the Kirtland to the northeast in these sections is almost exclusively the result of the stratigraphic rise in the position of the Pictured Cliffs Sandstone. However, these three sections collectively illustrate the thinning of the Fruitland and the Kirtland toward the southeastern part of the San Juan Basin. In section *A–A′* the thickness of the Fruitland and the Kirtland between the base of the Ojo Alamo and the top of the Pictured Cliffs ranges from 1,600 to 1,900 feet. In section *B–B′* the Kirtland and Fruitland thickness ranges from 350 to 900 feet. In section *C–C′* the thickness of this interval is from less than 10 feet to slightly more than 550 feet. This thinning, with the Ojo Alamo in contact with progressively older rocks in sections *B–B′* and *C–C′*, strikingly

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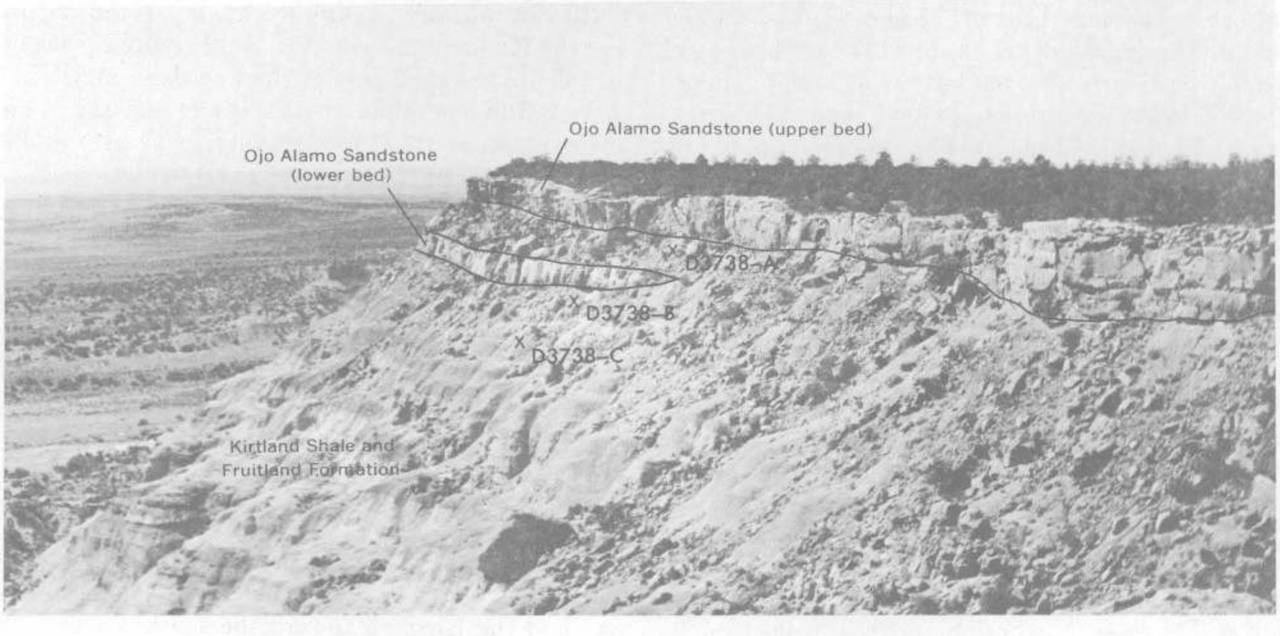
A



B

FIGURE 12.—Ojo Alamo Sandstone. *A*, Pinchout of a lower sandstone sheet of the Ojo Alamo Sandstone in the SE¼SE¼ SW¼ sec. 9, T. 19 N., R. 2 W., on the south edge of Mesa Portales, 11 miles southwest of Cuba, N. Mex. *B*, Closeup view; locations of USGS paleobotany localities D3738–A, –B, and –C are shown.

illustrates the beveling of the Fruitland and the Kirtland throughout the San Juan Basin area prior to deposition of the Ojo Alamo. Figure 13 also shows the thinning of the Fruitland and the Kirtland in the basin prior to deposition of the Ojo Alamo. The maximum amount of thinning indicated by this isopach map is 2,100 feet.

To restate the problem of the basal contact of the Ojo Alamo Sandstone, subsurface evidence indicates that throughout the San Juan Basin the basal contact of the Ojo Alamo is unconformable with underlying rocks, whereas in places on the outcrop, for example on Mesa Portales, the contact apparently is conformable and transitional because basal sandstone beds of the Ojo Alamo intertongue with underlying shale beds of the Kirtland. In the past, the following explanations have been offered to resolve this problem: (1) There is no unconformity at the base of the Ojo Alamo. The thinning of the Fruitland and Kirtland rocks toward the southeast in the San Juan Basin is the result of less original deposition of these rocks in the southeast. (2) The sandstone beds, which intertongue with underlying shales, are not Ojo Alamo sandstone beds but, rather, are Fruitland or Kirtland sandstone beds. This interpretation assumes that a basal Ojo Alamo unconformity is present at the base of a sandstone bed stratigraphically above the intertonguing sandstones and shales.

The first explanation was proposed by Dane (1936, p. 118–119). Dane mapped the Fruitland and Kirtland rocks throughout a large area in the southeastern San Juan Basin and found intertonguing of basal sandstone beds of the Ojo Alamo and underlying shales. He believed that this intertonguing indicated "a transitional change in sedimentation," and he concluded that no unconformity was present at the base of the Ojo Alamo and that the thinning of the Kirtland and Fruitland interval from west to east was depositional. Thinning of the Fruitland and Kirtland rocks toward the southeastern part of the basin due to less deposition, however, does not agree with subsurface data which indicate that sediment was being derived from the southwest and was filling in and pushing back the Pictured Cliffs Sea toward the northeast.

The second explanation was proposed by Baltz (1967, fig. 8) to explain the sandstone pinchouts on the east side of Mesa Portales. The authors carefully examined the basal Ojo Alamo contact on the east and south sides of Mesa Portales and found that in several places a sandstone bed which pinched out into underlying shale in one direction merged with an overlying sandstone bed in another direction. Also, no single sandstone with an unconformable base could be traced throughout the Mesa Portales area.

A third explanation is here offered to resolve the apparently conflicting data regarding the basal Ojo Alamo contact. The authors believe that an obscure unconformity is present in some areas in the shale and siltstone sequence beneath, but near, the base of the Ojo Alamo. The unconformity, which represents the erosion surface from which as much as 2,100 feet of rock was stripped away, may coincide with the Cretaceous-Tertiary time boundary. The sequence of rocks lying between the unconformity and the Ojo Alamo is probably relatively thin, so that on electric-log cross sections *A–A′* through *F–F′* (pl. 2) the unconformity seems to be at the base of the Ojo Alamo; the unconformity itself is not apparent on logs. This rock sequence above the unconformity is transitional with the Ojo Alamo in parts of the basin as Dane (1936) suggested. However, in many areas the Ojo Alamo probably was deposited directly on the erosion surface.

Fossils and Age

The Ojo Alamo Sandstone has not yielded macrofossils diagnostic of age. In the past, paleontologists assigned dinosaur remains to the Ojo Alamo, particularly in the vicinity of Ojo Alamo Arroyo, the type locality of the Ojo Alamo Sandstone. Baltz, Ash, and Anderson (1966) discussed these early assignments and concluded that the rocks in which the dinosaur remains were found are not part of the rock-stratigraphic Ojo Alamo but rather are part of the Kirtland Shale. Plant remains are relatively numerous in the Ojo Alamo, but they are principally in the form of silicified wood, which has little age significance. F. H. Knowlton, however, identified fossil leaves collected from the Ojo Alamo at three localities on the west side of the San Juan Basin and stated (in Reeside, 1924) that two of the collections suggested a Tertiary age but that the leaves in the third collection were too broken to identify with any certainty.

Anderson (1960) made pollen and spore collections from the Ojo Alamo at two localities in the southeastern part of the San Juan Basin. He concluded that the collections suggested a Tertiary age for the Ojo Alamo. Anderson later identified pollen and spores collected from the Ojo Alamo near Barrel Springs Arroyo, and he stated (Baltz and others, 1966, p. D17) that this Ojo Alamo florule "does not directly fix the age of the restricted Ojo Alamo Sandstone * * *." He further stated, however, that this florule contains "forms that are known to occur also in the Fort Union Formation and other formations generally considered to be of Paleocene age * * *."

R. H. Tschudy examined rock samples collected by the authors at USGS Paleobotany localities D3738–A and –B (figs. 10, 12) on the south edge of Mesa Portales

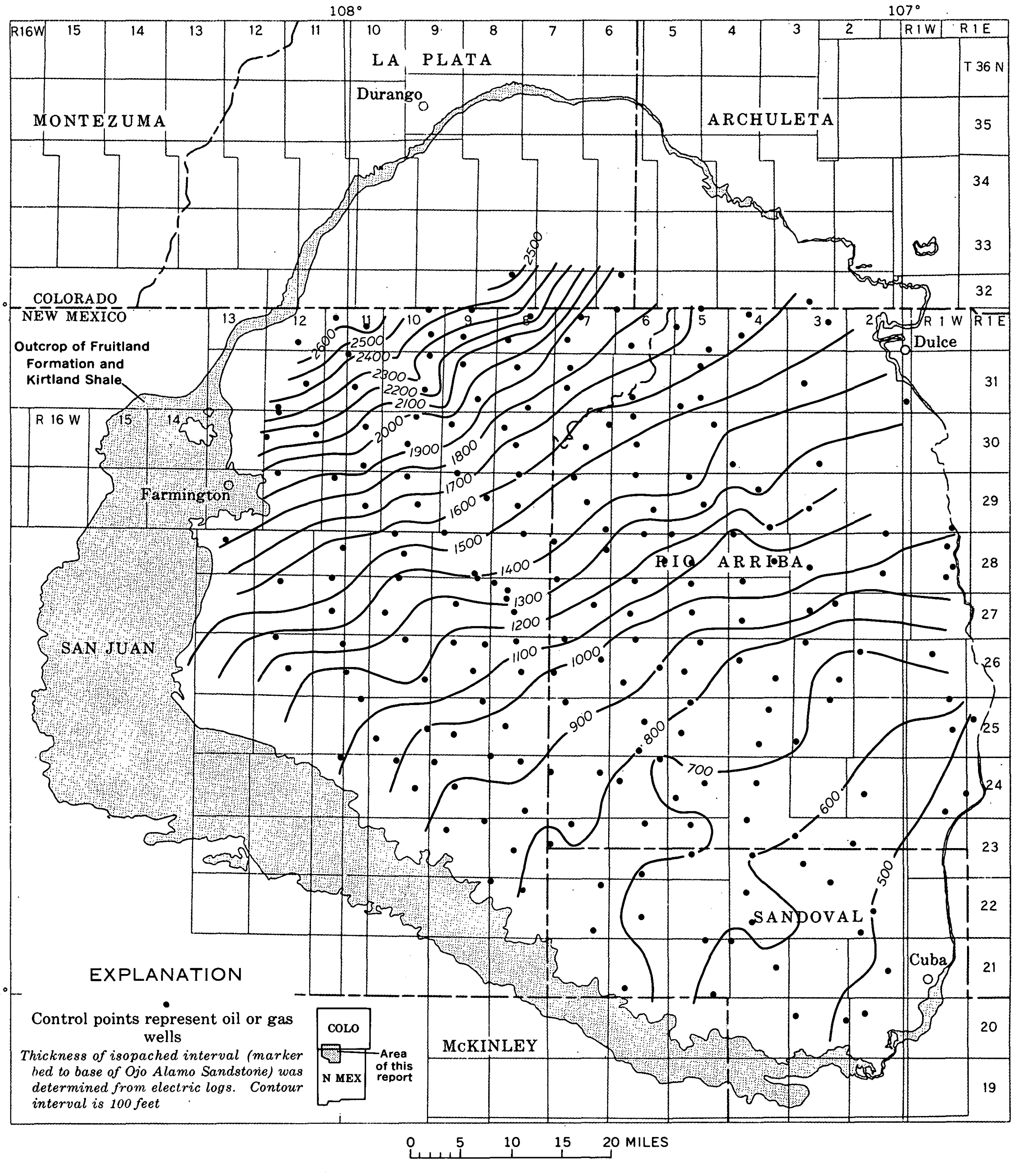


FIGURE 13.—Isopach map of the interval between the Huerfanito Bentonite Bed of the Lewis Shale and the base of the Ojo Alamo Sandstone.

in the SE¼SE¼SW¼ sec. 9, T. 19 N., R. 2 W. The sample from locality D3738-A was from a black silty shale bed 10 feet beneath the base of the massive sandstone bed capping Mesa Portales; the sample from locality D3738-B was from a thin black shale bed in a sequence of interbedded buff sandstone and silty shale 5.5 feet beneath the base of the lower sandstone bed of the Ojo Alamo (fig. 12*B*). The palynomorphs identified by Tschudy (written commun., 1968) from these localities are listed in table 1. Tschudy reported on the palynomorphs from locality D3738-A as follows: "This assemblage is clearly of Paleocene age and is equivalent to the assemblages found by Anderson in the Ojo Alamo Sandstone." He further stated that "Sample D3738-B is from the Tertiary."

It is clear from table 1 and figures 10 and 12 that the palynological Tertiary-Cretaceous boundary is in the 36-foot interval between localities D3738-B and D3738-C, below the lower sandstone bed shown pinching out on the south edge of Mesa Portales in figure 12. This finding is significant for two reasons: (1) It conflicts with the interpretation by Baltz (1962, 1967) and Baltz, Ash, and Anderson (1966) that an unconformity which represents the Cretaceous-Tertiary boundary is present at the base of the uppermost sandstone bed of the Ojo Alamo capping Mesa Portales; since the palynological boundary is below the lowermost Ojo Alamo sandstone bed. (2) It indicates that the uppermost part of the Kirtland (mapped undivided with the Fruitland in the Mesa Portales quadrangle) is Paleocene in age, at least in places in the southeastern part of the basin.

Palynological evidence suggests a possible unconformity beneath the Ojo Alamo Sandstone on Mesa Portales. R. H. Tschudy (written commun., 1967) reported:

It is possible to postulate a hiatus between the Cretaceous and Paleocene at this locality. The genus *Araucariacites* [table 1] has not been found in rocks younger than Campanian in the Rocky Mountain Region. Moreover, the Cretaceous assemblages found in your samples are different from those found in the latest Cretaceous of the Raton Formation. However, it must be emphasized that we do not have enough control data from your area to do more than guess at a possible hiatus. For example, the closest area from which we have control on the occurrence of *Araucariacites* in the Upper Cretaceous is northern Colorado. Furthermore, we know that several floral provinces existed during Late Cretaceous time.

An effort was made to determine if the Tertiary-Cretaceous boundary coincides with a lithologic change. In some places on Mesa Portales, and elsewhere in the basin, a bed of rusty-brown friable coarse-grained, in some places conglomeratic, sandstone as much as several inches thick is present below and near the base of the lowermost sandstone bed of the Ojo Alamo. This conglomeratic sandstone may be a lag deposit and could mark the Tertiary-Cretaceous boundary in some areas. Unfortunately, this sandstone bed is usually not well exposed, and it is difficult to trace. Exposures can be seen below the base of the Ojo Alamo above the roadcut shown in figure 6 and on the south edge of Mesa Portales below and west of the lower part of the Ojo Alamo Sandstone pinchout in the west-central part of sec. 10, T. 19 N., R. 2 W. However, in some localities, for example in the bluffs south of Farmington, a rusty-brown conglomeratic sandstone is the basal part of the lowermost Ojo Alamo sandstone bed. In such areas the base of the Ojo Alamo, the unconformity, and the Tertiary-Cretaceous boundary are probably coincident.

UPPER CRETACEOUS, PALEOCENE, AND YOUNGER ROCKS

ANIMAS FORMATION AND YOUNGER ROCKS

The Fruitland Formation and the Kirtland Shale are overlain by the Upper Cretaceous and Paleocene Animas Formation throughout most of the San Juan Basin north of the limit of the Ojo Alamo Sandstone (fig. 9). At the outcrop the Animas is distinct from the units underlying it in that it contains an abundance of rock material of volcanic origin. It is conglomeratic and characteristically contains boulders and pebbles of andesite in a tuffaceous matrix; the conglomerate beds are interbedded with variegated shale and sandstone. Less commonly, conglomerate beds contain pebbles of quartz, quartzite, and chert. The Animas Formation was divided (Barnes and others, 1954) into the basal Upper Cretaceous McDermott Member and an unnamed Upper Cretaceous and Paleocene upper member in the northwestern part of the San Juan Basin; however, the McDermott Member has not been differentiated in the northeastern part of the basin, and there the Animas Formation is considered to be of Paleocene age.

The Animas is limited to the northern part of the basin. It attains a thickness of 2,670 feet on the outcrop near the La Plata–Archuleta County boundary line in Colorado (Reeside, 1924, pl. 2). On the east and west sides of the basin, the Animas loses its identity because it interfingers to the south with the Nacimiento Formation. On the west side of the basin, the Animas cannot be traced southward much beyond the New Mexico–Colorado border; on the east side, the southernmost limit of the Animas is probably near Dulce, N. Mex. In the subsurface, the southern limit of the Animas has not been located because of the difficulty in differentiating the Animas from the Nacimiento on electric logs.

The nature of the upper and lower contacts of the Animas is problematical. Some geologists believe that both contacts are conformable, whereas others believe that both contacts are unconformable. In the authors' opinion, the thinning of the Fruitland and the Kirtland beneath the Animas from 1,200 feet at the outcrop northeast of well 9 in section *A–A′* (pl. 2) to less than 300 feet at the outcrop north of well 13 in section *B–B′* indicates that more than 900 feet of Fruitland and Kirtland rocks may have been removed by erosion in the northeastern part of the basin prior to deposition of the Animas. The isopach map of the Fruitland and the Kirtland (fig. 11) shows the thinning of these rocks toward the east side of the basin. The convergence of the basal Animas contact and underlying formation boundaries in the northeast in section *A–A′* (pl. 2) and in the north in section *D–D′* (pl. 2) also indicates beveling of the Fruitland and Kirtland rocks and possible truncation of the Ojo Alamo Sandstone before deposition of the Animas.

The Nacimiento Formation may overlie the Kirtland Shale in the northwestern part of the basin in the area west of the La Plata River and north of Pinyon Mesa. The Tertiary rocks in this area have never been mapped in detail, so the exact relationship of the Animas and the Nacimiento in this part of the basin is not known. In all probability, however, the Animas grades laterally into the Nacimiento with a gradual compositional change from abundant andesitic material in the north to no andesitic material in the south.

R. H. Tschudy examined a coal sample collected by the authors from a 0.6-foot-thick coal bed located about 130 feet stratigraphically above the base of the Nacimiento Formation in the NE¼SW¼SW¼ sec. 12, T. 20 N., R. 2 W., on a spur extending southward from Cuba Mesa. The palynomorphs identified by Tschudy from this locality (USGS paleobotany loc. D3803) are listed in table 1. Tschudy (written commun., 1966) reported:

> This assemblage is of definite early Paleocene age. Some of the species identified have been reported previously by Anderson (1960) from the Nacimiento and Ojo Alamo Formations. Some of the species recovered from this sample were not mentioned by Anderson. This may suggest that this sample was from a stratigraphically higher position than any of the samples studied by Anderson.

The Eocene San Jose Formation overlies the Kirtland on Bridge Timber Mountain in a small area north of the New Mexico–Colorado border in the northwestern part of the basin (Barnes and others, 1954), and according to Baltz (1967, p. 42), the San Jose rests unconformably on rocks as old as Lewis Shale in sec. 23, T. 22 N., R. 1 W., a few miles northeast of Cuba, in the southeastern part of the basin.

In the northeastern part of the basin, a large number of north-trending dikes and sills occur (pl. 1). The dikes are vertical for the most part and range in thickness from 1 to 30 feet. The intrusives, which are biotite-hornblende lamprophyres, cut rocks as young as the San Jose Formation and, thus, are younger than this unit. The dikes contain free oil in vesicles in some places (Dane, 1948). Faulting occurred both before and after the intrusion of the igneous rocks; however, the intrusions apparently were subsequent to the major folding in the area.

STRUCTURE

The structural setting of the San Juan Basin and the structural elements of the basin and the area surrounding it are shown in figure 14. The Central Basin area shown in this map coincides roughly with the San Juan Basin of this report. The Central Basin is structurally bounded by the Hogback monocline on the northwest, north, and east sides. In the southern and southwestern parts of the basin there is no sharp structural boundary; the rocks dip gently in toward the basin axis across the entire Chaco Slope.

The internal basin structure is shown in the contour map of the Huerfanito Bentonite Bed (fig. 15). This map shows the steep dip of the beds into the basin in the northwestern, northern, and eastern parts and the relatively gentle and even dip in the southwestern and southern parts. The basin is distinctly asymmetric, characterized by an irregular northwest-trending axis that is about one-third of the distance across the basin from the north side. The Central Basin area is modified very little by faulting or folding. In a report on the structural geology of the Colorado Plateau, Kelley and Clinton (1960, p. 22) stated that "the fracture systems of the San Juan Basin bear little regular relationship to the over-all form of the basin; rather they are more a part of the irregular structures that reflect irregular deformation of the basin from place to place."

The exact time of formation of the structural San Juan Basin is difficult to determine. The isopach map (fig. 13) of the interval between the Huerfanito Bentonite Bed and the base of the Ojo Alamo gives no indication of truncation around the west, south, or east sides of the basin, so the basin probably had not yet started to form, at least in these areas, at the time that the Ojo Alamo was deposited. The first definite evidence of uplift around the basin rim is the overstepping nature of the basal San Jose Formation contact in the Bridge Timber Mountain area in the northwest, and northeast of Cuba in the southeast. Thus, the present basin configuration must have started to develop after deposition of the Ojo Alamo and prior to deposition of the San Jose. Lakebed deposits of the Nacimiento Formation indicate the presence of a closed basin prior to deposition of the San Jose.

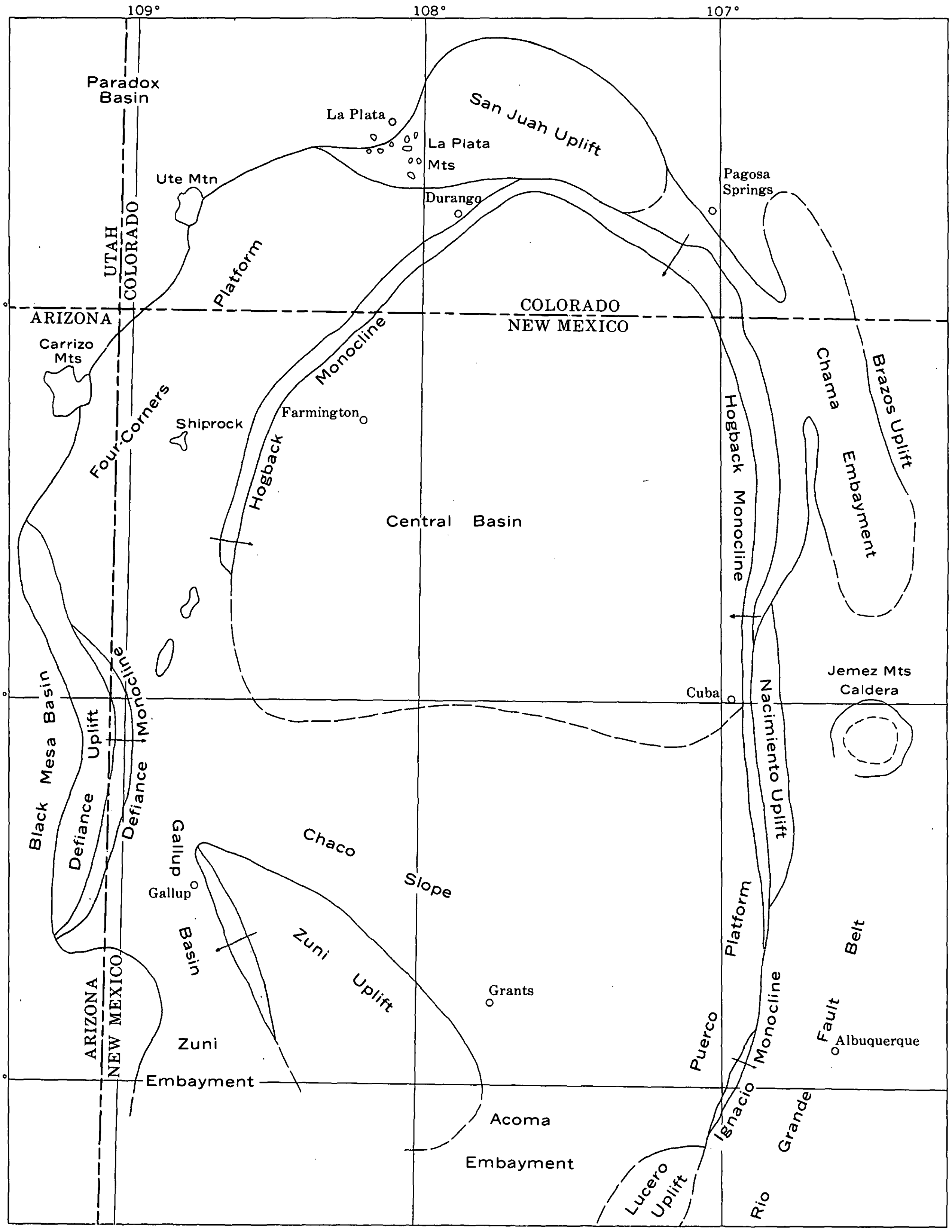


FIGURE 14.—Structure map of the San Juan Basin. After Kelley (1951, p. 125).

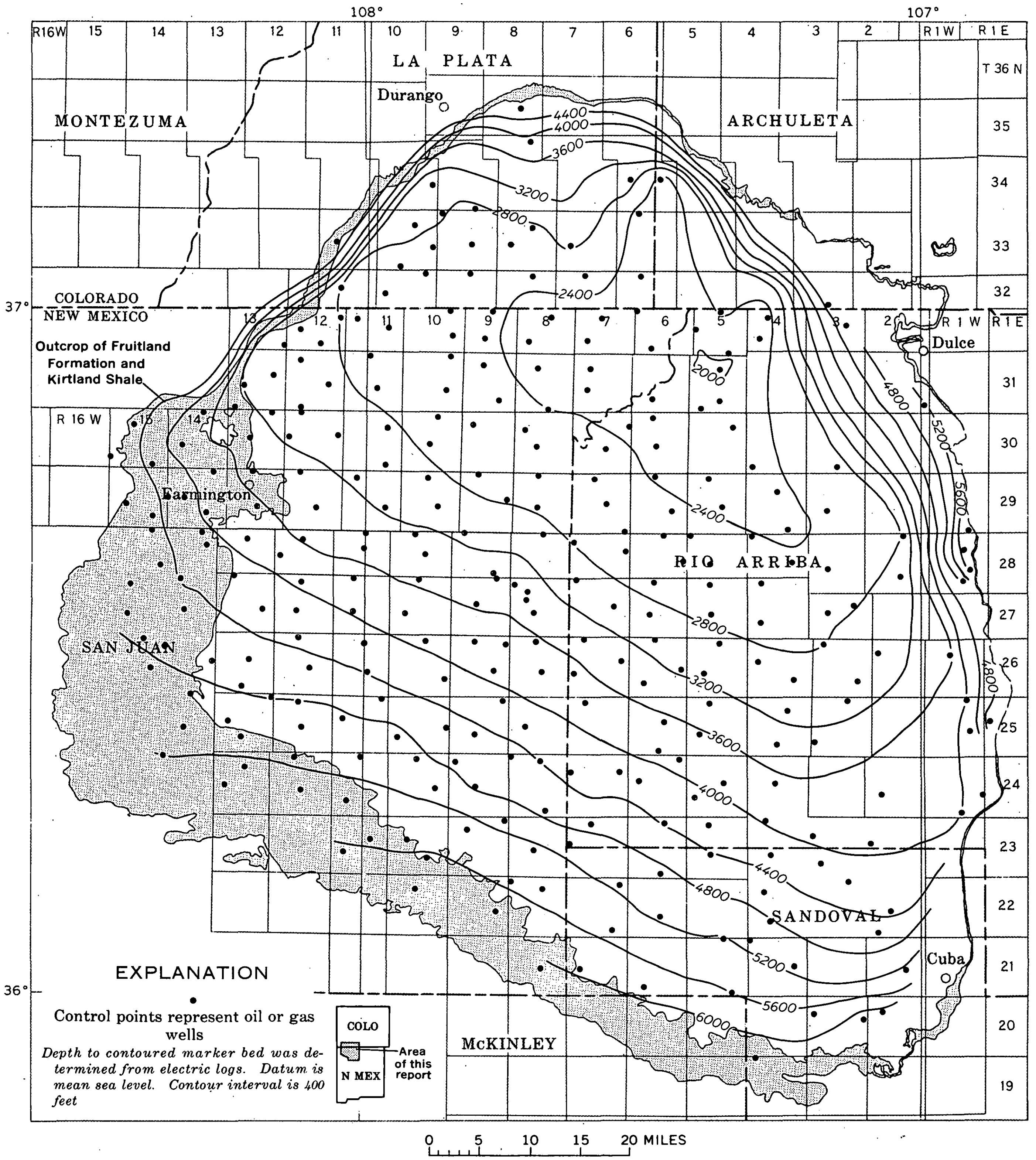


FIGURE 15.—Contour map of the Huerfanito Bentonite Bed.

GEOLOGIC HISTORY

The final retreat of the Late Cretaceous sea from the San Juan Basin area was accompanied by deposition of the nearshore and beach deposits that now compose the Pictured Cliffs Sandstone. The orientations of the Pictured Cliffs shoreline as the sea regressed to the northeast across the basin area are indicated in figure 7. The shoreline trends were northwest most of the time, but a shift to nearly an east trend is indicated in the central part of the basin. The Pictured Cliffs shoreline was rising stratigraphically as the sea was filled in and pushed out of the basin area. During regression of the Pictured Cliffs Sea, minor transgressive-regressive cycles occurred frequently and resulted in both local thickening of the Pictured Cliffs and intertonguing of the Pictured Cliffs with the overlying Fruitland Formation.

On the landward side of the Pictured Cliffs shoreline, three environments of deposition paralleled the shoreline and migrated to the northeast as the sea regressed (fig. 5). The sediments of a given environment thus continuously overlapped the sediments of the next seaward environment, except during minor transgressions of the sea. Figure 16 is a diagrammatic paleogeographic map of these three environments, showing a swamp environment closest to the shoreline, a flood-plain environment farther away from the shore, and a river and flood-plain environment even farther inland. In all probability, these environments were, at least in part, a function of the change of gradient of the paleoslope. The steepest gradient was in the river and flood-plain environment, and the swamp environment was nearly flat. The observed sedimentary relations indicate that there was a rising highland southwest of the present San Juan Basin area. Sediment-laden streams flowed northeast from this highland and ultimately emptied into the Pictured Cliffs Sea. These streams were aggrading throughout much of the present San Juan Basin area.

Eventually, the Pictured Cliffs Sea regressed out of the San Juan Basin area, and an unknown thickness of Fruitland and Kirtland rocks was laid down on top of the Pictured Cliffs Sandstone. In northeastern New Mexico, the Trinidad Sandstone is the highest regressive marine sandstone, so it is probable that both the Trinidad and the Pictured Cliffs represent sandstone deposited at and near the shoreline of the retreating sea (here called the Pictured Cliffs Sea). The Trinidad is overlain by the coal-bearing Vermejo Formation, which is undoubtedly analogous to (although probably younger than) the Fruitland Formation. Earlier writers suggested that a landmass existed between the northeastern and northwestern parts of New Mexico during Pictured Cliffs time and that the Pictured Cliffs Sea was receiving sediment from both the east and west

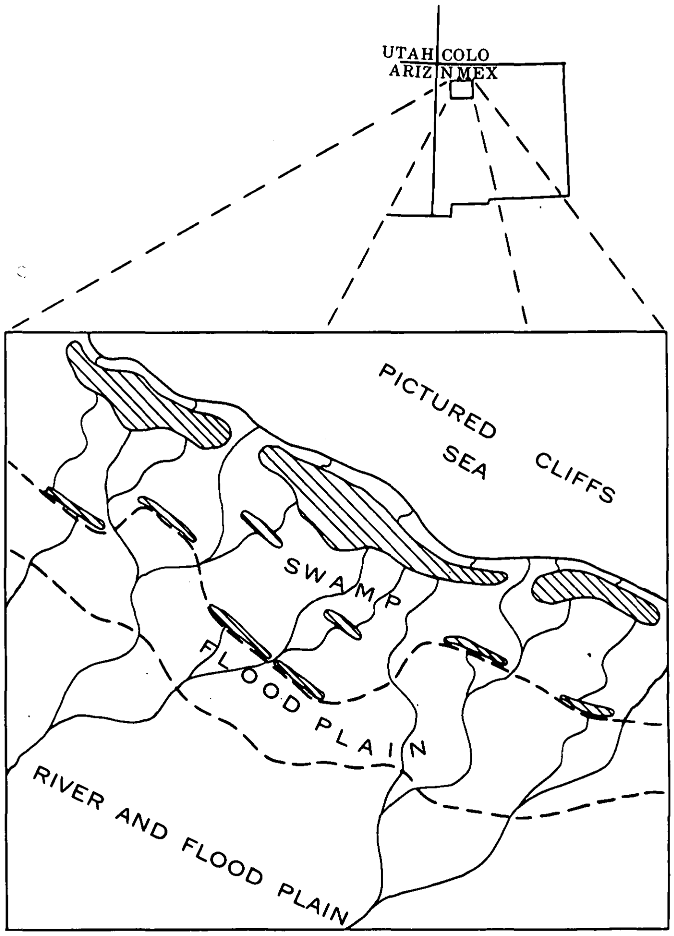


FIGURE 16.—Diagrammatic paleogeographic map showing environments of deposition of the rocks that now compose the Fruitland Formation and the Kirtland Shale.

sides of this landmass at that time. If this land area did exist as Baltz (1967, fig. 7) showed, then the Pictured Cliffs Sandstone should be equivalent in age in parts of the northern and southern San Juan Basin and also it should be equivalent in age to part of the Trinidad Sandstone in the Raton Basin. Unfortunately, the age of the Trinidad in the Raton Basin relative to the Pictured Cliffs is not known. The evidence relating to the age of the Pictured Cliffs of the San Juan Basin, however, indicates that the Pictured Cliffs becomes progressively younger from southwest to northeast. Thus, it seems probable that the Pictured Cliffs shoreline was regressing to the northeast as the sea left the present basin area, which indicates that there was no landmass immediately northeast of the area at that time.

Silver (1950, p. 119) suggested that "a late Cretaceous basin of deposition" existed in the northwestern part of the present San Juan Basin area. He based this hypothesis on an isopach map (his fig. 3) of "the combined Fruitland and Kirtland formations" which showed, as does figure 11 of this report, a thickening of the Kirtland and Fruitland in the northwestern part of the basin. In later reports (1951, 1957), Silver referred to this basin as the Kirtland basin. The data developed in this report indicate that there was no Kirtland basin of deposition in the northwestern or western part of the San Juan Basin. The greater thickness of the Fruitland and Kirtland in the northwestern part of the basin appears to be the result of the combined effects of the stratigraphic rise of the Pictured Cliffs Sandstone to the northeast (fig. 7), the progressively lower stratigraphic position of the Ojo Alamo Sandstone to the southeast (fig. 13), and the progressively lower stratigraphic position of the Animas Formation to the north and northeast (pl. 2). In other words, the thicker Fruitland and Kirtland rocks in the northwestern part of the San Juan Basin reflect erosional episodes after the Kirtland and Fruitland rocks were laid down, rather than greater original sediment accumulation in a basin existing during Kirtland and Fruitland time.

Evidence of volcanism that occurred during deposition of the Fruitland Formation and the Kirtland Shale can be found in several parts of the San Juan Basin. In the southeast, near Cuba, bentonitic shales are present in the lower part of the Fruitland. In the Ojo Alamo Arroyo area, purple shales containing andesite debris (Reeside, 1924) occur in the Kirtland. In the Pinyon Mesa area in the northwestern part of the basin, bentonitic shales are present in the Fruitland, and volcanic tuff beds occur in the Kirtland. The location of the volcanic vents is unknown; they may have been located north, west, and southeast of the basin area at different times. The final Upper Cretaceous episode of volcanism is represented by the coarse andesite conglomerate and tuff beds of the McDermott Member of the Animas Formation in the northwestern part of the basin.

During the time of Fruitland and Kirtland deposition, there was probably uplift east or southeast of the present basin area in the vicinity of the Nacimiento uplift of figure 14. This highland probably served for a time as a source area for the Fruitland, Kirtland, and Pictured Cliffs and speeded the retreat of the Pictured Cliffs Sea from the eastern basin area to such an extent that swamps did not form, and today there is little coal in this area.

After deposition of the Kirtland and McDermott rocks, the basin area was tilted toward the northwest and a basin-wide cycle of erosion followed. This cycle resulted in the removal of as much as 2,100 feet of sediment in the southeastern part of the basin. The areas in Tps. 29 and 30 N., R. 1 W., and T. 26 N., R. 1 E., where the Pictured Cliffs Sandstone, Fruitland Formation, and Kirtland Shale are absent and the Lewis Shale is overlain by the Ojo Alamo Sandstone (pl. 1), probably represent areas which were relatively slightly uplifted at the time of erosion. The area in Tps. 27 and 28 N., R. 1 W., where a remnant of Pictured Cliffs Sandstone and Fruitland Formation crops out probably represents an area of local downwarping during the erosion cycle.

Figure 13, an isopach map of the interval from the Huerfanito Bentonite Bed to the base of the Ojo Alamo Sandstone, indicates the amount of rock removed by erosion in the basin area and also shows the trend of the thinning, which is primarily from northwest to southeast. The pre-Ojo Alamo surface was probably a relatively flat peneplain. Thus, if the isopachs in figure 13 are thought of as structure-contour lines and the values as below-sea-level values, then this isopach map is probably a fair representation of the basin area structure contoured on the Huerfanito just prior to Ojo Alamo deposition. Cross sections through the basin at that time are shown in *B* of figures 17 and 18. Figure 13 also indicates that the basin structure as we know it today had not yet started to form before the Ojo Alamo Sandstone was deposited, at least not in the part of the basin covered by the isopachs. If there had been some tectonism around the area of the present basin rim, the isopachs would tend to curve where they approach the rim, but they do not. The few irregularities that do occur in the isopachs could represent either pre-Ojo Alamo paleotopography or localized post-Huerfanito tectonism.

The source of the Ojo Alamo was, for the most part, west of the present basin area, as evidenced by the eastward decrease in the size of the pebbles contained in the Ojo Alamo conglomerates. This decrease in pebble size was observed in surface outcrops in the southern part of the basin and is indicated in the subsurface by the absence of pebbles in a core from a well in sec. 36, T. 29 N., R. 4 W., described by Fassett (1968a, b). Apparently the gradients of the streams carrying Ojo Alamo sediment into the basin decreased from west to east, so that coarser gravels were deposited on the west side of the basin and progressively finer grained material was deposited eastward. Baltz (1967, p. 33) wrote that the strikes of channel edges and crossbedding measurements near Farmington "indicate that in this part of the basin the Ojo Alamo was deposited by streams flowing from the west-northwest and the northwest * * *." Other sources of sediment to the south or east may have existed (Baltz, 1967, p. 33). The depositional conditions in the northern part of the basin area at the time the Ojo Alamo was being deposited to the south are not known. At the present time, no Ojo Alamo Sandstone is present in the northern part of the basin. Whether it is absent because of lack of deposition or removal by erosion after it was deposited is not known.

The Nacimiento Formation was deposited on top of the Ojo Alamo. The Nacimiento and the Ojo Alamo intertongue throughout most of the basin area, and the contact of these units is probably conformable, at least in the southern two-thirds of the basin. The Nacimiento may overlap the Ojo Alamo in the northwestern part of the basin. It apparently directly overlies the Kirtland Shale in the area north of Pinyon Mesa and west of the La Plata River just south of the Colorado–New Mexico border. The nature of the lower Nacimiento contact north of Pinyon Mesa has not been determined. If the contact is unconformable, it would indicate that the northwest rim of the basin had been uplifted and beveled after deposition of the Ojo Alamo Sandstone and prior to deposition of the Nacimiento Formation.

The next phase of basin development was probably uplift along the Hogback monocline (fig. 14), principally in the Colorado part of the basin and in the northeastern New Mexico part. This episode of uplift resulted in and was accompanied by erosion and beveling of the Fruitland and Kirtland and possibly the Nacimiento and the Ojo Alamo around the north rim of the basin.

It is not possible to determine if the thinning of the Fruitland and Kirtland rocks southeastward in the northeastern part of the basin is the result of the pre-Ojo Alamo erosion cycle, the pre-Animas erosion cycle, or a combination of both. The convergence of the basal Animas contact and underlying contacts illustrated in sections *A–A′* and *D–D′* (pl. 2) indicates that there were at least two cycles of erosion in the northern part of the basin that resulted in beveling of the Fruitland and Kirtland.

The pre-Animas erosion cycle was followed by an outbreak of volcanic activity north of the basin, possibly in the area of the La Plata Mountains (fig. 14), that resulted in deposition of the upper member of the Animas in the northwestern part of the basin and the Animas in the northeastern part. After deposition of the Animas, renewed uplift along the Hogback monocline in the northern and eastern parts of the basin resulted in erosion, at least in the Bridge Timber Mountain area in the northwestern part and in an area about 8 miles northeast of Cuba in the southeastern part (Baltz, 1967, p. 53). In both these areas, the San Jose Formation was deposited unconformably and at a sharp angle to the underlying rocks. The full extent of the pre-San Jose erosion in the basin area has not yet been determined. As the San Jose was being deposited, the basin probably continued to form and ultimately achieved its present configuration. Some time after the San Jose was deposited, a large number of dikes and sills were intruded in the northeastern part of the basin. The dikes have a north-south alinement, and according to Dane (1948), they are probably Miocene in age and were "intruded subsequent to the major period of folding of the rocks."

The sequence of major geologic events discussed above that affect the uppermost Cretaceous rocks of the San Juan Basin is shown diagrammatically on the north-south and east-west cross sections in figures 17 and 18. Both figures represent three points in time in the geologic history of the basin: (1) after deposition of the Kirtland rocks and before deformation, (2) after uplift and basin-wide beveling but before deposition of the Ojo Alamo, and (3) the present time.

In summary, it seems that the only erosional cycle that affected the entire basin area, after the deposition of the Pictured Cliffs Sandstone, was that preceding deposition of the Ojo Alamo Sandstone. This stage in the basin development is represented by *B* in figures 17 and 18. The erosional cycle was probably the result of northwestward tilting of the entire basin area. The authors believe that other erosional cycles occurred along the north and east sides of the basin as the Hogback monocline was being formed, but that during these cycles deposition was relatively continuous in the interior of the basin. Thus, the unconformities at the base of the Animas and San Jose Formations that reflect past uplift and attendant erosion along the basin rim probably fade out and disappear toward the center of the basin.

FUEL RESOURCES

OIL AND GAS

Commercial gas was discovered in the Farmington Sandstone Member of the Kirtland Shale in 1921 when the Aztec Oil Syndicate completed its State No. 1 well in sec. 16, T. 30 N., R. 11 W., 1 mile south of Aztec, N. Mex. This well had an initial potential of 250,000 cubic feet of gas and 4 barrels of oil per day. Gas from the well was piped into Aztec and was used domestically throughout most of the 1920's, thereby establishing the first commercial use of natural gas in New Mexico (Barnes, 1950). The Aztec well became part of the Aztec Farmington gas field from which five wells ultimately produced. The field was abandoned in 1933. Since the first discovery, 74 wells have produced oil and gas from the Fruitland Formation and the Farmington Sandstone Member of the Kirtland Shale in the New Mexico part of the San Juan Basin. Thirty-five wells have produced gas from the Fruitland Formation at Ignacio dome in the Colorado part of the basin. The statistical summary of the pools is given in table 2; distribution of the pools is shown in figure 19.

Except for the Ignacio Blanco-Fruitland pool in La Plata County, Colo., the Kirtland and Fruitland reservoirs consist of small scattered stratigraphic traps. The extreme lenticularity of the sandstone beds in these

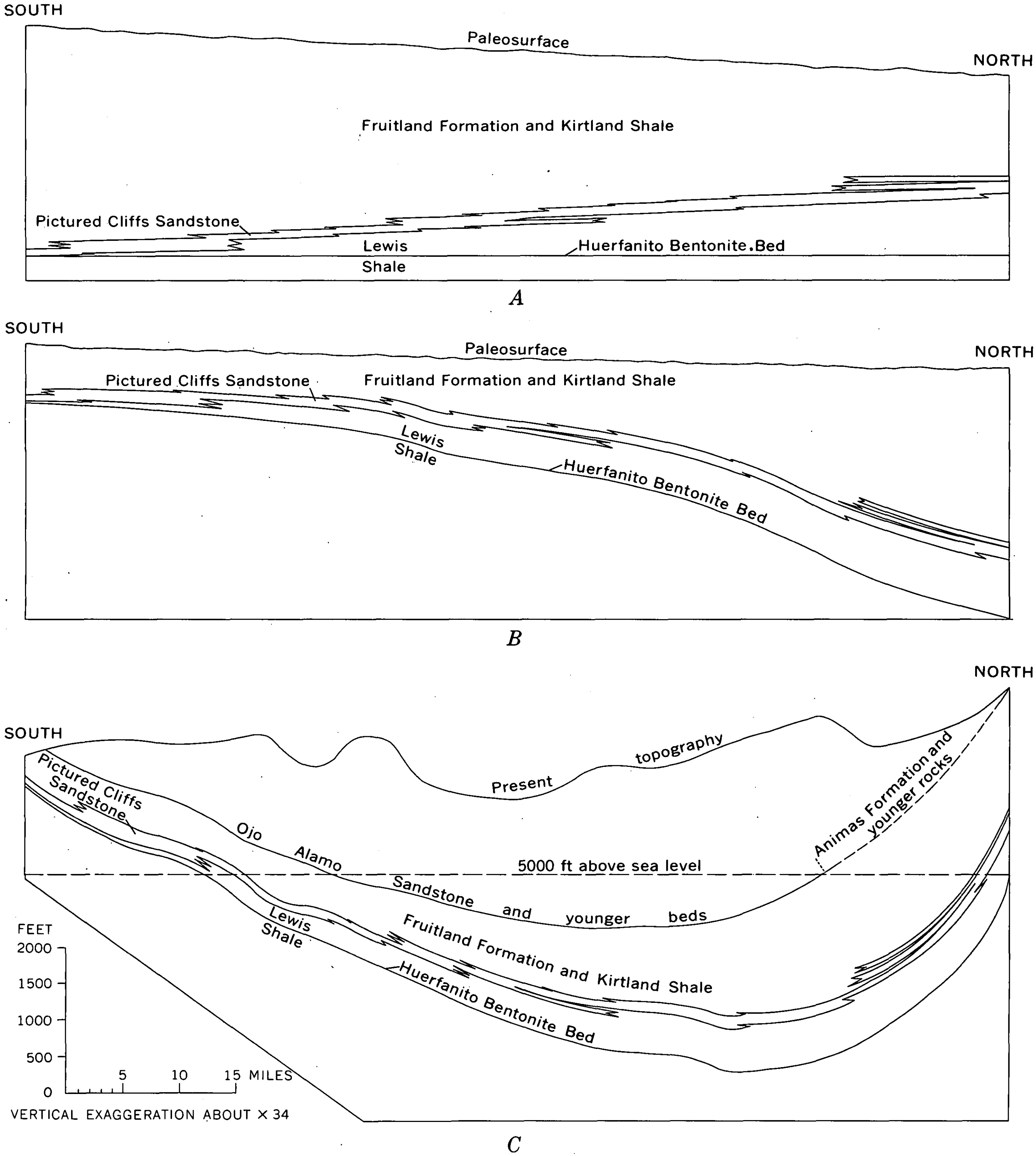


FIGURE 17.—North-south diagrammatic cross sections showing the probable sequence of geologic events that affected uppermost Cretaceous rocks. *A*, Depositional attitude of the upper part of the Lewis Shale, the Pictured Cliffs Sandstone, and the Fruitland Formation and Kirtland Shale before deformation of the rocks occurred; reference datum, Huerfanito Bentonite Bed. *B*, The same rock sequence after the southeastern part of the basin area was tilted and the Kirtland and Fruitland rocks were beveled by erosion; reference datum, paleosurface line. *C*, Present structure and topography of the basin; reference datum, mean sea level. These sections are along the line of cross section *D–D′* (pl. 2).

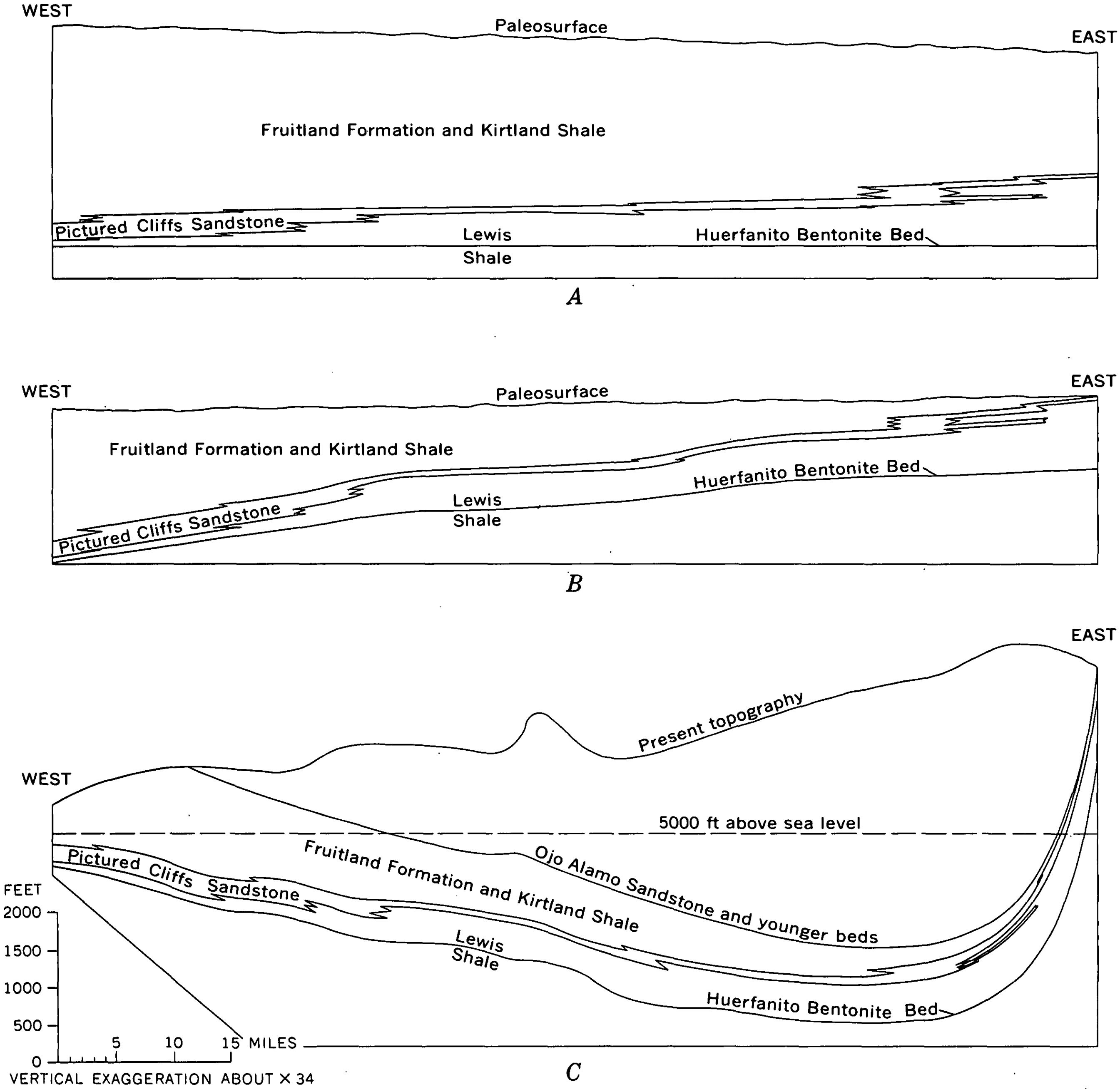


FIGURE 18.—East-west diagrammatic cross sections showing the probable sequence of geologic events that affected uppermost Cretaceous rocks. *A*, Depositional attitude of the upper part of the Lewis Shale, the Pictured Cliffs Sandstone, and the Fruitland Formation and Kirtland Shale before deformation of the rocks occurred; reference datum, Huerfanito Bentonite Bed. *B*, The same rock sequence after the southeastern part of the basin area was tilted and the Kirtland and Fruitland rocks were beveled by erosion; reference datum, paleosurface line. *C*, Present structure and topography of the basin; reference datum, mean sea level. These sections are along the line of cross section *F–F′* (pl. 2).

TABLE 2.—*Statistical summary of oil and gas pools of the Kirtland Shale and the Fruitland Formation*

[MCF, thousand cubic feet of gas; MCFPD, thousand cubic feet of gas per day; BO, barrels of oil; BOPD, barrels of oil per day. Number at left is oil or gas field number in fig. 19]

No.	Pool name	Discovery date	Discovery well	Location			Initial production	Total wells that produced	Number of wells producing	Accumulated production
				Sec.	T. N.	R. W.				
				NEW MEXICO						
										Jan. 1, 1966
1	Aztec Farmington	1921	Aztec Oil Syndicate State No. 1.	16	30	11	250 MCFPD, 4 BOPD	5	0	Unknown
2	Aztec Fruitland	June 19, 1952	F. L. Harvey Hare No. 1	14	29	11	470 MCFPD	-----------	32	6,834,146 MCF, 2,114 BO
3	No. Aztec Fruitland.	Apr. 24, 1954	El Paso Gage No. 1	20	30	10	206 MCFPD	1	0	15,138 MCF
4	Bloomfield Farmington.	July 1924	Bloomfield Oil & Gas Saiz No. 1.	14	29	11	3 BOPD	29	4	40,010 BO
5	Cottonwood Fruitland	Nov. 11, 1953	Pan Am S.J.U. 32-5 No. 2 M.	35	32	5	396 MCFPD	0	-----------	
6	Flora Vista Fruitland	Dec. 28, 1956	N. W. Prod. Blanco 30-12 No. 3L.	10	30	12	10,651 MCFPD	5	5	701,087 MCF
7	Gallegos Fruitland	Mar. 16, 1952	Western Dev. Douthit No. 2-A.	27	27	11	1,300 MCFPD	1	1	663,938 MCF, 13 BO
8	Kutz Farmington	Nov. 1, 1955	R&G Drlg. Co. No. 11 K.	28	28	11	2,000 MCFPD	3	3	211,428 MCF
9	Kutz Fruitland	Aug. 30, 1956	R&G Drlg. Co. Schlosser No. 25 J.	27	28	11	5,000 MCFPD	4	4	2,132,245 MCF, 912 BO
10	West Kutz Fruitland	Oct. 22, 1952	Locke Taylor Tycksen 1-A.	23	29	13	370 MCFPD	2	2	302,170 MCF
11	La Jara Fruitland	June 25, 1952	El Paso Abraham No. 1-B.	13	30	6	2,530 MCFPD	1	0	54,008 MCF
12	No. Los Pinos Fruitland.	July 31, 1953	Phillips S.J.U. 32-7 No. 3-A.	18	32	7	1,370 MCFPD	1	0	220,364 MCF
13	So. Los Pinos Fruitland.	Aug. 24, 1953	Phillips S.J.U. 32-7 No. 6-A.	17	31	7	1,790 MCFPD	1	1	377,956 MCF
14	Oswell Farmington	Jan. 1, 1932	Anna Oil Oswell No. 2-D.	34	30	11	25 BOPD	10	2	44,000 BO
15	Wyper Farmington	Aug. 2, 1946	Brown & Sterns Wyper No. 1-O.	29	30	12	750 MCFPD, 12 BOPD	2	0	6,852 BO
				Undesignated wells, Jan. 1, 1964						
16	Undesignated Farmington.		El Paso Omler Fed. No. 1	36	28	10	673 MCFPD	1	1	82,543 MCF
17	do	1955	Manana Gas Sullivan No. 1.	25	29	11	6,084 MCFPD	1	1	223,220 MCF
18	do		Pan Amer. Trujillo Unit No. 1.	21	29	10	5,011 MCFPD	1	0	8,191 MCF
19	do	1956	Redfern Redfern Fed. No. 3.	28	28	11	69 BOPD	1	0	1,933 BO
20	do	1959	Robert Elvis Bergin Fed. No. 1.	21	29	11	559 MCFPD	1	1	11,880 MCF
21	do		So. Union Prod. Armenta-Fed. No. 1.	27	29	10	2,120 MCFPD	1	1	170,043 MCF
22	Undesignated Fruitland.		Devonian Gas & Oil Fed. No. 1.	4	29	12	1,322 MCFPD	1	1	53,649 MCF
23	do		El Paso Bolack Fed. No. 1.	1	30	12	4,922 MCFPD	1	1	212,582 MCF
24	do	1963	So. Union Angels Peak No. 17.	13	28	11	4,900 MCFPD	1	1	216,816 MCF
				COLORADO						
										June 1, 1965
25	Ignacio Blanco-Fruitland.	1950	Stanolind Ute No. B-1	18	33	7	3,240 MCFPD	35	12	26,152,176 MCF
	Total							109	73	38,643,580 MCF, 95,834 BO

formations and the gentle dip of the rocks result in many updip porosity pinchouts. The lenticularity responsible for the oil and gas accumulations also limits their size. The sandstone beds in places contain gas under relatively high initial pressure, but completions in these beds have shown that the pressure usually declines rapidly. Reserves are generally small, and only a few of the wells have proved economical to complete and operate. Gas shows in the Kirtland and the Fruitland are ignored during most drilling in the San Juan Basin. In parts of the basin, however, it has become customary for drilling companies to take precautions against gas blowouts before penetrating the Kirtland and Fruitland, since at least five drilling rigs have been lost by fires owing to gas blowouts from these stratigraphic units.

The gas field at Ignacio is on a northwest-trending dome. Almost pure methane is produced from the coal zone in the Fruitland, which is highly fractured over the dome. The field has produced gas since 1950. The continuing production is attributed to the structural closure of the field, a highly developed fracture system, and a water drive which maintains the pressure of the reservoir. This field has produced more than two-thirds of all the gas that has been recovered from the Fruitland Formation and the Kirtland Shale (table 2).

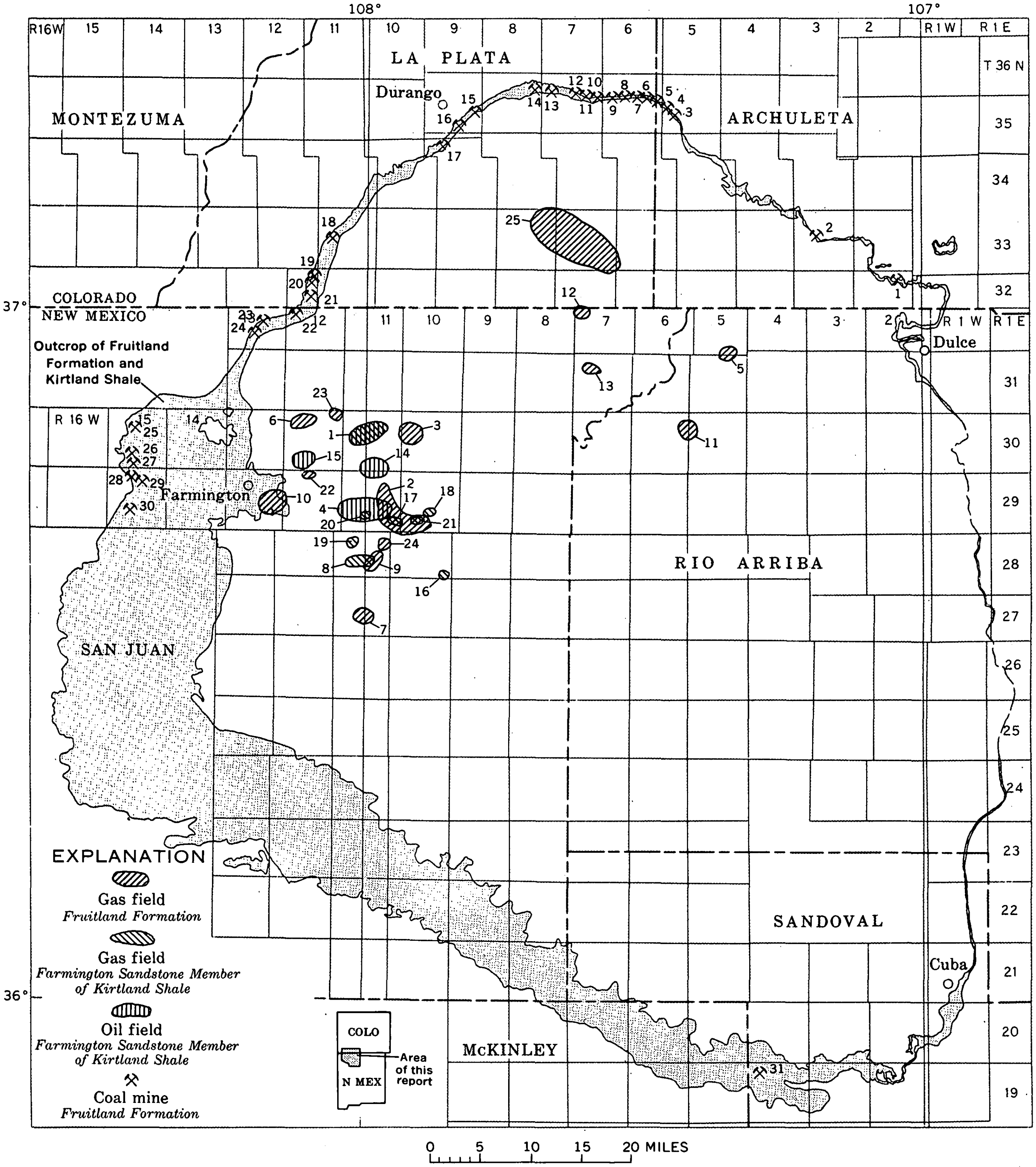


FIGURE 19.—Oil and gas fields and coal mines in the Fruitland Formation and the Farmington Sandstone Member of the Kirtland Shale. The numbered oil and gas fields are listed in table 2; the coal mines are listed in table 8.

Small isolated oil pools in the Farmington Sandstone Member of the Kirtland Shale are the only known oil accumulations in the San Juan Basin that probably originated in nonmarine rocks. The sandstone lenses that contain the oil are enclosed in fresh-water shale and are separated from the nearest marine deposits of the area, the Pictured Cliffs Sandstone, by several hundred feet of swamp and flood-plain sediment comprising the Fruitland Formation and the lower part of the Kirtland Shale. The oil is of high gravity, 56°–59° API, but the production rate is low, and the wells produce much connate water. As of January 1966, four fields had produced a cumulative total of 95,834 barrels of oil from the Farmington Sandstone Member. The total includes small amounts of distillate from some Fruitland gas fields.

URANIUM

Only one published report of uranium mineralization in the Fruitland Formation, the Boyd deposit, is known. This deposit is described by Clinton and Carithers (1956, p. 449) as follows:

> The Boyd deposit is in a tuffaceous sandstone of the Fruitland formation on a mesa 12 miles northwest of Farmington, N. Mex. About 40 tons of ore containing 0.15 to 0.20 percent U_3O_8 have been mined from a sharply defined light-pink zone at the base of the tuffaceous sandstone. Just above the ore zone is 1 foot of gray sandstone that grades upward into barren buff-colored, tuffaceous sandstone. Beneath the ore there is a thin zone of gray sandstone; this in turn is separated from a 1-foot bed of mudstone and sandstone containing carbonaceous fragments and marine (or brackish water?) gastropods by a sharp, scoured contact. Bentonitic and tuffaceous beds underlie the fossiliferous unit. The uranium mineral is too fine to be readily identified.
>
> The ore, exposed in an area of about 25 by 50 feet in an open pit, is from 3 inches to 36 inches thick. The ore body occupies a shallow depression scoured into the subjacent, tuffaceous sediments. It is on the flank of the Hogback monocline in beds dipping 12° SE. The pink color of the ore unit is due to iron oxide.

The authors visited the Boyd location in July 1968. It appears that little, if any, development work has been done at the deposit in recent years. A few shallow bulldozer trenches were seen in the area near the old workings, but none appeared to be recent cuts.

COAL

ORIGIN AND DISTRIBUTION

Coal in the Fruitland Formation occurs chiefly in northwest-trending elongate lenticular bodies whose long axes parallel the strand lines of the Pictured Cliffs Sea. The organic material that formed the coal beds accumulated, for the most part, in a belt of long, relatively narrow coastal swamps which formed behind the barrier beaches of the sea. The general character and the physical dimensions of the coal beds indicate that the belt of swamps generally ranged in width from 6 to 20 miles. Individual swamps ranged in size from small bogs to inundated areas of more than 100 square miles. Some swamps existed for only a brief time; they are recorded by thin usually silty and discontinuous streaks of coal and carbonaceous shales. Other swamps persisted for long periods, during which sufficient organic debris accumulated to compact into coal beds more than 30 feet thick. Between these extremes were all degrees of size and duration.

The belt of swamps was dissected in places by the winding distributaries of sluggish streams. A few larger rivers crossed it from the south and the west, carrying sand to the beaches and fine silt and clay to the open sea. Encroaching over the landward side of the swamps, through a wide transition zone, were broad, low flood plains. At some points the environment of the flood plain protruded deep into the swamp belt. In other areas, far inland, the vegetal matter, which today forms scattered lenses of coal in the upper part of the Fruitland Formation, was accumulating in small isolated bogs. A diagrammatic illustration of Fruitland environmental zones is shown in figure 16.

The general regression of the Late Cretaceous sea was interrupted repeatedly by minor transgressions and oscillations of the shoreline. The brief transgressions temporarily displaced the barrier beaches and coastal swamps landward (southwestward) geographically and upward stratigraphically so that today the Fruitland coals in places intertongue with the marine Pictured Cliffs Sandstone. In some areas, coal zones, separated by thick intertongues of sandstone, siltstone, and shale, occur one above another over a stratigraphic interval of 300 or more feet. At most places the upper coal zones of these areas are the landward extensions of thick coal deposits which built up behind barrier beaches to the northeast. As each minor transgression began, the coastal swamps were pushed inland and covered previously deposited flood-plain sediment. The magnitude of the transgression or the duration of a period of oscillation determined the distance of the inland migration of the swamps and controlled the thickness of the resulting coal deposits. Typically, the thickest Fruitland coal beds occur immediately southwest of the pronounced stratigraphic rises of the Pictured Cliffs Sandstone. In a northeast direction the coal beds wedge out abruptly against intertonguing sandstones of the Pictured Cliffs. Toward the southwest they are first split by and then grade into flood-plain deposits. In a northwest trend the coal zones maintain a relatively consistent overall thickness for many miles, although individual beds may split, thin, pinch out, merge, or terminate abruptly against channel deposits.

The depositional relations described above resulted, in most areas, in the concentration of the thickest and most extensive of the Fruitland coals in the lowest part of the formation. In places, however, the lowest approximately 100 feet of the Fruitland is barren of coal beds. Such barren areas may be explained as follows: (1) The areas may represent large stream channels in which deposits of silt, sand, and mud were the first Fruitland sediments; (2) the areas may have resulted from postswamp erosion—streams cut channels through the peat deposits and the channels subsequently filled with clastics, resulting in a gap or "want" in the coal beds; or (3) some relatively deep lagoons and lakes did not support plant growth or preserve the organic remains necessary for coal formation but instead filled with fine clastics and mud that locally formed the lowermost Fruitland beds.

The subsurface thickness and distribution of Fruitland coal beds in the San Juan Basin, shown on plate 3, were determined by interpretation of the electronic-log records and drilling-rate charts of holes drilled by petroleum companies. The locations of the drill holes and surface sections are shown on plate 3. Most of the measured sections were taken from published reports, but those near the east margin and the southeast corner of the basin were measured by the authors. The control points and the source of information are listed in table 3.

TABLE 3.—*Wells and measured sections used for plotting coal resources*

Number on pl. 3	Published reference or company	Measured section or well name	Location		
			Sec.	T. N.	R.
		Colorado			
1	Zapp (1949)	75	27	35	9 W.
2	do	Composite of 82 and 83	17	35	8 W.
3	Barnes (1953)	Composite of 2 and 3	12	35	8 W.
4	do	10	9	35	7 W.
5	do	13, Schutz mine	14	35	7 W.
6	do	18	18	35	6 W.
7	do	24, Shamrock mine No. 1, 2, 3	13	35	6 W.
8	do	30	33	35	5 W.
9	Northwest Production Corp	Bondad 34–10 No. 1–32	32	34	10 W.
10	Barnes, Baltz, and Hayes (1954)	56	9	34	10 W.
11	Zapp (1949)	66	5	34	9 W.
12	do	69 (Carbon Junction)	5	34	9 W.
13	Consolidated Oil and Gas, Inc	Spring Creek No. 2–29	29	34	6 W.
14	Wood, Kelley, and MacAlpin (1948)	1	4	34	5 W.
15	do	2	24	34	5 W.
16	Barnes, Baltz, and Hayes (1954)	39	30	33	11 W.
17	do	Composite of 49 and 50	3	33	11 W.
18	Val R. Reese and Associates, Inc	Ute No. 2–34	34	33	11 W.
19	Pacific NW Pipeline Corp	Bondad 33–10 No. 4–3	3	33	10 W.
20	U.S. Smelting, Refining and Mining Co	So. Ute 33–10 No. 2–35	35	33	10 W.
21	Northwest Production Corp	Bondad 33–9 No. 20-5	5	33	9 W.
22	Pacific NW Pipeline Corp	Bondad 33–9 No. 30–21	21	33	9 W.
23	do	Bondad 33–9 No. 12–1	1	33	9 W.
24	Compass Exploration, Inc	Black Mesa No. 1–33	33	33	8 W.
25	Pacific NW Pipeline Corp	Ignacio 33–8 No. 10–2	2	33	8 W.
26	do	Ignacio 33–7 No. 8–32	23	33	7 W.
27	Consolidated Oil and Gas, Inc	Superior Ute No. 1–6	6	33	6 W.
28	Wood, Kelley, and MacAlpin (1948)	3	16	33	3 W.
29	do	4	32	33	2 W.
30	do	5, Klutter Mountain	20	33	1 W.
31	Barnes, Baltz, and Hayes (1954)	34, Fort Lewis mine	1	32	12 W.
32	Feldt and Maytag	Ute Govt. No. 1	4	32	6 W.
33	Pacific NW Pipeline Corp	NW Cedar Hill 32-10 No. 10–8	8	32	10 W.
34	El Paso Natural Gas Co	Carter Ute No. 2	23	32	10 W.
35	Skelly Oil Co	Sam Burch No. 2	4	32	9 W.
36	Compass Exploration, Inc	Southern Ute No. 1–10	10	32	11 W.
37	Stanolind Oil and Gas Co	Southern Ute No. 1	22	32	3 W.
		New Mexico			
38	Hayes and Zapp (1955)	44	21	32	13 W.
39	do	53	18	32	12 W.
40	Pan American Petroleum Corp	Fed. Gas Unit No. 1	20	32	12 W.
41	El Paso Natural Gas Co	Moore No. 6	25	32	12 W.
42	Great Western Drilling Co	Decker No. 3	17	32	11 W.
43	El Paso Natural Gas Co	S.J.U. 32–9 No. 48	14	32	10 W.
44	Pacific NW Pipeline Corp	S.J.U. 32–9	9	32	9 W.
45	El Paso Natural Gas Co	S.J.U. 32–9 No. 63	36	32	9 W.
46	Pacific NW Pipeline Corp	S.J.U. 32–8 Mesa 9–20	20	32	8 W.

TABLE 3.—*Wells and measured sections used for plotting coal resources*—Continued

Number on pl. 3	Published reference or company	Measured section or well name	Location: Sec.	T. N.	R.
		New Mexico—Continued			
47	El Paso Natural Gas Co	Allison No. 16 (MD)	15	32	7 W.
48	do	Allison No. 13	12	32	7 W.
49	do	Allison No. 17	24	32	7 W.
50	Pacific NW Pipeline Corp	S.J.U. 32-5 No. 6–10	10	32	6 W.
51	El Paso Natural Gas Co	S.J.U. 32-5 No. 14	26	32	6 W.
52	LaPlata Gathering System, Inc	S.J.U. 32-5 No. 1–31	31	32	5 W.
53	Belco Petroleum Corp	Carracas Mesa Unit No. 1–26	26	32	5 W.
54	Phillips Petroleum Co	Mesa Unit No. 32–4 No. 1–29	29	32	4 W.
55	do	Mesa Unit No. 32–4 No. 2–16	16	32	4 W.
56	Pan American Petroleum Corp	Pagosa Jicarilla No. 1	23	32	3 W.
57	Hayes and Zapp (1955)	22	26, 35	31	15 W.
58	do	26	29	31	14 W.
59	do	34	23	31	[1] 14 W.
60	do	37	7, 18	31	13 W.
61	Southern Union Production Co	Fed. Lea No. 1	34	31	13 W.
62	Ohio Oil Co	Ohio Govt. No. 1–20	20	31	12 W.
63	El Paso Natural Gas Co	Case No. 7	19	31	11 W.
64	do	Heaton No. 9	32	31	11 W.
65	Delhi-Taylor Oil Corp	Mudge No. 1	10	31	11 W.
66	Wood River Oil and Refining Co., Inc	Lamb No. 3	21	31	10 W.
67	El Paso Natural Gas Co	S.J.U. 32-9 No. 64	2	31	9 W.
68	Pacific NW Pipeline Corp	S.J.U. 32-8 Mesa 8–22	22	31	8 W.
69	do	S.J.U. 31–6 No. 5–31	31	31	6 W.
70	do	Rosa Unit No. 10–13	13	31	6 W.
71	do	Rosa Unit No. 15–29	29	31	5 W.
72	Shar-Alan Oil Co	Carson No. 1	10	31	5 W.
73	Humble Oil and Refining Co	Jic. Tr. 29–1	32	31	2 W.
74	J. S. Hinds and J. E. Fassett	Unpub. outcrop data		31	1 W.
75	Hayes and Zapp (1955)	8	28	30	15 W.
76	A. C. Bruce, Jr	Fed. Pipkin No. 1	5	30	14 W.
77	Stone Drilling, Inc	Kirtland No. 1–20	20	30	14 W.
78	Compass Exploration, Inc	Aztec No. 2–35	35	30	14 W.
79	Texas National Petroleum Co	Govt. No. 1	29	30	13 W.
80	Southern Union Production Co	Fed. No. 2–25	25	30	13 W.
81	Northwest Production Corp	Blanco 30–12 No. 1–4	4	30	12 W.
82	Pubco Petroleum Corp	State No. 30	36	30	12 W.
83	Tennessee Gas Transmission Co	Blanco State No. 1	2	30	11 W.
84	International Oil Co	E. E. Fogelson No. 1–25	25	30	11 W.
85	El Paso Natural Gas Co	Sunray No. 1–J (PM)	7	30	10 W.
86	LaPlata Gathering System, Inc	Riddle No. 2	23	30	10 W.
87	Delhi Oil Corp	Florence-Fed 2–10	30	30	9 W.
88	El Paso Natural Gas Co	Howell No. 4–C	18	30	8 W.
89	do	Gartner No. 8	26	30	8 W.
90	do	Manning No. 1–A	20	30	6 W.
91	do	S.J.U. 30–5 No. 29–14	14	30	5 W.
92	do	S.J.U. 30–5 No. 32–26	26	30	5 W.
93	do	S.J.U. 30–4 No. 31	14	30	4 W.
94	do	S.J.U. 30–4 No. 32	33	30	4 W.
95	Sunray DX Oil Co	Jicarilla Tr. No. 1	34	30	3 W.
96	Hayes and Zapp (1955)	Composite of 4 and 6	3	29	15 W.
97	El Paso Natural Gas Co	Foutz No. 1	12	29	15 W.
98	Sunray Mid-Continent Petroleum Co	N. M. Fed No. 1–6	15	29	14 W.
99	Humble Oil and Refining Co	Navajo L No. 3	26	29	14 W.
100	Tennessee Gas Transmission Co	USA Glenn Callow	33	29	13 W.
101	Pan American Petroleum Corp	Gallegos Can. No. 144 Unit No. 1.	16	29	12 W.
102	El Paso Natural Gas Co	Bloomfield No. 1	17	29	11 W.
103	Redfern and Herd, Inc	Nye No. 1	32	29	11 W.
104	International Oil Co	Fogelson No. 1–11	11	29	11 W.
105	Congress Oil Co	Congress No. 4	35	29	11 W.
106	LaPlata Gathering System, Inc	Houck No. 2–12	12	29	10 W.
107	H.D.H. Drilling Co	San Juan No. 2	33	29	9 W.
108	El Paso Natural Gas Co	MV Strat test No. 3	21	29	8 W.
109	do	S.J.U. 29–7 No. 65	22	29	7 W.
110	Pacific NW Pipeline Corp	S.J.U. 29–6 Mesa 20–8	8	29	6 W.
111	El Paso Natural Gas Co	S.J.U. 29–5 No. 13–30	30	29	5 W.
112	do	S.J.U. 29–5 No. 32–29 (MD)	29	29	5 W.
113	do	S.J.U. 29–5 No. 48–15	15	29	5 W.
114	do	S.J.U. 29–4 No. 14–31	31	29	4 W.
115	do	S.J.U. 29–4 No. 16–36	36	29	4 W.
116	Pacific NW Pipeline Corp	Jic. Ind. A–2	30	29	3 W.

See footnote at end of table.

TABLE 3.—*Wells and measured sections used for plotting coal resources*—Continued

Number on pl. 3	Published reference or company	Measured section or well name	Location Sec.	T. N.	R.
	New Mexico—Continued				
117	Phillips Petroleum Co	Indian D No. 1	21	29	3 W.
118	Smith Drilling Co	Jic. S-1	19	29	2 W.
119	Aztec Oil and Gas Co	Stinking Lake No. 1	35	29	1 W.
120	Bauer and Reeside (1921)	Composite of 161–163 (Ojo Alamo Arroyo).	30	28	[1] 15 W.
121	Floyd J. Ray	Cole No. 1	22	28	15 W.
122	Sunray DX Oil Co	Gulf-Navajo No. 1	21	28	14 W.
123	British-American Oil Producing Co	Scott D No. 1	20	28	13 W.
124	Pan American Petroleum Corp	Gallegos Cany. No. 116	24	28	13 W.
125	Sunray DX Oil Co	Gallegos Cany. No. 127	21	28	12 W.
126	Pan American Petroleum Corp	Gallegos Cany. No. 125	24	28	12 W.
127	Redfern and Herd, Inc	Lucerne "C" No. 1	21	28	11 W.
128	Angel Peak Oil Co	Angel Peak No. 20–B	24	28	11 W.
129	Pan American Petroleum Corp	J. C. Davidson No. G–1	21	28	10 W.
130	El Paso Natural Gas Co	Michener No. 4–A (PM)	28	28	9 W.
131	do	Bolack No. 3–B (PM)	33	28	8 W.
132	do	S.J.U. 28–7 No. 73 (PM)	28	28	7 W.
133	do	S.J.U. 28–6 No. 76	23	28	6 W.
134	do	S.J.U. 28–5 No. 32	20	28	5 W.
135	do	S.J.U. 28–5 No. 13	9	28	5 W.
136	do	S.J.U. 28–5 No. 25	13	28	5 W.
137	do	S.J.U. 28–4 No. 14–29	29	28	4 W.
138	Pacific NW Pipeline Corp	Jicarilla L No. 2	16	28	3 W.
139	Skelly Oil Co	Jicarilla No. 1–A	3	28	2 W.
140	Gulf Oil Corp	Jicarilla 298 No. 1	10	28	1 W.
141	J. S. Hinds and J. E. Fassett	Unpub. outcrop data		28	1 W.
142	Bauer and Reeside (1921)	Composite of 183–186	2	27	[1] 16 W.
143	do	Composite of 201–205	22	27	[1] 16 W.
144	Davis Oil Co	Budd-Navajo No. 1	17	27	15 W.
145	William Callaway	Navajo No. 1	14	27	15 W.
146	Miami Oil Producers, Inc	Ojo Alamo No. 1	14	27	14 W.
147	Royal Development Co	Ojo Amarilla No. 2	6	27	13 W.
148	Sunray DX Oil Co	Hoska-ne-nos-wot No. 1	22	27	13 W.
149	Stanolind Oil and Gas Co	USA E. H. Newman No. 1	31	27	13 W.
150	Sunray Mid Continent Co	Fed. J. No. 1	35	27	13 W.
151	Southwest Production Co	Thompson Fed No. 2	10	27	12 W.
152	Tenneco Oil Co	Watson Unit No. 1 "A"	21	27	12 W.
153	Texaco Inc	Navajo "AA" No. 1	19	27	11 W.
154	British-American Oil Producing Co	Scott No. 8	22	27	11 W.
155	Tennessee Gas Transmission Co	Bolack Gas Unit A No. 1	2	27	11 W.
156	Stanolind Oil and Gas Co	Huerfano No. 6	31	27	10 W.
157	Pan American Petroleum Corp	J. C. Gordon No. 2	22	27	10 W.
158	El Paso Natural Gas Co	Lodewick No. 8	19	27	9 W.
159	J. Glenn Turner (for Turner-Webb)	Huerfanito No. 43–22	22	27	9 W.
160	Southern Union Gas Co	Navajo No. 3–B	19	27	8 W.
161	El Paso Natural Gas Co	Bolack No. 9 (PM)	31	27	8 W.
162	do	S.J.U. 28–7 No. 98 (MD)	29	27	7 W.
163	do	S.J.U. 28–7 No. 93 (PM)	9	27	7 W.
164	do	S.J.U. 28–7 No. 64	22	27	7 W.
165	do	Rincon No. 97 (PM)	18	27	6 W.
166	do	S.J.U. 28–6 No. 23	9	27	6 W.
167	do	S.J.U. 27–5 No. 19	20	27	5 W.
168	do	S.J.U. 27–5 No. 21	3	27	5 W.
169	do	S.J.U. 27–5 No. 33	26	27	5 W.
170	do	S.J.U. 27–4 No. 16 (MD)	17	27	4 W.
171	do	S.J.U. 27–4 No. 17 (PM)	29	27	4 W.
172	Phillips Petroleum Co	Indian "C" No. 1	20	27	3 W.
173	Magnolia Petroleum Co	Jicarilla "G" No. 2	25	27	3 W.
174	Northwest Production Corp	NE No. 1–16	16	27	2 W.
175	Magnolia Petroleum Co	Jicarilla No. 1	20	27	2 W.
176	J. S. Hinds and J. E. Fassett	Unpub. outcrop data		27	1 W.
177	Bauer and Reeside (1921)	Composite of 239–242 and 250 (Pina Veta China Arroyo).		26	[1] 16 W.
178	do	Composite of 277, 279, 281, 282, 289, 301 (Klaychin Arroyo).		26	16 W.
179	Shell Oil Co	Burnham No. 1	14	26	15 W.
180	British-American Oil Producing Co	Navajo No. 1	15	28	14 W.
181	Skelly Oil Co	A. L. Duff No. 13	18	26	13 W.
182	Benson-Montin-Greer Drilling Corp	Foster No. 4	15	26	13 W.
183	El Paso Natural Gas Co	Sullivan No. 1–C	17	26	12 W.
184	do	Nelson No. 1–A	9	26	12 W.

See footnote at end of table.

TABLE 3.—*Wells and measured sections used for plotting coal resources*—Continued

Number on pl. 3	Published reference or company	Measured section or well name	Location Sec.	T. N.	R.
		New Mexico—Continued			
185	Skelly Oil Co	Navajo D No. 1	13	26	12 W.
186	Pan American Petroleum Corp	O. H. Randel No. 4	15	26	11 W.
187	El Paso Natural Gas Co	Huerfano No. 104	17	26	10 W.
188	do	Huerfano No. 92	7	26	9 W.
189	Turner-Webb	Ballard 11–15	15	26	9 W.
190	Southern Union Gas Co	Newsome No. 1–A	15	26	8 W.
191	El Paso Natural Gas Co	Hamilton State No. 7	32	26	7 W.
192	Caulkins Oil Co	Breech No. 307 (MD)	13	26	7 W.
193	El Paso Natural Gas Co	Johnson State No. 1	32	26	6 W.
194	Northwest Production Corp	West No. 1–7	7	26	5 W.
195	do	Indian W No. 2–5	5	26	5 W.
196	Tenneco Oil Co	Jicarilla B No. 5	21	26	5 W.
197	Southern Union Gas Co	Jicarilla No. 2–H	17	26	4 W.
198	do	Jicarilla No. 2–A	14	26	4 W.
199	Magnolia Petroleum Co	Jicarilla D No. 2	14	26	3 W.
200	Northwest Production Corp	Jicarilla E No. 3–34	34	26	3 W.
201	Cabot Carbon Co	Humble Fed. B No. 1	16	26	2 W.
202	Bolack, Greer, et al	Bolack No. 1	9	26	1 W.
203	J. S. Hinds and J. E. Fassett	Unpub. outcrop data		26	1 E.
204	Bauer and Reeside (1921)	Composite of 338–340, 349, 350 (Brimhall Wash).		25	16 W.
205	Amerada Petroleum Corp	Navajo T. R. No. 19–1	21	25	14 W.
206	Gulf Oil Corp	Pinabete Navajo No. 1	3	25	14 W.
207	F. R. Anderson	Federal No. 11–18	18	25	13 W.
208	British-American Oil Producing Co	Ross No. 2	24	25	13 W.
209	Shell Oil Co	Govt. No. 41–21	21	25	12 W.
210	do	Bisti Wtr. Well W No. 1	24	25	12 W.
211	do	Carson No. 3	7	25	11 W.
212	do	Govt. A No. 21–22	22	25	11 W.
213	El Paso Natural Gas Co	McKee No. 1	1	25	11 W.
214	Wellshire Development Co	Ma-Ga-El No. 2	19	25	10 W.
215	El Paso Natural Gas Co	Brookhaven No. 3–A	29	25	10 W.
216	Consolidated Oil and Gas, Inc	Sunshine No. 1–13	13	25	10 W.
217	M. B. Rudman	Federal No. 21–1	21	25	9 W.
218	Texas National Petroleum Co	Govt. No. 1–25–9	1	25	9 W.
219	Davis Oil Co	Govt.-Mead No. 1	24	25	9 W.
220	El Paso Natural Gas Co	Quitzau No. 13	15	25	8 W.
221	do	Harvey State No. 2	16	25	7 W.
222	Superior Oil Co	Hightower-Govt. No. 1–24	24	25	7 W.
223	El Paso Natural Gas Co	Harvey State No. 11	16	25	6 W.
224	Kay Kimbell	Salazar-Federal No. 1–22	22	25	6 W.
225	Humble Oil and Refining Co	Jicarilla J–4	6	25	5 W.
226	Amerada Petroleum Corp	Jicarilla Apache No. F–10	16	25	5 W.
227	El Paso Natural Gas Co	Jicarilla No. 67–5	29	25	5 W.
228	Amerada Petroleum Corp	Jic-Apache A No. 5	25	25	5 W.
229	El Paso Natural Gas Co	Jicarilla No. 2–C	15	25	4 W.
230	Skelly Oil Co	C. W. Roberts No. 3	18	25	3 W.
231	Southern Union Gas Co	Lebow No. 1	14	25	3 W.
232	El Paso Natural Gas Co	Federal No. 15	3	25	2 W.
233	San Juan Gas Corp	Federal 27–IC	27	25	2 W.
234	Skelly Oil Co	N. M. Fed. "E" No. 1	18	25	1 W.
235	Bolack-Greer, Inc	Canada Ojitos No. 1–16	16	25	1 W.
236	Mtn. States Petroleum Corp	Gavilan No. 31–1–C	31	25	1 W.
237	Bolack-Greer, et al	Bolack No. 1–14	14	25	1 W.
238	Bolack-Greer Inc	Canada Ojitos No. 1–23	23	25	1 W.
239	J. S. Hinds and J. E. Fassett	Unpub. outcrop data		25	1 E.
240	Bauer and Reeside (1921)	Composite of 360–363, 370, 375 (Medio Arroyo).		24	16 W.
241	Davis Oil Co	Perry Navajo No. 1	6	24	14 W.
242	Monsanto Chemical Co	Chaco No. 1	20	24	13 W.
243	Humble Oil and Refining Co	Tanner Unit No. 1	21	24	12 W.
244	H. I. Fanning	Vanderslice No. 1	13	24	12 W.
245	Magnolia Petroleum Co	Beamon-Fed. No. 1	29	24	11 W.
246	Phillips Petroleum Co	Gallegos No. 1	14	24	11 W.
247	Forest Oil Corp	Huerfano Fed. No. 1	13	24	10 W.
248	Gulf Oil Corp	S. Huerfano Fed. No. 1–X	15	24	9 W.
249	Exeter Drilling Co	Escrito Fed. No. 1	20	24	8 W.
250	Lemm and Maitatico	Govt. No. 1	34	24	8 W.
251	Ray Smith, Trustee	Federal No. 2	13	24	8 W.
252	Standard Oil Co. of Texas	Federal No. 1	27	24	7 W.
253	Pan American Petroleum Corp	John S. Dashko No. 1	15	24	7 W.

See footnote at end of table.

TABLE 3.—*Wells and measured sections used for plotting coal resources*—Continued

Number on pl. 3	Published reference or company	Measured section or well name	Location Sec.	T. N.	R.
		New Mexico—Continued			
254	Val R. Reese and Associates, Inc	Lybrook No. 1–19	19	24	6 W.
255	El Paso Natural Gas Co	Bolack No. 1E	35	24	6 W.
256	do	Bolack No. 1–D	13	24	6 W.
257	do	Jicarilla No. 4–A	15	24	5 W.
258	Amerada Petroleum Corp	Jicarilla Apache No. El	30	24	4 W.
259	Magnolia Petroleum Co	Jillson-Fed. No. 1	7	24	3 W.
260	El Paso Natural Gas Co	Lindrith No. 35	15	24	3 W.
261	do	Lindrith No. 30	18	24	2 W.
262	San Juan Gas Corp	Federal A No. 13	13	24	2 W.
263	Shar-Alan Oil Co	E. A. Down-Fed. No. 1	16	24	1 W.
264	Magnolia Petroleum Co	Duff-Fed. No. 1	27	24	1 W.
265	Reading and Bates, Inc	Duff No. 1	24	24	1 W.
266	J. S. Hinds and J. E. Fassett	Unpub. outcrop data	----	24	1 E.
267	Bauer and Reeside (1921)	Composite of 388–390 (Hunters Wash).	1	23	15 W.
268	do	Composite of 419, 420, 443, 432, 434, 433, 430.	23	13	14 W.
269	Humble Oil and Refining Co	Tanner Unit No. 3	5	23	12 W.
270	Bauer and Reeside (1921)	Composite of 520, 521, 524, 526, 528.	------	23	12 W.
271	Shell Oil Co	Meyer Govt. No. 3	20	23	11 W.
272	do	Meyer Govt. No. 1	14	23	11 W.
273	E. B. LaRue, Jr.	Kinebeto No. 2	17	23	10 W.
274	Great Western Drilling Co	Lucy English No. 1	25	23	10 W.
275	do	Chaco Unit No. 1	14	23	9 W.
276	do	Chaco Unit No. 3	21	23	8 W.
277	El Paso Natural Gas Co	Sapp No. 1–A	18	23	7 W.
278	Rhodes Drilling Co	Elkins Fed. No. 1	13	23	7 W.
279	S. D. Johnson	Chapman No. 1	20	23	6 W.
280	Sinclair Oil and Gas Co	Tex. Nat'l Fed. No. 1	25	23	6 W.
281	Sunray DX Oil Co	N. M. Apache No. 1	21	23	5 W.
282	Pubco Petroleum Corp	Jic. 23–5 No. 23–11	23	23	5 W.
283	San Juan Drilling Co	Vanderslice No. 1	21	23	4 W.
284	Caswell Silver	Jicarilla No. 2–S	19	23	3 W.
285	U.S. Smelting, Refining and Mining Co.	Jicarilla No. 1	7	23	3 W.
286	El Paso Natural Gas Co	Jicarilla 183–2	27	23	3 W.
287	Wagenseller and August	Mobile-Apache No. 9–P	12	23	3 W.
288	Shar-Alan Oil Co	Jicarilla "L" No. 3	15	23	2 W.
289	Magnolia Petroleum Co	Evans Fed. No. 1	18	23	1 W.
290	Shar-Alan Oil Co	Northcut No. 1	2	23	1 W.
291	Bauer and Reeside (1921)	Composite of 537, 538, 546, 541	10, 11	22	11 W.
292	E. B. LaRue, Jr	Kinebeto No. 4	9	22	10 W.
293	Bauer and Reeside (1921)	Composite of 560, 559 (Escavada Wash).	25, 26	22	10 W.
294	Great Western Drilling Co	So. Chaco No. 1	9	22	9 W.
295	Humble Oil and Refining Co	So. Chaco No. 3	23	22	9 W.
296	do	So. Chaco No. 4	10	23	8 W.
297	Northwest Production Corp	22–7 No. 1–23	23	22	7 W.
298	Plymouth Oil Co	Tomas No. 1	22	22	6 W.
299	Humble Oil and Refining Co	Jic. "B" No. 1	1	22	5 W.
300	Skelly Oil Co	Jic. "E" No. 1	8	22	4 W.
301	Exeter Drilling Co	Jicarilla Apache No. 1	28	22	4 W.
302	Bonanza Oil Co	Jicarilla No. 1	2	22	3 W.
303	Lloyd H. Smith	Jicarilla No. 32–1	32	22	2 W.
304	Shar-Alan Oil Co	Humble Dakota No. 1	21	22	2 W.
305	J. S. Hinds and J. E. Fassett	Unpub. outcrop data		22	1 W.
306	Ray McGlothlin	Federal No. 1	22	21	8 W.
307	Davis Oil Co	Govt. Co-op No. 1	20	21	7 W.
308	Kingsley-Locke Oil Co	Miles KL No. 1	21	21	6 W.
309	Shell Oil Co	Pool Four No. 1	22	21	5 W.
310	Roy Furr	Sun-Fed. No. 1	14	21	4 W.
311	Sun Oil Co	McElvain Govt. No. 1	23	21	2 W.
312	J. S. Hinds and J. E. Fassett	Unpub. outcrop data		21	1 W.
313	Dane (1936)	Measured coal sec	8	20	7 W.
314	do	do	23	20	7 W.
315	Davis Oil Co	McCollum Govt. No. 1	12	20	6 W.
316	Austral Oil Co., Inc	Salvador Toledo Heirs No. 1	23	20	5 W.
317	Atlantic Refining Co	Torreon No. 3	15	20	3 W.
318	A. N. Brown	Magnolia Fed. No. 1	8	20	2 W
319	J. S. Hinds and J. E. Fassett	Unpub. outcrop data		20	1 W.

See footnote at end of table.

TABLE 3.—*Wells and measured sections used for plotting coal resources*—Continued

Number on pl. 3	Published reference or company	Measured section or well name	Location Sec.	T. N.	R.
		New Mexico—Continued			
320	Dane (1936)	Measured coal sec	12	19	6 W.
321	do	Composite of 2, 7, 9		19	5 W.
322	J. S. Hinds and J. E. Fassett	Unpub. outcrop data	11	19	4 W.
323	do	do	7	19	3 W.
324	do	do	8	19	2 W.

[1] Projected.

The most commonly available logs for wells in the San Juan Basin are electric, induction-electric, and gamma ray–neutron (radioactivity) logs. Also available for this study were several dozen drilling-rate logs which the authors collected from various oil companies. Figure 20 illustrates the character of the response to Fruitland coal beds on an induction-electric log, a drilling-rate log, and a gamma ray–neutron log. The logs illustrated in this figure are of the lower part of the Fruitland interval at well control location 52 (pl. 3). Characteristic of the coal are high resistivity, sometimes with but usually without a spontaneous potential, a very rapid drilling rate, and low radiation intensity for both gamma ray and neutron responses.

The rapid drilling penetration rate is very distinctive of coal in the Fruitland Formation at depths of more than 1,500 feet. The drilling speeds for all rock types in the formation are rapid at shallower depths, and distinctions on the drilling-rate log are not pronounced.

The gamma ray–neutron log curves reliably identify Fruitland coal beds at any depth. Both curves are deflected far to the left on the log scale, which indicates very low radiation intensity. The gamma ray instrument measures the intensity of natural radioactivity. Natural gamma rays originate chiefly from three radioactive elements: uranium, thorium, and potassium. The combined activity of these elements in each lithology is recorded on the gamma ray log. These elements are present in very low proportions in Fruitland coal beds, and consequently, the coal beds have a very low gamma radiation intensity. The neutron log records gamma radiation which is induced by bombardment of the formations with neutrons from a radioactive source in the logging tool. The neutrons emitted by the source are captured by atoms in the formation. The capturing atom emits a powerful gamma ray which is registered by a counter in the tool. Before capture is possible, however, the fast neutrons must be slowed to thermal speed. This speed loss is caused by collision of the neutrons with atoms in the formation. Carbon and hydrogen atoms are among the most effective in slowing and capturing the neutrons. The high concentration of carbon and hydrogen atoms in coal results in the capture of most of the neutrons within inches of the source. The counter in most logging tools is 12 or more inches above the source and is shielded from the source by a tungsten shield. As a result, the gamma rays emitted by capture of neutrons near the source never reach the counter and are not registered. High carbon and hydrogen content in the rock near the source results in a very low intensity of neutrons penetrating deeper into the formation and so results in a low neutron-gamma counting rate. Because coal consists primarily of carbon and hydrogen, it is readily identifiable on neutron logs of the Fruitland Formation by characteristically very low radiation intensity readings.

The electric and induction-electric logging instruments measure the electrical resistivity of the rocks and the differences in their spontaneous potentials. Coal is normally highly resistive to electrical currents and is characterized by a marked deflection of the resistivity curves to the right on the electric logs. In the northern half of the San Juan Basin, the Fruitland Formation contains numerous highly resistive beds, probably compact calcite-cemented sandstone or siltstone, that have electrical properties similar to those of the coal beds (for example, the bed between 3,290 and 3,300 ft in fig. 20). Determination of coal from electric logs in this part of the basin, therefore, must be supported by drilling-rate logs or radioactivity logs, either of which can be used to differentiate other high resistivity beds from coal beds. In the southern and western parts of the basin, coal is normally the only highly resistive rock in the formation, and the coal beds may be identified directly from the electric logs with a high degree of accuracy (fig. 2).

Normally, the Fruitland coal beds do not cause a marked deflection of the spontaneous-potential curves. Such deflections may occur, however, where the coal is fractured and contains water or gas or where partings of other rock types are present within the coal beds. Thus, spontaneous-potential variations are of limited value for coal-bed identification.

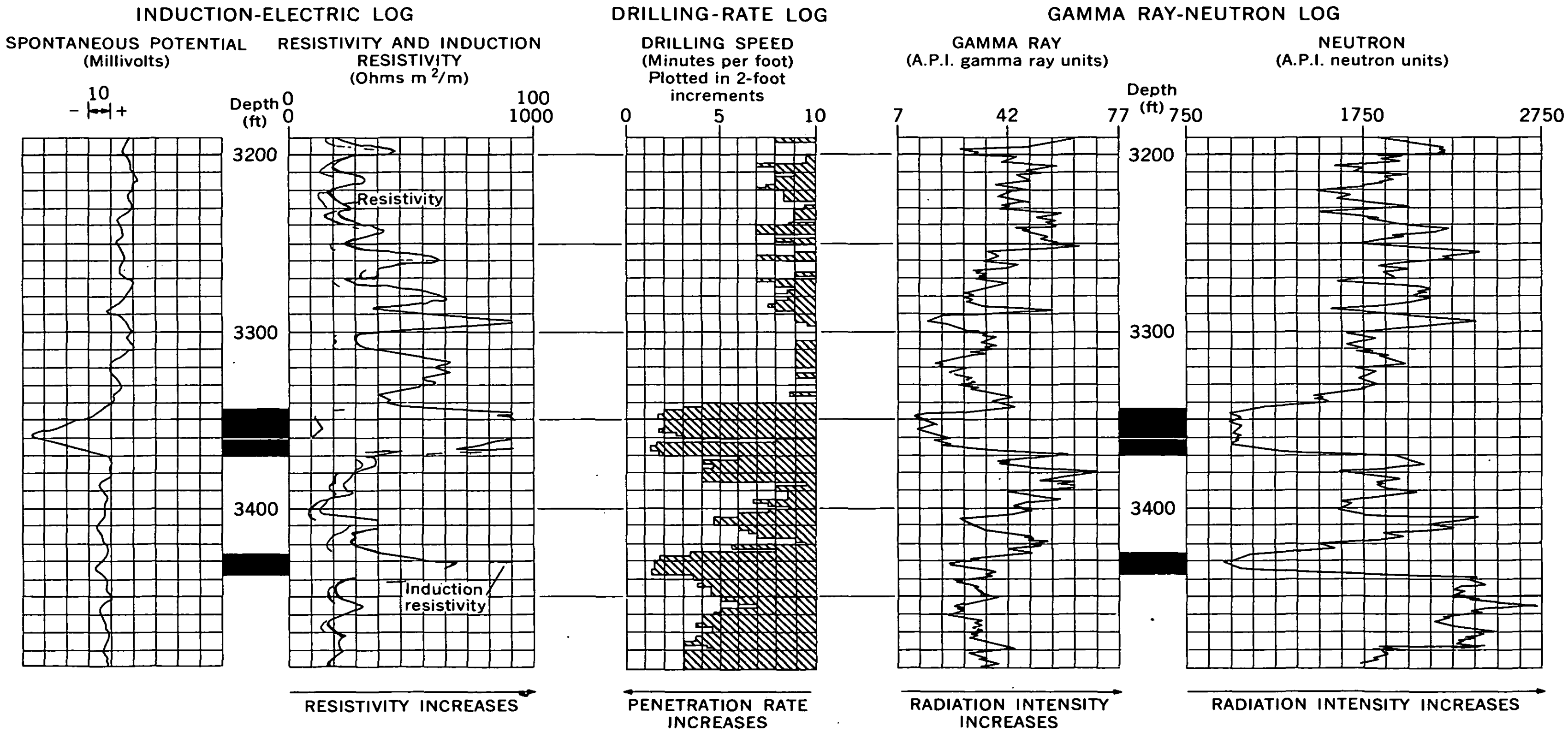


FIGURE 20.—Induction-electric, drilling-rate, and radioactivity logs through the lower part of the Fruitland Formation at well control location 52, showing characteristics of the response to coal.

Other types of well logs, particularly acoustic (sonic) logs and focused varieties of electric logs (micrologand microlaterolog of Schlumberger, FoRxo log and guard log of Welex), are useful in delineating coal beds. By the use of these logs, the boundaries of the coal beds can be established within 6 or less inches, and partings of 6 or less inches in the coal beds can be detected. Logs of these types through the Fruitland Formation, however, are available for only a small number of wells in the San Juan Basin.

Conventional electric logs are run with sondes in which the shortest electrode spacing is normally 16 inches. Coal beds thinner than the 16-inch spacing are not recorded definitively on the logs, and for this reason such thin beds were ignored in this study except in areas where they are the only coal present or where they constitute a significant part of the total coal. Partings as thin as 12 inches are usually detectable in the coal beds by use of conventional logs. Thinner partings in a predominantly coal sequence generally can not be identified without the aid of one of the more detailed logs mentioned above. Therefore, some of the coal beds illustrated undoubtedly contain partings as much as 12 inches thick which are not shown. Where thin partings are numerous, however, they tend to reduce the resistivity readings recorded through a coal section. In a section of thinly interbedded coal and partings, only those coal beds thicker than the spacing of the electrodes on the logging sonde are clearly recorded, and only such clearly recorded beds were used. The authors believe, therefore, that only a few of the coal sections shown (pl. 3) contain as much as 10 percent of interbedded thin partings included in the coal measurements. The surface sections from the literature were generalized to conform with the format of the log interpretations. Most thin partings less than 12 inches thick were omitted from the surface sections.

Figure 21 is an isopach map that shows the total thickness of coal in the Fruitland Formation. The map shows that, in spite of the extreme lenticularity of individual beds and the random occurrence of most of the higher coal beds, clearly defined patterns of distribution of the total coal in the formation are visible. In the southwest corner of the basin, where the oldest preserved Fruitland coals are exposed in outcrop, an area centered around T. 23 N., R. 12 W., shows the total coal thickness exceeding 30 feet, and an irregular area around this shows total coal thicknesses of 20–30 feet. The area of relatively thick coal is adjacent to the southwesternmost of the two major stratigraphic rises in the position of the Pictured Cliffs Sandstone previously discussed. Stratigraphic cross sections *A–A′*, *B–B′*, *C–C′*, and *F–F′* of plate 2 illustrate these stratigraphic rises.

Southeastward along the outcrop from the area of thick coal, a narrow band (fig. 21) contains total measured coal thicknesses of less than 10 feet. This area is anomalous in that it occurs along the same trend as the thicker beds to the northwest. The delineation of the narrow band is based on scattered measured sections of coal zones taken from Dane (1936). The coal beds along this stretch of outcrop are commonly burned or covered, and good exposures are rare. The apparent lack of thick coal in this area is probably due to this surface burning and poor exposure. Future exploration by drilling may show the presence of considerably more coal than is currently shown in this area.

Northeastward from the areas just discussed, a belt 10–20 miles wide contains total coal thicknesses of less than 20 feet and in many places of less than 10 feet. This belt extends across the southwest third of the basin and represents a time of relatively uninterrupted regression of the coastline, although many minor oscillations occurred. In general, the width of the belt is greater in the southeastern part of the basin, and the cumulative thickness of coal in the southeastern part of the belt is much less than in the northwest. This indicates that withdrawal of the sea was somewhat more rapid in the southeast than in the northwest at that time, affording less time in the southeast for the accumulation of organic material in the coastal swamps. (See p. 15.) The total thickness of the coals in the northwestern part of this belt is about double that of the southeastern part, and the width of the belt is about half as great in the northwest. Isolated areas within the northwestern part, however, have total coal thicknesses of less than 10 feet and more than 20 feet. These anomalies probably reflect local paleotopographic features of the coastal area. The areas of thin total coal may have been areas of a few feet of local relief, and the thicker coal patches may represent local depressions.

Northeastward from the belt of thin total coal, the coal thickness increases steadily across the basin for the next 20 miles. The cumulative coal thickness reaches a maximum of more than 70 feet in a northwest-trending band near the central part of the basin (fig. 21). The northeast limits of this thick buildup are defined by the trend of the northeasternmost and largest of the two principal stratigraphic rises of the Pictured Cliffs Sandstone. This rise extends generally along a line from T. 25 N., R. 1 W., in New Mexico through T. 34 N., Rs. 9 and 10 W., in Colorado. In the southeast, the extensive swamps of this zone appear to have ended near the base of a well-drained highland. The uplift which caused the highland was probably centered near the area of the present Nacimiento Mountains, but some uplift at the time may have occurred along the monocline which forms the east rim of the San Juan Basin. Slight uplift

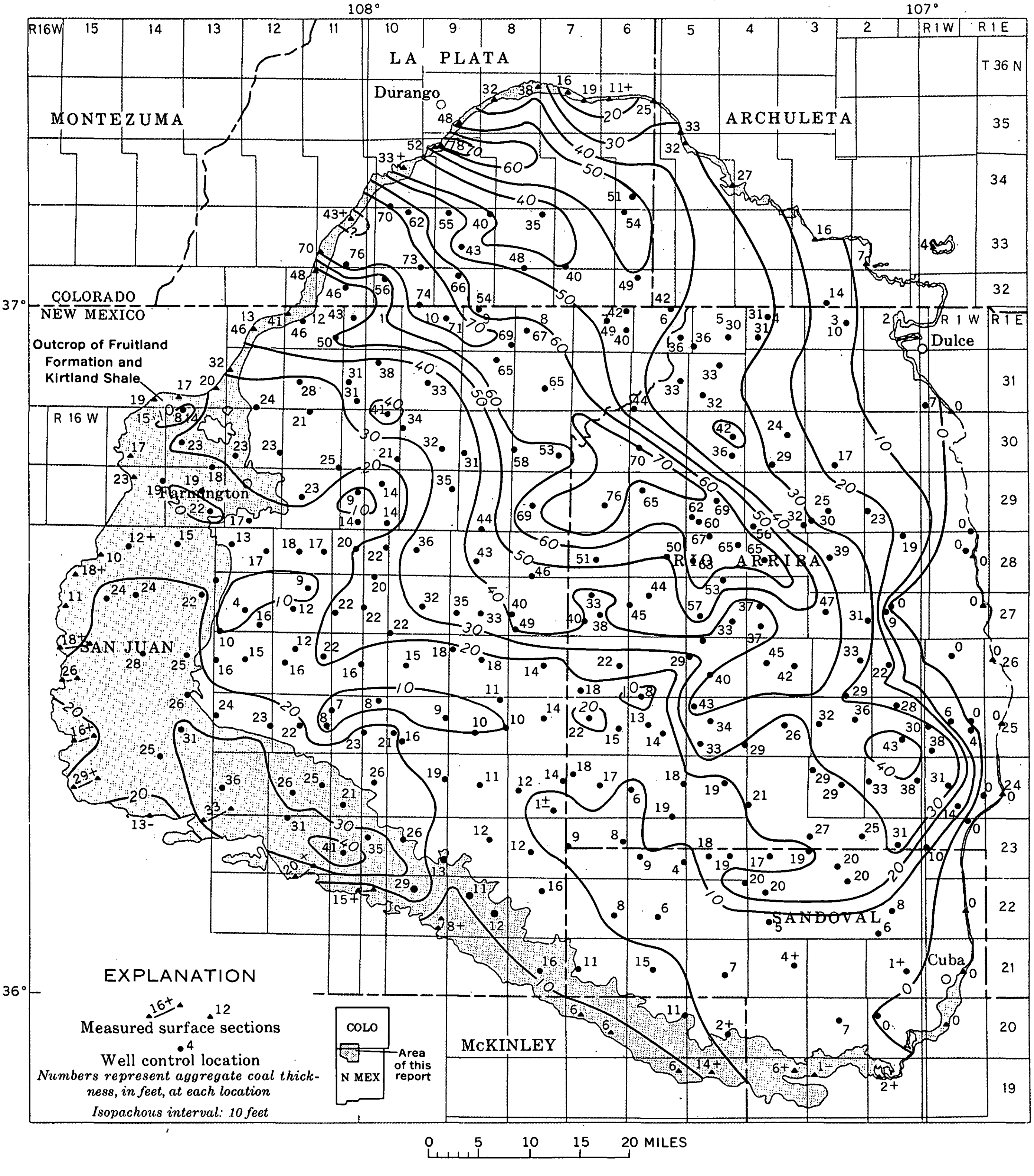


FIGURE 21.—Isopach map of total thickness of coal in the Fruitland Formation.

along the monocline during Fruitland deposition explains the abrupt southeastward termination of the thick coal deposits and the absence of significant Fruitland coal beds in a narrow strip along the east side of the basin (fig. 21).

After the prolonged oscillation of the strand line, which caused the buildup of the Fruitland Formation's most extensive thick coal beds, the sea again receded northeastward. Withdrawal was intermittent, and a second area of coal totaling more than 50 feet in cumulative thickness developed in the Colorado part of the basin while thicknesses of less than 50 feet were accumulating in the New Mexico part. As the receding shoreline approached the northeast limits of the present basin, its rate of withdrawal accelerated. The total coal thicknesses decrease abruptly in the extreme northeastern part of the basin, as exemplified by the cumulative 4 feet of coal in the Klutter Mountain outlier in T. 33 N., R. 1 W., in Colorado.

In summary, the coal in the Fruitland Formation is distributed in a series of northwest-trending belts across the San Juan Basin. The thicker coal zones are adjacent to and southwest of stratigraphic rises in the position of the Pictured Cliffs Sandstone. Along the east edge of the basin, uplift prevented the accumulation and preservation of the organic debris necessary for coal formation, and a band from 2 to 10 miles wide is barren of significant coal beds. To the north and northwest, the coals are truncated by the present erosion surface along the monocline that bounds the San Juan structural basin. To the south and southwest, thinning of the Lewis Shale indicates that within a few miles of the present outcrop the beds of the Fruitland Formation formerly merged with the coal measures of the Menefee Formation of the Mesaverde Group. The intervening Lewis Shale wedged out, and the Pictured Cliffs Sandstone merged with the Cliff House Sandstone of the Mesaverde Group before in turn wedging out into combined Menefee and Fruitland rocks.

Figure 22 is an isopach map that records at each control location the thickest individual coal beds that contain no partings in excess of 3 feet thick. This map, in general, reflects the pattern of the total coal thickness map (fig. 21). The areas of thickest total coal deposition generally contain the thickest individual beds. It must be emphasized that the measurements recorded on this map are not necessarily of the same or correlative coal beds; they represent the particular bed that reaches the maximum thickness at the point of measurement. Although the thickest beds may be continuous between two or three control points, they ultimately split, thin, or pinch out, and other beds thicken or merge and become dominant. Many of the local variations on this map are due to the separation of beds beyond the arbitrary 3-foot limit on partings. This is unavoidable because any other choice of limit on included parting thickness would give similar results.

Areas of thick total coal generally contain several thick beds in two or more major zones and a few thin, scattered beds. The thickest beds are usually in the lowest zone near the bottom of the formation, but in some places beds in higher zones are dominant. In most areas of thin total coal, only a single major bed or zone is present, and it is nearly always in the lowest part of the formation and in most places lies directly above the Pictured Cliffs Sandstone. In such areas the regression of the sea was relatively rapid, and the encroachment of the flood-plain environment followed swiftly. The details of the vertical distribution of the coal beds are described in the next section.

CORRELATION

Because of environmental variations which controlled deposition and preservation, individual Fruitland coal beds are extremely lenticular, and reliable correlations can be made only by direct tracing along the outcrop or by evaluation of data from closely spaced drill holes. Efforts at surface tracing have been generally unsatisfactory in most areas owing to cover, burning of the beds, or complex stratigraphic intertonguing. Along the northwest edge of the basin, Barnes, Baltz, and Hayes (1954) found that

> Individual beds of coal are lenticular and cannot be followed in the Red Mesa area for more than 2 or 3 miles, but the basal coal sequence as a whole is fairly continuous, except where it pinches out against intertonguing beds of the Pictured Cliffs sandstone.

In the Durango area, Zapp (1949) reported,

> It was found, however, that the thick growth of vegetation over most of the area makes visual tracing of coal beds or associated nonmarine strata impossible, and natural and artificial exposures are too few to permit interpolation. * * * It appears probable that core drilling with spacing of not more than half a mile will be necessary to establish the position of all the coal beds of commercial importance.

Zapp further stated:

> The Fruitland formation at most places contains at least three coal zones, with the thickest zone in the lower 100 feet of the formation and usually at or near the base. The "Carbonero" bed near Carbon Junction south of Durango consists of about 80 feet of thin coal beds separated by numerous thin partings and is the thickest coal deposit thus far reported in the San Juan Basin. Beginning about a quarter of a mile northeast of Carbon Junction, this bed is split into two widely separated thinner beds by a tongue of the Pictured Cliffs sandstone. To the southwest it thins as various portions of the bed are replaced by nonmarine sandstone and shale of the Fruitland formation.

In his graphic section of the coal at Carbon Junction, Zapp showed a 1-foot-thick bed of bony coal on top of the Pictured Cliffs Sandstone, overlain by about 3 feet of sandy shale and 33 feet of coal containing many thin

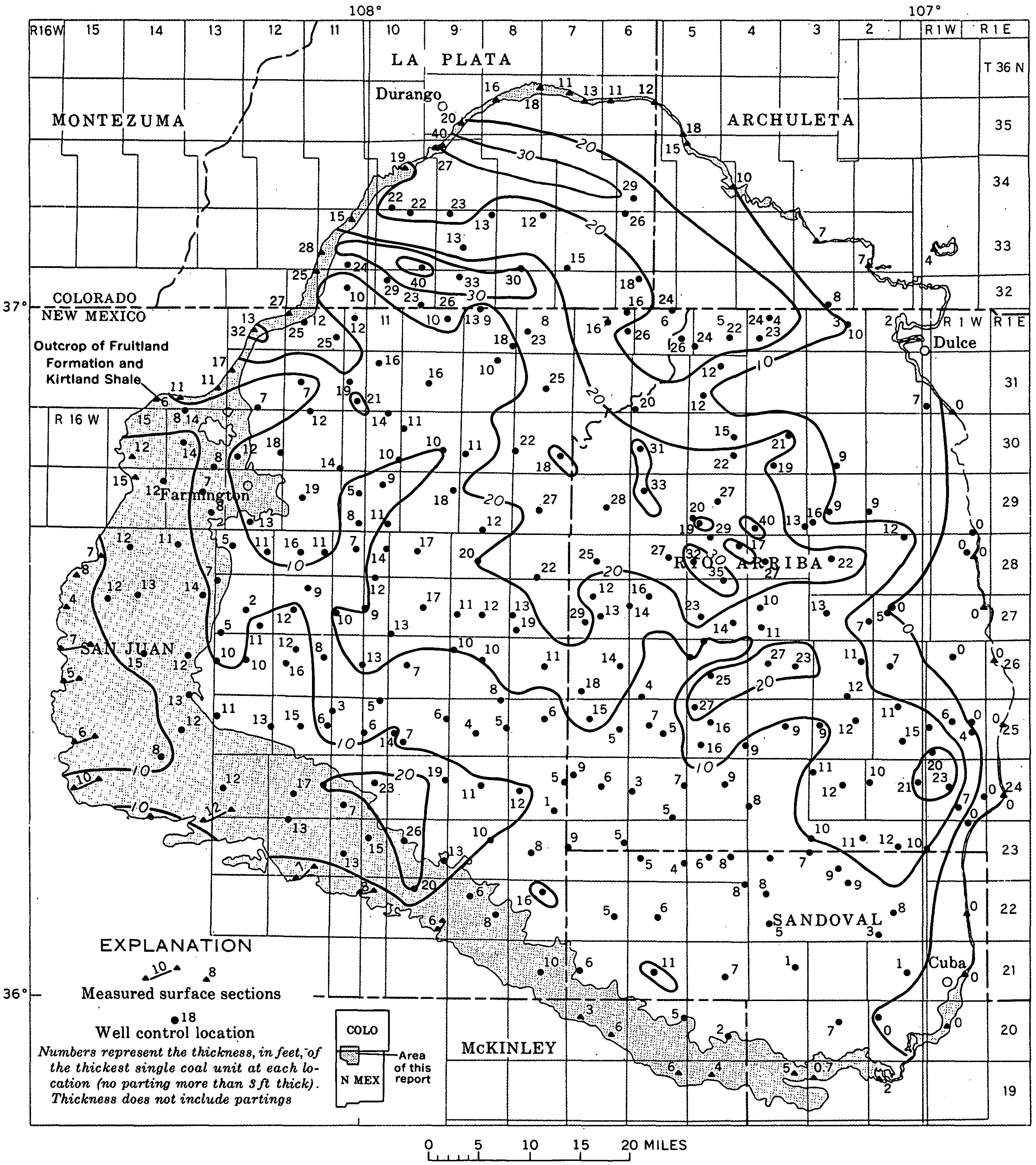


FIGURE 22.—Isopach map of the thickest individual coal units (no parting in excess of 3 ft thick) in the Fruitland Formation.

partings. About 5 feet of siltstone and sandstone overlie the 33-foot bed and separate it from an overlying coal bed about 40 feet thick. The number and thickness of partings in the 40-foot bed were not shown. Zapp showed an additional 5 feet of coal that contained two 6-inch partings approximately 150 feet above the 40-foot bed. The total coal thickness at Carbon Junction is, thus, about 78 feet if the basal 1-foot bed of bony coal and the thin partings are disregarded. This is the thickest total coal section reported in the basin (No. 12 on pl. 3). The next thickest sections were recorded at coal control locations No. 18, T. 33 N., R. 11 W., Colo., and No. 109, T. 29 N., R. 7 W., N. Mex. (pl. 3). At location 18, 76 feet of coal is present in two major zones and in three other separate beds. At location 109, 76 feet of coal is distributed among several beds in three major zones. At the Carbon Junction location, 73 feet of coal that contains a 5-foot parting near the middle is in one major unit. No occurrence comparable to this coal unit was found in any other part of the basin. The abrupt lateral facies change of the basin's thickest coal bed as described by Zapp illustrates the difficulties encountered in attempted correlations of individual beds in the Fruitland Formation.

Barnes (1953), reporting on the Fruitland coals of the Ignacio area of Colorado, stated: "Few individual coal beds have been correlated between measured sections because of the uncertainties caused by the lenticularity of the strata of the Fruitland formation and the scarcity of exposures." He did, however, correlate one 13-foot coal bed for 2½ miles. In their study of southern Archuleta County, Colo., in the extreme northeastern part of the basin, Wood, Kelley, and MacAlpin (1948) did not map or correlate coal beds.

In the Barker Dome–Fruitland area of New Mexico on the northwest edge of the basin, Hayes and Zapp (1955) indicated that one coal bed is correlative for more than 15 miles, although midway in its course it crosses one of four significant stratigraphic rises of the Pictured Cliffs Sandstone that they mapped in this area. This particular rise on their coal sections displaces the Pictured Cliffs Sandstone approximately 100 feet upward in the section. They found that in the area covered by their map, "The Fruitland formation contains at least 16 coal beds with thicknesses of 30 inches or more, though not more than 4 beds are present at any one locality." Bauer and Reeside (1921) had apparently traced the main bed of Hayes and Zapp in their study of the coal in San Juan County, N. Mex. Although they were able to trace this and other beds for some miles in the northern part of San Juan County, they recognized that "extensive correlations are doubtful south of the San Juan [River]. In the extreme southern part of the field the coal beds decrease in number, thickness, and extent * * *." This statement qualifies their maps, which show numerous isolated coal outcrops connected by dashed lines, whereas many others extend for only a short distance. It is noted, however, that the beds studied by Bauer and Reeside crop out over a large area nearly parallel to the northwest depositional trend of the coal zones, and thus correlation should be more reliable than in areas where the present outcrop crosses the depositional trend, as is the case in the northern part of the basin in Colorado.

Dane (1936) commented on the excessive lenticularity of the coal in the southern and southeastern parts of the basin. In the extreme southeast corner of the basin, Fassett (1966) traced a 4-foot-thick coal bed for more than 4 miles around Mesa Portales. The bed pinches out in sec. 35, T. 20 N., R. 2 W., and, except for a 1.5-foot-thick coal bed which crops out near the center of sec. 20, T. 24 N., R. 1 E., is the last known occurrence of outcropping coal in the Fruitland Formation along the east side of the basin between this point and T. 31 N., R. 1 W.

The present study of Fruitland coal beds was done mainly through the use of logs from drill holes spaced from 2 to more than 6 miles apart throughout the area of the San Juan Basin. The same stratigraphic conditions found on the outcrop by previous writers were found throughout the basin in the subsurface. Correlation of coal beds at angles to the generally northwest trend of deposition is complicated because the beds wedge out abruptly northeastward against intertonguing sandstones of the Pictured Cliffs Sandstone; correlation to the southwest is difficult because the beds are first split by and then grade into nonmarine sandstone and shale, which was deposited behind and along the trailing edge of the Fruitland swamps. These transitions generally take place within a distance of only a few miles. Correlation of the coal beds in a northwest direction is more reliable because this is the trend of the elongate axis of the coal bodies and the beds retain their identity farther in this direction. Between widely spaced control points, however, correlation along the northwest trend has proved only slightly more feasible than correlation at angles to it. Some of the variables that disrupt the continuity of the coal beds along their depositional trend are: (1) Channel sandstone deposits and associated stream deposits filled the channels of the streams which flowed across the coal swamps to the coast. Some streams were contemporaneous with adjacent swamps, and the coal beds thin toward the channels by lateral facies change. The horizontal separation of time-equivalent coal beds adjacent to such channels may be several thousand feet. Other streams eroded previously deposited material, and the channel filling causes a disruption of only a few hundred feet in the lateral continuity of the coal. (2) Scattered areas among the swamps that had a few feet of topographic relief were apparently above the swamp water level and were too well drained to allow preservation of organic material. These may have been localities of buried beach dunes or bars or the preserved levees and bars of abandoned stream channels. The coal beds thin and split over these areas or terminate on their flanks. (3) At other places among the coastal swamps, fine clastics filled lakes and lagoons. Such areas may be reflected in the present sediments where coal beds disappear laterally into a sequence of carbonaceous mudstone and shale. (4) The environment of the flood plain extended irregularly far into the swamplands, causing wide gaps in the continuity of some of the coal beds, particularly those above the basal part of the formation. (5) Irregularities of the shoreline probably caused indentations along the seaward edge of the swamp zone. (6) Differential compaction of sediments during diagenesis has probably caused some contemporaneous coal beds to occupy different stratigraphic positions, whereas beds of different ages may lie in the same stratigraphic plane.

Correlation of Fruitland coal beds by comparing their stratigraphic position is subject to considerable error. This is shown by comparison of coal sections 109–118 (pl. 3). Sections 109 and 118 are 26 miles apart in an east-west direction. The graphic columns show that sections 109–118 each contain a thick coal unit that rests directly on the Pictured Cliffs Sandstone. By comparison of stratigraphic position, these coals would seem correlative. However, examination of figure 7 shows that the stratigraphic position of the coal at section 118 is at least 300 feet higher than the coal at section 109 owing to upward stratigraphic migration of the Pictured Cliffs. Thus, some or none of the basal coals shown in the graphic illustrations between sections 109 and 118 may be correlative between adjacent locations, but such correlation is not certain and if attempted over distances of more than a few miles is impossible.

In summary, the band of coastal swamps was generally continuous along the Late Cretaceous shoreline, but individual swamps were limited in area and separated from one another by the paleogeographic features described above. These features shifted laterally through time, causing the coal swamps to migrate over all parts of the coastal area. The result was an averaging of the total amount of coal deposited in belts or zones paralleling the shore so that the total coal thickness was due to the oscillations of the shoreline rather than to the transitory environments of the swampland. The Fruitland coal deposits as a whole form a decipherable pattern, but few individual coal beds are traceable at the surface or in the subsurface for more than a few miles. Dependable correlation of the coal beds requires control spacing of not more than 1 or 2 miles and even less spacing in areas of very abrupt facies change. Because of the spacing of control points used in this study, individual coal beds have not been correlated. The reader may make tentative correlations from the graphic columns on plate 3, but he is cautioned that such correlations can be only suggestive. If he chooses to correlate zones, rather than beds, he is reminded that, although a thick coal zone generally lies above the Pictured Cliffs Sandstone, the age and stratigraphic position of the Pictured Cliffs change progressively across the basin.

CHARACTER AND QUALITY

The physical properties of Fruitland coal have been described in numerous reports. In summary, the coal is hard, brittle, and black; it decomposes, or slacks, on exposure to weather and cannot be stored for long periods. It contains, in places, many woody charcoal fragments and small lumps of fossil resin. Iron sulfide, in the form of small grains and veinlets of pyrite and marcasite (FeS_2), has been observed by the authors in many well cuttings and cores.

Table 4 shows analyses of 67 samples of Fruitland coal taken from 65 locations in the San Juan Basin. The locations are shown and numbered in figure 23. Locations 19, 59, and 61 are coal core holes; locations 62 through 65 are surface outcrops; the remainder are well locations. An attempt was made to sample the lowest coal bed or zone at each location. Two separate zones were sampled at locations 14 and 23. At outcrop locations (62–65) only one bed more than 1 foot thick is present.

The samples from the well locations were obtained by collecting rotary-drill cuttings from shale shakers as the cuttings from coal zones were discharged from the borehole. After collection, the cuttings were thoroughly mixed to insure representative sampling and then were washed at the well site to remove drilling mud. The samples were dried by a cool forced-air current and floated in carbon tetrachloride (specific gravity 1.59) to remove rock cuttings and cavings picked up by the sample in the mud column during circulation (the specific gravity of coal ranges generally from 1.2 to 1.5). Any shale or sand partings and carbonaceous material with a specific gravity greater than 1.59 were removed through flotation. The lighter fraction from the floating process was sent to the U.S. Bureau of Mines laboratory at Pittsburgh, Pa., for analysis. The resultant Btu values are maximum figures for the heating values of the coals sampled. With the exception of the sample from location 59, the samples from the coal core holes and outcrops were

TABLE 4.—*Analyses of coal samples from the Fruitland Formation*

[Form of analysis: A, as received; B, moisture free; C, moisture and ash free]

Sampled location in fig. 23	U.S. Bureau Mines lab. No.	Well or other source	Location: Section	T.N.	R.W.	Approximate depth interval of sample (ft.)	Form of analysis	Proximate: Moisture	Volatile matter	Fixed carbon	Ash	Sulfur	Heating value (Btu)	Remarks
						Colorado								
1	H-38041	El Paso Nat. Gas Bondad 34-10 No. 3X.	36	34	10	2,406-2,438	A	0.9	20.8	51.7	26.6	0.8	11,230	
							B	....	21.0	52.2	26.8	.8	11,330	
							C	....	28.7	71.3	....	1.1	15,480	
2	H-55350	Mobil Oil Schofield Auto 31X-5.	NE¼ 5	32	7	2,656-2,669	A	.8	21.5	56.4	21.3	.7	12,140	
							B	....	21.6	56.9	21.5	.7	12,240	
							C	....	27.6	72.4	....	.8	15,600	
3	H-46452	Atlantic Refn. Southern Ute 32-10 No. 15-1.	NE¼ 15	32	10	2,825-2,890	A	2.3	23.6	54.6	19.5	.7	12,070	
							B	....	24.2	55.9	19.9	.7	12,360	
							C	....	30.2	69.8	....	.9	15,440	
						New Mexico								
4	H-33642	La Plata Gathering San Juan Unit 32-50 No. 2-27	SE¼ 27	32	6	2,811-2,830	A	1.1	20.6	50.6	27.7	0.6	11,020	
							B	....	20.8	51.2	28.0	.6	11,130	
							C	....	28.9	71.1	....	.9	15,470	
5	H-55381	Delhi-Taylor Wickens No. 1.	NE¼ 24	32	10	3,370-3,400	A	1.5	24.4	44.9	29.2	.7	10,690	
							B	....	24.8	45.5	29.7	.7	10,860	
							C	....	35.3	64.7	....	1.0	15,440	
6	H-16696	El Paso Nat. Gas Rosa Unit No. 41.	SW¼ 5	31	5	3,124-3,136	A	1.6	23.5	50.0	24.9	.7	11,550	
							B	....	23.8	50.9	25.3	.7	11,740	
							C	....	31.9	68.1	....	1.0	15,720	
7	H-50012	Delhi-Taylor Barrett No. 1.	SW¼ 20	31	9	3,230-3,255	A	1.3	33.7	49.2	15.8	.7	12,830	
							B	....	34.1	49.9	16.0	.7	13,000	
							C	....	40.6	59.4	....	.9	15,470	
8	H-15777	El Paso Nat. Gas Case No. 9.	SW¼ 8	31	11	2,710-2,740	A	1.7	40.3	47.0	11.0	.7	13,350	
							B	....	41.0	47.9	11.1	.7	13,580	
							C	....	46.1	53.9	....	.8	15,280	
9	H-19884	Consolidated Oil & Gas Mitchell No. 1-5.	SW¼ 5	31	12	2,215-3,000	A	2.4	39.4	47.3	10.9	.5	13,090	
							B	....	40.4	48.5	11.1	.5	13,410	
							C	....	45.5	54.5	....	.6	15,100	
10	H-15141	Consolidated Oil & Gas Freeman No. 1-11.	NE¼ 11	31	13	1,776-1,782	A	2.3	37.9	43.6	16.2	1.3	12,040	
							B	....	38.8	44.7	16.5	1.3	12,320	
							C	....	46.5	53.5	....	1.6	14,760	
11	H-15142	El Paso Nat. Gas S.J.U. 30-6 No. 37.	NE¼ 10	30	6	3,100-3,105	A	1.5	24.1	49.4	25.0	.7	11,310	
							B	....	24.5	50.1	25.4	.7	11,480	
							C	....	32.8	67.2	....	.9	15,380	
12	H-50079	Delhi-Taylor Moore No. 6.	NE¼ 5	30	8	2,800-3,028	A	1.7	32.6	41.4	24.3	1.8	11,250	
							B	....	33.2	42.1	24.7	1.8	11,440	
							C	....	44.0	56.0	....	2.4	15,190	
13	H-35925	El Paso Nat. Gas Turner No. 3.	SE¼ 28	30	9	2,385-2,390	A	1.5	39.9	45.5	13.1	2.2	12,960	
							B	....	40.5	46.2	13.3	2.2	13,150	
							C	....	46.7	53.3	....	2.5	15,170	
14(a)	H-19882	El Paso Nat. Gas Ludwick No. 20.	SW¼ 29	30	10	2,340-2,360	A	2.3	33.1	39.9	24.7	.7	10,800	Uppermost of two samples from this location.
							B	....	33.9	40.9	25.2	.7	11,060	
							C	....	45.3	54.7	....	.9	14,790	
14(b)	H-19883	do	SW¼ 29	30	10	2,505-2,515	A	2.6	41.7	44.5	11.2	.6	13,080	Lowermost of two samples from this location.
							B	....	42.9	45.6	11.5	.6	13,420	
							C	....	48.4	51.6	....	.7	15,160	
15	H-13062	Aztec Oil & Gas Ruby Jones No. 1.	NE¼ 7	30	11	2,020-2,030	A	1.4	37.2	44.1	17.3	.6	12,010	
							B	....	37.7	44.8	17.5	.6	12,180	
							C	....	45.7	54.3	....	.7	14,770	
16	H-15140	Southwest Production Sullivan No. 1.	NE¼ 22	30	12	1,713-1,742	A	2.2	38.8	45.3	13.7	.6	12,370	
							B	....	39.7	48.3	14.0	.6	12,640	
							C	....	46.1	53.9	....	.7	14,700	
17	H-16308	R&G Drilling Lunt No. 62.	NW¼ 18	30	13	1,425-1,440	A	2.8	40.4	44.7	12.1	.6	12,390	
							B	....	41.6	45.9	12.5	.6	12,750	
							C	....	47.5	52.5	....	.7	14,570	
18	H-19399	Compass Exploration Federal No. 1-31A.	NE¼ 31	30	13	1,070-1,080	A	5.7	38.8	43.0	12.5	.6	11,840	
							B	....	41.2	45.5	13.3	.6	12,540	
							C	....	47.4	52.6	....	.7	14,460	
19	H-78945	N.M.P.S.C.C. Core Hole No. 7.	21	30	15	69-70	A	5.6	39.7	43.3	11.4	.7	11,850	Sample from coal core—not floated in CCl_4. A is air-dried analysis.
							B	....	42.0	46.0	12.0	.7	12,540	
							C	....	47.8	52.2	....	.8	14,260	
20	H-18102	El Paso Nat. Gas S.J.U. 29-5 No. 17.	NE¼ 5	29	5	3,175-3,200	A	2.2	29.3	44.8	23.7	.8	11,460	
							B	....	30.0	45.8	24.2	.8	11,720	
							C	....	39.5	60.5	....	1.1	15,470	
21	H-7560	El Paso Nat. Gas S.J.U. 29-6 No. 66.	SW¼ 9	29	6	3,575-3,580	A	1.2	27.7	42.6	28.5	.6	10,780	
							B	....	28.0	43.1	28.9	.6	10,910	
							C	....	39.4	60.6	....	.8	15,330	
22	H-16310	Aztec Oil & Gas Cain No. 16-D.	SW¼ 30	29	9	1,985-2,005	A	1.6	41.1	46.6	10.7	.7	13,310	
							B	....	41.7	47.5	10.8	.7	13,520	
							C	....	46.8	53.2	....	.7	15,160	
23(a)	H-27541	Aztec Oil & Gas Grenier "B" No. 3.	SW¼ 5	29	10	2,065-2,080	A	2.3	39.1	42.1	16.5	1.9	12,020	Uppermost of two samples from this location.
							B	....	40.0	43.1	16.9	2.0	12,300	
							C	....	48.1	51.9	....	2.4	14,800	
23(b)	H-27540	do	SW¼ 5	29	10	2,150-2,160	A	2.0	40.6	47.6	9.8	.5	13,300	Lowermost of two samples from this location.
							B	....	41.4	48.6	10.0	.5	13,560	
							C	....	46.0	54.0	....	.6	15,070	
24	H-13060	Tidewater N.M.-Fed. No. 12-E.	SE¼ 12	29	11	2,065-2,070	A	2.1	38.7	47.9	11.3	.6	12,830	
							B	....	39.5	48.9	11.6	.6	13,100	
							C	....	44.7	55.3	....	.7	14,820	
25	H-3028	International Oil Fogelson No. 1-9.	NW¼ 9	29	11	1,905-1,910	A	1.8	39.9	43.9	14.4	.7	12,360	
							B	....	40.6	44.8	14.6	.7	12,590	
							C	....	47.6	52.4	....	.8	14,750	
26	H-3030	Tennessee Oil & Gas Cornell Gas Unit A No. 1.	NW¼ 10	29	12	1,740-1,750	A	2.1	40.0	44.8	13.1	.5	12,340	
							B	....	40.9	45.7	13.4	.5	12,600	
							C	....	47.2	52.8	....	.6	14,560	

TABLE 4.—*Analyses of coal samples from the Fruitland Formation*—Continued

[Form of analysis: A, as received; B, moisture free; C, moisture and ash free]

Sampled location in fig. 23	U.S. Bureau Mines lab. No.	Well or other source	Location			Approximate depth interval of sample (ft.)	Form of analysis	Proximate					Heating value (Btu)	Remarks
			Section	T.N.	R.W.			Moisture	Volatile matter	Fixed carbon	Ash	Sulfur		
						New Mexico—Continued								
27	H-8360	Aztec Oil & Gas	SW¼ 20	29	13	1,125–1,140	A	5.6	39.0	41.3	14.1	0.6	11,580	
		Hagood No. 21-G.					B	--------	41.3	43.8	14.9	.6	12,260	
							C	--------	48.5	51.5	--------	.7	14,420	
28	H-4052	Aztec Oil & Gas	SE¼ 34	29	13	1,635–1,640	A	3.5	39.6	43.2	13.7	.5	11,910	
		Hagood No. 13-G.					B	--------	41.0	44.8	14.2	.6	12,330	
							C	--------	47.8	52.2	--------	.6	14,370	
29	H-4051	Humble Oil & Gas	SE¼ 36	29	14	1,490–1,495	A	4.1	40.0	40.6	15.3	.7	11,600	
		Humble No. L-9.					B	--------	41.7	42.3	16.0	.7	12,100	
							C	--------	49.7	50.3	--------	.9	14,400	
30	H-3855	El Paso Nat. Gas	NE¼ 19	28	4	4,115–4,120	A	1.6	31.1	43.7	23.6	.7	11,580	
		S.J.U. 28-4 No. 28.					B	--------	31.6	44.4	24.0	.7	11,770	
							C	--------	41.6	58.4	--------	.9	15,480	
31	H-7224	El Paso Nat. Gas	SW¼ 28	28	5	3,323–3,345	A	2.6	31.6	39.0	26.8	.6	10,640	
		S.J.U. 28-5 No. 50.					B	--------	32.5	40.0	27.5	.6	10,920	
							C	--------	44.8	55.2	--------	.9	15,070	
32	H-13779	El Paso Nat. Gas	NE¼ 30	28	8	2,185–2,195	A	1.9	33.7	35.1	29.3	.6	10,270	
		Florence No. 10-C.					B	--------	34.3	35.8	29.9	.7	10,460	
							C	--------	48.9	51.1	--------	.9	14,920	
33	H-13061	Aztec Oil & Gas	SW¼ 17	28	9	1,985–1,990	A	1.4	36.1	42.1	20.4	.8	11,670	
		Reid No. 23-D.					B	--------	36.6	42.7	20.7	.8	11,830	
							C	--------	46.2	53.8	--------	1.0	14,920	
34	H-5472	Aztec Oil & Gas	NW¼ 16	28	10	1,842–1,853	A	1.6	38.4	40.7	19.3	.6	11,760	
		Caine No. 13.					B	--------	39.0	41.4	19.6	.6	11,950	
							C	--------	48.5	51.5	--------	.8	14,870	
35	H-12704	Redfern & Herd	SW¼ 10	28	11	1,490–1,500	A	2.1	39.8	43.4	14.7	.6	12,190	
		Redfern & Herd No. 5.					B	--------	40.7	44.3	15.0	.6	12,460	
							C	--------	47.9	52.1	--------	.7	14,670	
36	H-24567	Sunray Mid-Continent	NW¼ 18	28	12	1,305–1,315	A	3.0	38.9	44.4	13.7	.6	12,010	
		Gallegos No. 122.					B	--------	40.1	45.8	14.1	.6	12,390	
							C	--------	46.8	53.2	--------	.7	14,430	
37	H-7225	Pan American	NW¼ 16	28	13	1,705–1,715	A	4.1	39.4	42.8	13.7	.6	11,740	
		Holder No. 7.					B	--------	41.1	44.6	14.3	.6	12,240	
							C	--------	47.9	52.1	--------	.7	14,290	
38	H-18101	El Paso Nat. Gas	SW¼ 32	27	4	3,935–3,945	A	2.2	33.9	37.9	26.0	.7	10,780	
		S.J.U. 27-4 No. 30.					B	--------	34.6	38.8	26.6	.7	11,010	
							C	--------	47.2	52.8	--------	.9	15,020	
39	H-33317	E Paso Nat. Gas	SE¼ 23	27	5	3,250–3,260	A	3.1	34.4	39.5	23.0	.8	11,080	
		S.J.U. 27-5 No. 74.					B	--------	35.6	40.7	23.7	.9	11,440	
							C	--------	46.6	53.4	--------	1.1	15,010	
40	H-33643	El Paso Nat. Gas	SW¼ 21	27	6	3,165–3,180	A	1.4	39.3	44.5	14.8	.9	12,690	
		Rincon Unit No. 171.					B	--------	39.8	45.2	15.0	.9	12,870	
							C	--------	46.9	53.1	--------	1.1	15,150	
41	H-35788	El Paso Nat. Gas	SE¼ 13	27	7	3,130–3,140	A	2.3	32.9	34.3	30.5	.8	9,900	
		Rincon Unit No. 177.					B	--------	33.7	35.1	31.2	.8	10,130	
							C	--------	48.9	51.1	--------	1.2	14,720	
42	H-21490	El Paso Nat. Gas	NE¼ 8	27	8	2,800–2,820	A	1.9	29.5	32.9	35.7	.6	9,170	
		Schwerdtfeger No. 20-A.					B	--------	30.0	33.6	36.4	.6	9,350	
							C	--------	47.2	52.8	--------	1.0	14,700	
43	H-12705	Aztec Oil & Gas	SW¼ 8	27	9	2,215–2,230	A	2.2	36.7	41.2	19.9	.8	11,440	
		Whitley No. 6-D.					B	--------	37.5	42.1	20.4	.8	11,700	
							C	--------	47.1	52.9	--------	1.1	14,700	
44	H-13063	Aztec Oil & Gas	NW¼ 29	27	9	2,135–2,145	A	2.7	38.3	40.4	18.6	.8	11,650	
		Hudson No. 5-D.					B	--------	39.3	41.6	19.1	.8	11,970	
							C	--------	48.6	51.4	--------	1.0	14,800	
45	H-15776	Aztec Oil & Gas	SW¼ 12	27	10	1,900–1,905	A	2.2	40.4	44.0	13.4	.6	12,520	
		Hanks No. 14-D.					B	--------	41.3	45.1	13.6	.6	12,790	
							C	--------	47.9	52.1	--------	.7	14,820	
46	H-5021	British-American Oil	NE¼ 14	27	11	1,920–1,930	A	3.3	40.8	43.9	12.0	.6	12,370	
		Fullerton No. 8					B	--------	42.2	45.4	12.4	.6	12,790	
							C	--------	48.1	51.9	--------	.7	14,600	
47	H-3031	Southwest Production	NE¼ 26	27	12	1,900–1,910	A	2.6	41.2	40.5	15.7	.6	11,810	
		Cambell No. 2.					B	--------	42.3	41.6	16.1	.6	12,120	
							C	--------	50.4	49.6	--------	.7	14,440	
48	H-36175	Royal Development	SW¼ 6	27	13	1,214–1,245	A	4.3	39.7	44.6	11.4	.7	11,970	
		Ojo Amarillo No. 2.					B	--------	41.4	46.7	11.9	.7	12,500	
							C	--------	47.0	53.0	--------	.8	14,190	
49	H-32698	Caulkins Oil	NE¼ 2	26	6	3,184–3,200	A	1.3	38.9	41.4	18.4	.7	12,130	
		State "A" MD No. 62.					B	--------	39.4	41.9	18.7	.7	12,290	
							C	--------	48.4	51.6	--------	.9	15,120	
50	H-5020	Kay Kimbell	SW¼ 19	26	7	2,105–2,150	A	2.5	38.1	41.2	18.2	.6	11,760	
		Leiberman No. 5.					B	--------	39.1	42.2	18.7	.6	12,060	
							C	--------	48.1	51.9	--------	.8	14,830	
51	H-12706	Southwest Production	NE¼ 5	26	11	1,700–1,705	A	3.6	40.6	39.3	16.5	.7	11,540	
		Ted Henderson No. 1.					B	--------	42.1	40.8	17.1	.7	11,970	
							C	--------	50.8	49.2	--------	.8	14,430	
52	H-37832	Merrion & Associates	SW¼ 35	25	6	2,455–2,465	A	3.6	36.3	35.6	24.5	.8	10,440	
		Federal No. 3-35.					B	--------	37.7	36.9	25.4	.8	10,830	
							C	--------	50.5	49.5	--------	1.1	14,510	
53	H-16695	Century Exploration	SW¼ 21	25	9	1,620–1,625	A	4.2	31.5	33.3	31.0	.9	9,280	
		Mobil-Rudman No. 2.					B	--------	32.8	34.8	32.4	.9	9,680	
							C	--------	48.6	51.4	--------	1.4	14,310	
54	H-40806	Standard of Texas	SW¼ 16	25	13	1,156–1,208	A	9.5	30.9	43.3	16.3	1.8	10,270	Abnormal moisture content may be due to inadequate drying of sample during preparation process.
		State No. 1.					B	--------	34.1	47.9	18.0	2.0	11,340	
							C	--------	41.6	58.4	--------	2.5	13,820	
55	H-32405	El Paso Nat. Gas	NE¼ 22	24	3	3,194–3,205	A	2.1	38.7	36.7	22.5	.7	10,990	
		Lindrith No. 42.					B	--------	39.5	37.5	23.0	.7	11,230	
							C	--------	51.3	48.7	--------	1.0	14,580	

TABLE 4.—*Analyses of coal samples from the Fruitland Formation*—Continued

[Form of analysis: A, as received; B, moisture free; C, moisture and ash free]

Sampled location in fig. 23	U.S. Bureau Mines lab. No.	Well or other source	Location: Section	Location: T.N.	Location: R.W.	Approximate depth interval of sample (ft.)	Form of analysis	Proximate: Moisture	Proximate: Volatile matter	Proximate: Fixed carbon	Proximate: Ash	Sulfur	Heating value (Btu)	Remarks
New Mexico—Continued														
56	H-22075	Val Reese & Assoc. Bobby "B" No. 2-31.	NE¼ 31	24	6	2,070–2,090	A	3.6	41.1	40.6	14.7	0.7	11,840	
							B	--------	42.6	42.2	15.2	.7	12,280	
							C	--------	50.2	49.8	--------	.9	14,480	
57	H-31101	Val Reese & Assoc. Lybrook No. 7-27.	NE¼ 27	24	7	2,140–2,150	A	4.4	40.9	41.2	13.5	.6	11,790	
							B	--------	42.8	43.1	14.1	.6	12,340	
							C	--------	49.9	50.1	--------	.7	14,370	
58	H-5022	Dorfman Production Nancy Fed. No. 1.	SE¼ 12	24	8	2,525–2,535	A	3.9	35.4	33.7	27.0	1.1	9,960	
							B	--------	36.8	35.1	28.1	1.1	10,370	
							C	--------	51.2	48.8	--------	1.5	14,410	
59	H-19885	N.M.P.S.C.C DH-32-1.	NW¼ 32	24	13	100–112	A	12.0	32.5	39.3	16.2	.5	9,670	Coal core crushed and floated in CCl_4.
							B	--------	36.9	44.7	18.4	.6	10,990	
							C	--------	45.2	54.8	--------	.7	13,460	
60	H-16309	Val Reese & Assoc. Betty "B" No. 1-15.	NW¼ 15	23	7	2,180–2,195	A	5.7	39.3	40.8	14.2	.6	11,410	
							B	--------	41.7	43.3	15.0	.7	12,100	
							C	--------	49.1	50.9	--------	.8	14,240	
61	H-22722	N.M.P.S.C.C DH-3-2.	SW¼ 3	23	13	42–44	A	6.7	35.9	46.9	10.5	.6	11,320	Coal core not floated in CCl_4.
							B	--------	38.5	50.3	11.2	.6	12,140	
							C	--------	43.4	56.6	--------	.7	13,680	
62	I-2723	Fruitland outcrop	SW¼ 3	19	2	Surface	A	5.9	33.6	29.8	30.7	.6	7,370	Weathered coal from surface exposure. Not floated in CCl_4.
							B	--------	35.7	31.7	32.6	.7	7,830	
							C	--------	53.0	47.0	--------	1.0	11,620	
63	I-2722	do	SE¼ 7	19	2	do	A	6.5	37.0	35.0	21.5	.7	8,350	Do.
							B	--------	39.6	37.4	23.0	.7	8,930	
							C	--------	51.4	48.6	--------	.9	11,590	
64	H-99246	do	NE¼ 11	19	4	do	A	6.2	36.2	37.1	20.5	.5	8,610	Do.
							B	--------	38.6	39.6	21.8	.5	9,170	
							C	--------	49.3	50.7	--------	.6	11,730	
65	I-53220	Pit sample	SE¼ 9	19	5		A	5.8	35.8	31.0	27.4	.6	9,450	Sample from small prospect pit in Fruitland outcrop.
							B	--------	38.1	32.8	29.1	.6	10,040	
							C	--------	53.7	46.3	--------	.9	14,160	

not treated by flotation. They were prepared in the usual prescribed manner.

The analyses show that the coal of the Fruitland Formation is low in moisture and sulfur content. The low moisture values recorded for these samples may be due in part to the unavoidable drying of the samples during the flotation process. The coal core and outcrop samples, which were not floated in carbon tetrachloride, had moisture contents of about 5 or 6 percent, whereas the floated samples normally contained about 2–4 percent moisture. The core and outcrop samples, however, were from surficial or very shallow beds that undoubtedly were affected to some degree by weathering, and it is likely that their moisture contents are abnormally high. The low range of moisture in the well samples, taken from deeply buried and unweathered beds, is probably more representative of the coal. The question is whether surficial weathering or a brief bath in carbon tetrachloride has the greater effect on inherent moisture. The truly representative moisture content of unaltered Fruitland coals probably ranges between about 2 and 5 percent.

Analyses from mine samples in Colorado (George and others, 1937, p. 88–91) show a moisture range in the Fruitland coal of 2.5–11.6 percent. Of seven Fruitland coal analyses reported, however, only two had moisture of as much as 5 percent, and these were from samples which were taken within a few tens of feet of the entry of the mines (the location in the mine of one of the samples is given as "25 feet from outcrop" and of the other simply as "Back of entry"). Published analyses of Fruitland coal from mines in New Mexico show a somewhat higher range of moisture content—from about 6 percent to more than 16 percent. The coal beds in New Mexico, however, crop out over a wider area and have a much lower angle of dip than those in Colorado. Consequently, they have been subjected to a greater degree of weathering, and the moisture content of analyzed mine samples shows the influence of percolating ground water. Our data indicate that fresh, unweathered coal from the Fruitland Formation has a moisture content generally between 2 and 5 percent. The sulfur content of the coals is consistently somewhat less than 1 percent.

The ash content of Fruitland coal is variable but generally high in comparison with other western coals. The ash values in table 4 and several in published analyses of mine samples from the north and northwest edges of the basin are plotted in figure 24. As shown in this illustration, there are three general zones of ash distribution in the Fruitland coals across the San Juan Basin. An irregular area in the west-central part of the basin contains coal that has an ash content of 8–15 percent. An intermediate zone has ash content between 15 and 20 percent except for a few localities in which it is slightly less than 15 percent. The coal in the east half of the basin contains ash in amounts exceeding 20 percent, and four samples (three well samples and one

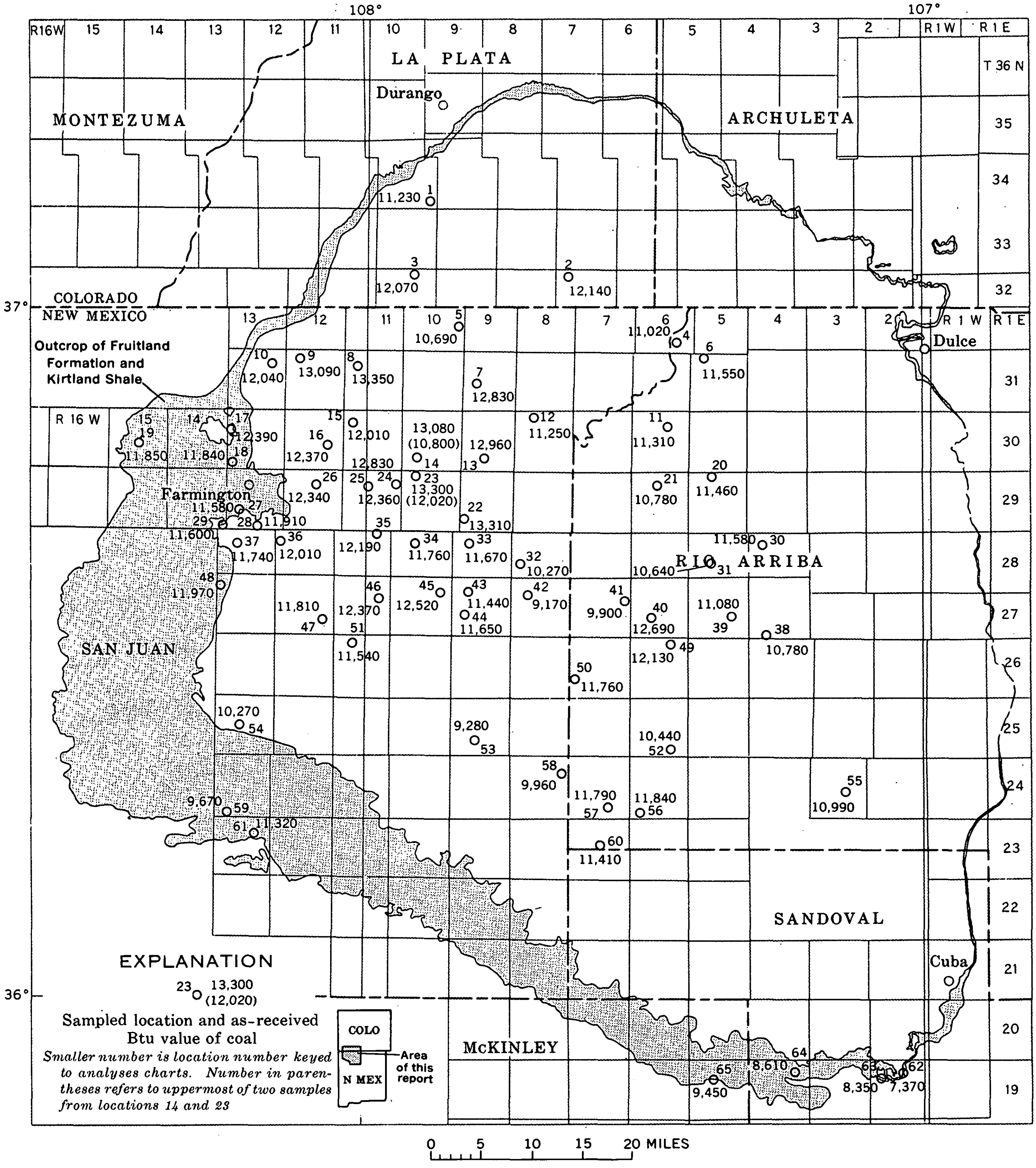


FIGURE 23.—Locations of drill holes and surface sections sampled for coal analyses and as-received Btu values of the samples.

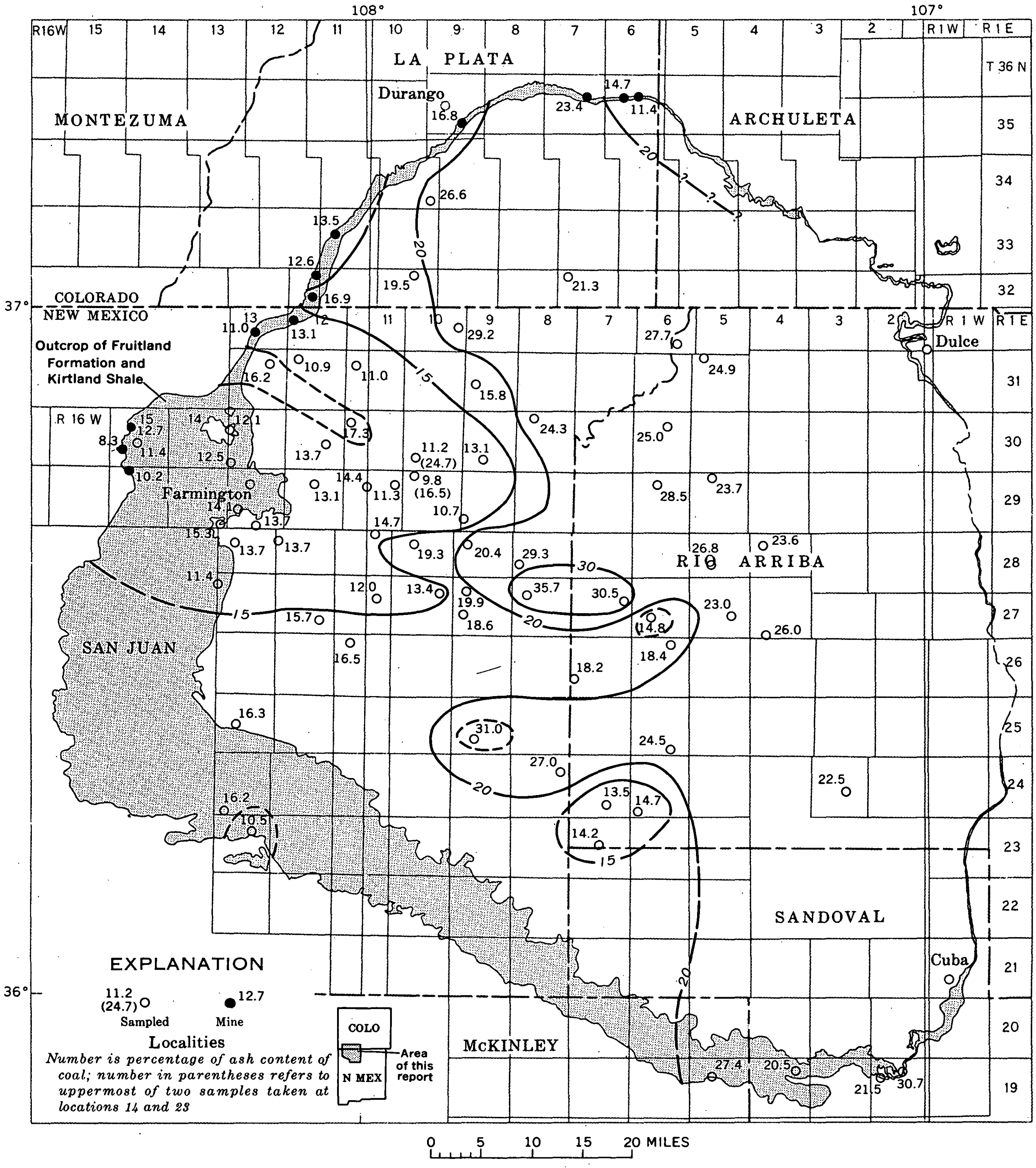


FIGURE 24.—Distribution of ash in coal samples from the Fruitland Formation. Contour values in percent; interval varies.

outcrop sample) yielded ash in excess of 30 percent. The zones do not follow depositional trends and are seemingly unrelated to bed thickness, fixed-carbon to volatile ratios, absolute (moisture and ash free) Btu values, or relative age of the coal beds. The distribution shows only that the east half of the basin area received a greater amount of extraneous matter in the swamp belt than did other areas. Analyses of the ash might offer clues to its origin and depositional history, but such analyses were not made for the present study.

The as-received Btu values (form of analysis A, table 4) of the coal beds sampled are plotted in figure 23. They range generally between 9,000 and 13,000. Anomalously low values of 7,370 and 8,350 were determined for the weathered outcrop samples from locations 62 and 63 in the extreme southeast corner of the basin. A few samples in the northwestern part of the basin had as-received Btu values exceeding 13,000, the highest being 13,350 at location 8. The distribution of the as-received values does not reveal a specific pattern. In general, the values are highest in the northwestern part of the basin and lowest in the south and southeast. The absolute heating values of Fruitland coals, which form the definite patterns described in the following paragraph, are obscured in the as-received analyses by the ash content.

The Btu values from the moisture- and ash-free analyses (form of analysis C, table 4) are plotted in figure 25. In contrast to the as-received values (fig. 23), these values show a definite pattern of distribution. Again, the outcrop samples in the southeast had low values. Whether this is due entirely to the weathered state of the coal or is inherent in the quality of the coal in this area is unknown. The latter would seem probable, because the outcrop sample from location 65 in T. 19 N., R. 5 W., had a near normal Btu value for Fruitland coal for both as-received and moisture- and ash-free analyses. Otherwise, the absolute Btu values increase regularly across the basin from 13,460 in the southwest to 15,720 in T. 31 N., R. 5 W. Zones characterized by about the same values trend northwest across the basin. They parallel almost exactly the zones of deposition that have been discussed and are shown in figure 21. These trends also reflect generally the present basin structural axis and may be related in part to depth of burial.

Two mine sample analyses (George and others, 1937, p. 88–91) indicate a reversal of the northeast trend of increasing absolute heat values in the extreme northeastern part of the basin and suggest a zone of lesser values across this area.

At locations 14 and 23 in Tps. 29 and 30 N., R. 10 W., analyses were made of coal from two zones. At both locations the lower coal had the highest Btu values. The short-dashed line around these locations in figure 25 shows where the 15,000 moisture- and ash-free Btu line would fall if the values from the upper coal zone were used.

Figure 26 shows the distribution of the fixed-carbon percentage of the coal from the moisture- and ash-free analyses. This map, like the map of moisture- and ash-free Btu values, reflects the depositional zones shown in figure 21. In the first area of coal buildup in the southwestern part of the basin, the analyses yielded absolute (moisture and ash free) fixed-carbon contents in excess of 55 percent. Across the zone of thin total coal, the fixed-carbon values range between 50 and 55 percent, except in the area of very thin coals in the southeast where the values are usually slightly less than 50 percent. Northeastward, across the zones of thickest coal accumulation, the fixed-carbon percentage increases to a maximum recorded 72.4 percent at location 2 in T. 32 N., R. 7 W., Colorado. Two mine sample analyses (George and others, 1937, p. 88–91) from the north edge of the basin indicate that the fixed-carbon percentage, like the Btu values, declines across the northeastern part of the basin to slightly less than 60 percent.

Fruitland coal has generally been considered subbituminous in rank in the New Mexico part of the San Juan Basin and low-grade bituminous in Colorado. Classification of the coal in these ranks has been based largely on the weathering tendency of the coal, bituminous coals being relatively unaffected by exposure. In a classification based solely on percentage of fixed carbon and heating value on a mineral-matter-free basis, most of the coal in the north half of the basin would range from high-volatile to medium-volatile bituminous in rank. Because of the known slacking tendency of the coal in the western part of the basin and the very high ash content of the coal in the east half of the basin, all the Fruitland coal is considered subbituminous for the purposes of this report. Resource calculations in a following section were made on the basis of the weight per ton of subbituminous coal.

OVERBURDEN

Figure 27 shows the thickness of rock overlying the Fruitland coal deposits. The thicknesses shown are from the land surface to the base of the Fruitland Formation, as measured on well logs. Owing to the mesa-canyon topography prevalent over much of the San Juan Basin, the depth to this datum may vary several hundred feet within short horizontal distances. Therefore, the isopachs on this map are average values.

The range of overburden thickness is from 0 to more than 4,000 feet. The thickest overburden noted occurs in sec. 13, T. 28 N., R. 5 W., New Mexico principal meridian, New Mexico, where it is 4,478 feet thick.

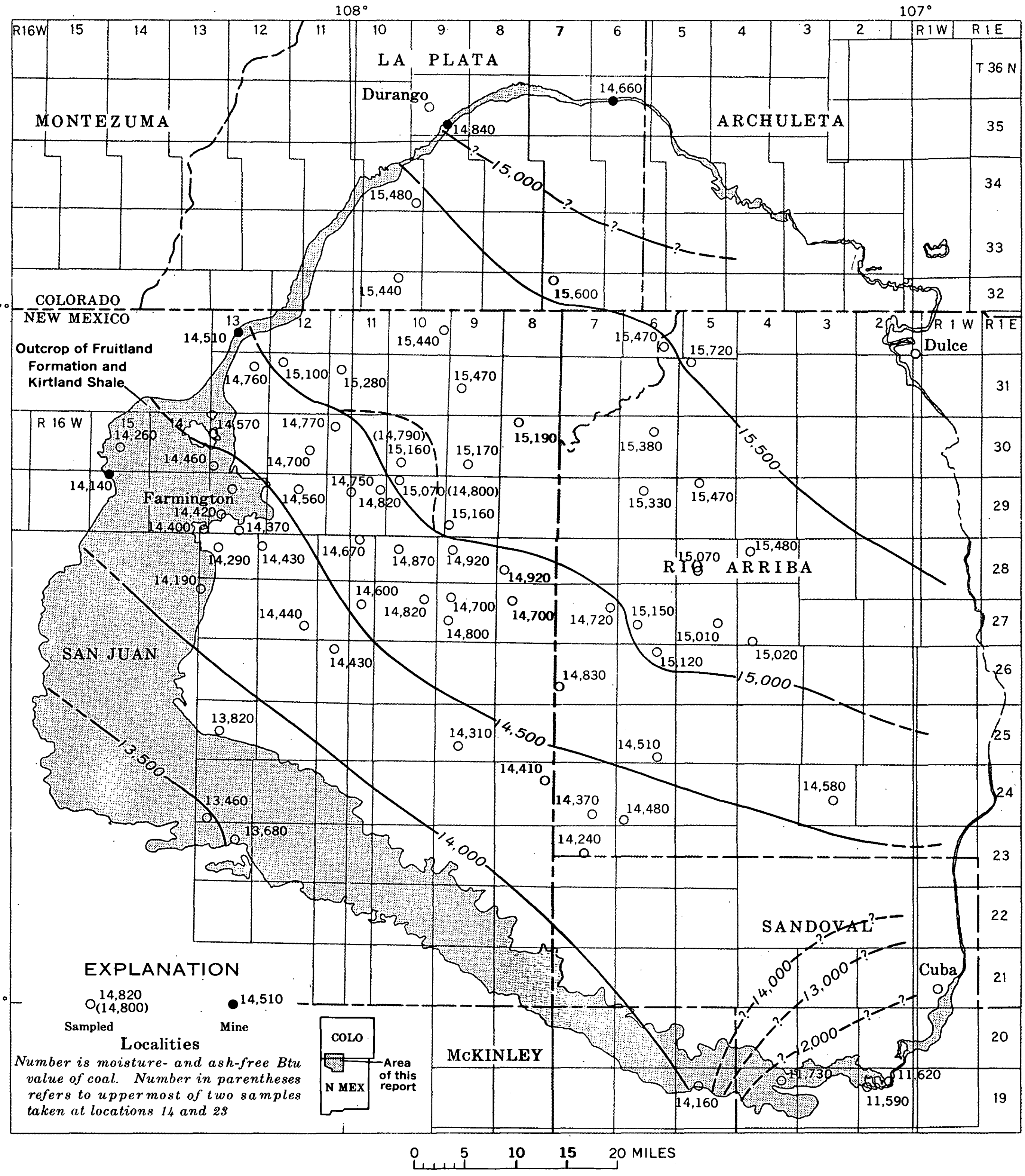


FIGURE 25.—Moisture- and ash-free Btu values of coal samples from the Fruitland Formation.

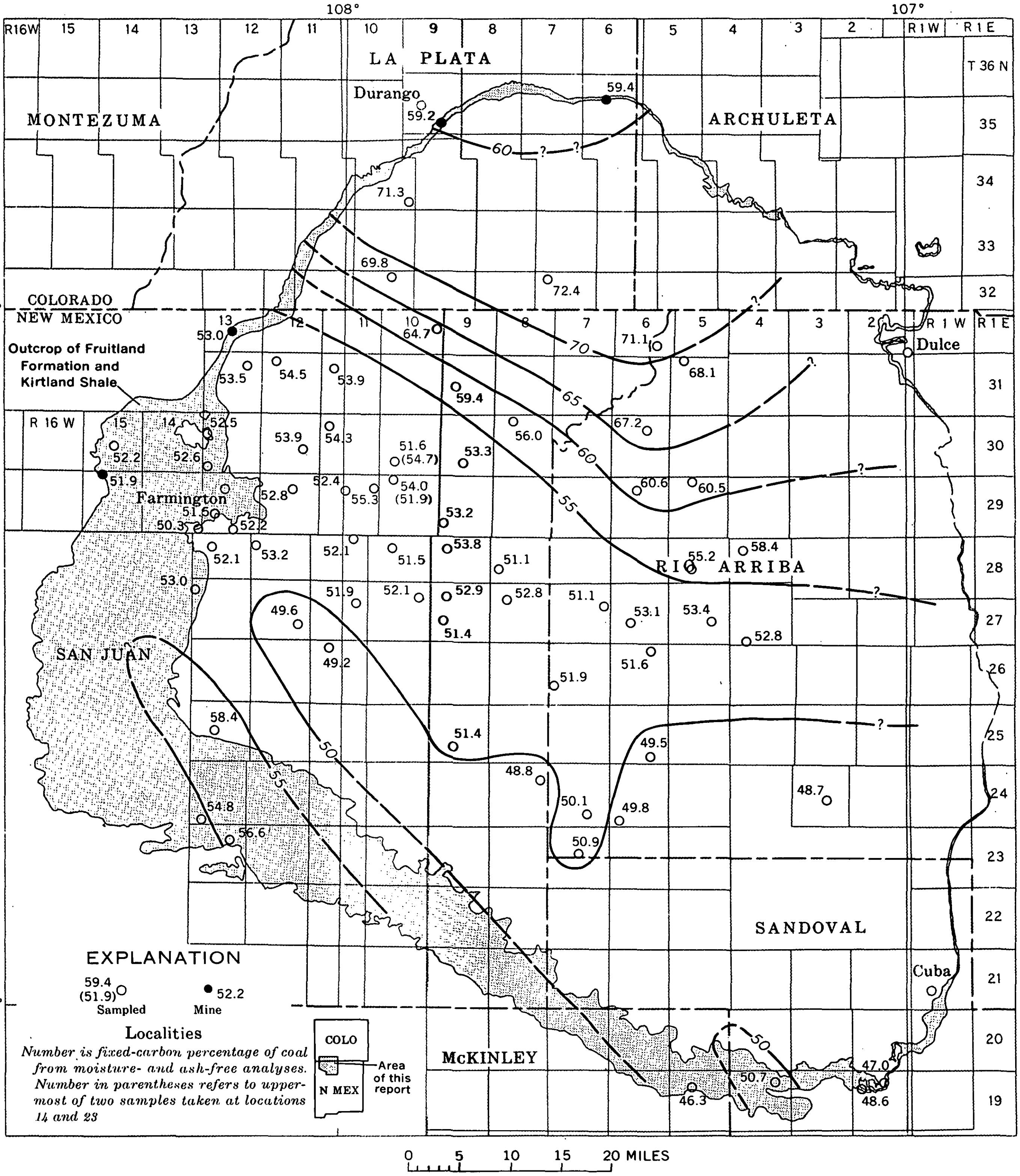


Figure 26.—Fixed-carbon percentage of coal samples from the Fruitland Formation. Contour values in percent; interval varies.

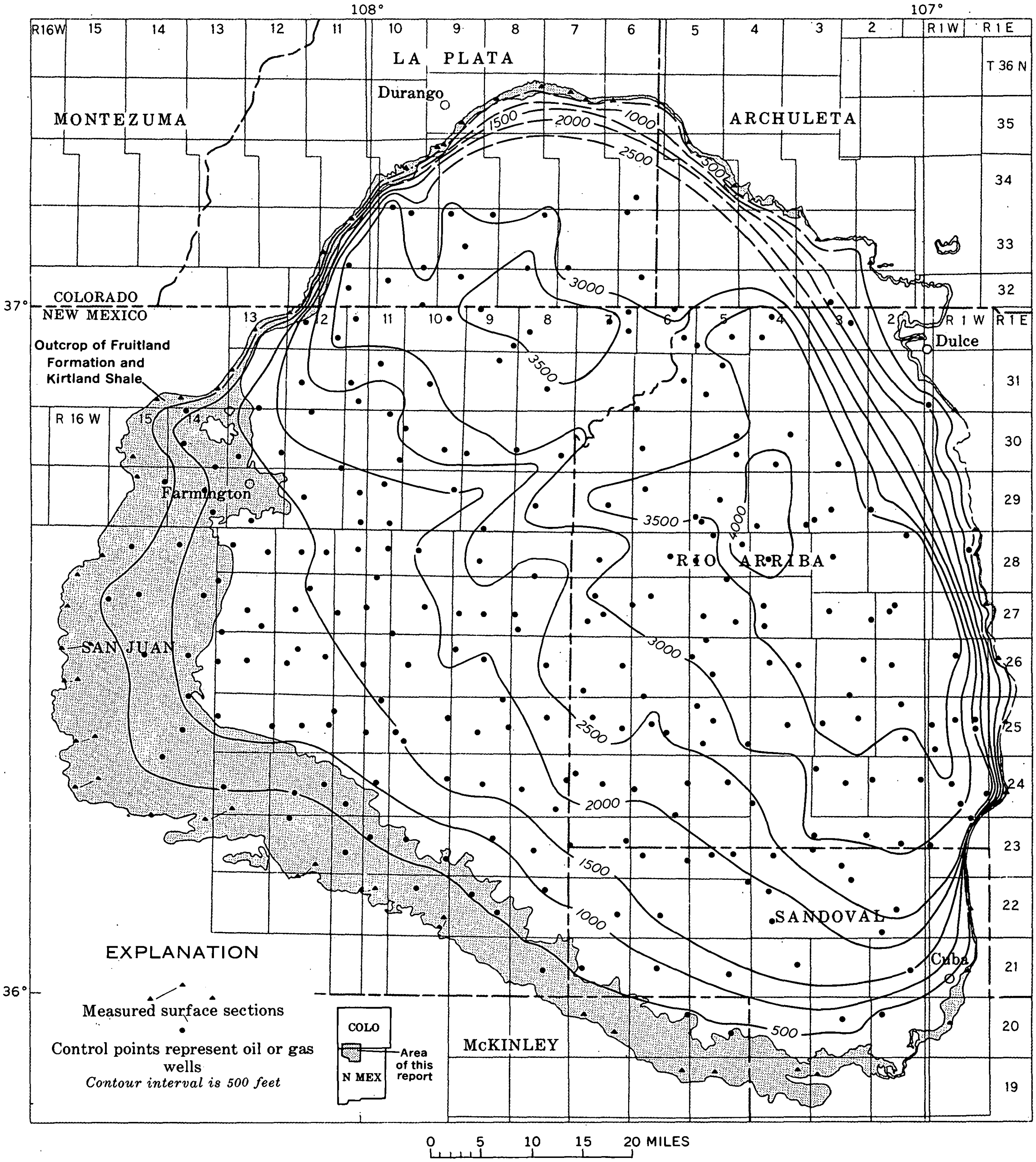


FIGURE 27.—Isopach map showing average thickness of overburden on Fruitland Formation coal deposits.

It includes sandstone and shale of the Fruitland Formation, Kirtland Shale, Ojo Alamo Sandstone, Nacimiento Formation, and San Jose Formation. In the northern part of the basin, the Kirtland Shale and the Animas Formation constitute the bulk of the overburden.

The existing pattern of overburden is primarily due to the structure of the basin combined with the present-day topographic surface. The structural relief in the basin is about 4,000 feet (fig. 15); the topographic relief ranges from about 5,100 feet to slightly more than 8,000 feet, a span of 2,900 feet. The thickest overburden occurs where areas of higher altitude overlie the lower parts of the structural basin.

Gently dipping beds and rolling topography along the south and west flanks of the basin result in a band 4–6 miles wide that is underlain by Fruitland coal beds at depths of less than 500 feet. Another band of approximately equal width lies to the northeast where the coal is less than 1,000 feet below the surface. Along the north and east sides of the basin, the Fruitland beds dip steeply basinward in monoclinal hogbacks and are generally more than 1,000 feet below the surface within 1 or 2 miles of their outcrops. For the most part, coal is absent from the Fruitland outcrop along the east side of the basin and lies at depths exceeding 2,000 feet where identified on well logs near the east rim of the basin. The thickest coal zones of the Fruitland crop out only along the northwest flank of the basin, where they dip abruptly to depths in excess of 2,000 feet.

RESOURCES

About 200 billion tons of coal is contained in the Fruitland Formation between its outcrop and its greatest depth of somewhat more than 4,000 feet. The following estimates of these coal resources were calculated with the assumption that all the coal in the formation is of subbituminous rank and as such has an average weight of 1,132,560 tons per square mile-foot (1,770 tons per acre-foot). This figure is the value assigned as the weight of subbituminous coal in the ground in all recent U.S. Geological Survey estimates of coal reserves (Averitt, 1961).

The coal is reported in three categories of bed thickness and six categories of overburden. The bed-thickness categories are the standard categories used by the Geological Survey in estimating subbituminous resources, except that the lower limit of thickness is 2 feet in this report instead of the 2½ feet of the standard. This difference was made because it is usually easy to interpret the response to Fruitland coal beds on well logs to the nearest foot, but it is difficult and unreliable on most logs to be specific to a 0.5-foot interval. Such determinations can be made accurately with some focused logs such as the microlog, microlaterlog, or sonic log (Schlumberger designations), but these logs are available for only a few wells in the San Juan Basin. The 2-foot-thickness limit was the lower limit of most of the beds recorded and illustrated in this study, and only these beds are included in the resource estimates.

The six categories of overburden used in reporting the resources are: 0–500 feet, 500–1,000 feet, 1,000–2,000 feet, 2,000–3,000 feet, 3,000–4,000 feet, and 4,000+ feet. Standard Geological Survey resource estimates are made to a depth of only 3,000 feet, owing in part to the fact that information is seldom available for greater depths. Even estimates for lesser depths are usually based largely on projected outcrop data. The coal is reported to 4,000+ feet in this report because the information gained during the investigation permits estimates to this depth as reliable as to any other. More than 85 billion tons of coal in the Fruitland Formation lies below 3,000 or more feet of overburden (tables 6, 7).

The resource tables are arranged according to zones of total coal thickness, because the percentage of coal in the different bed-thickness categories varies with the total amount of coal present. In areas of thin total coal, most of the resources are in comparatively thin beds. In the thicker coal zones, a large part of the coal is in beds more than 10 feet thick. The average percentage of coal within the respective bed-thickness categories was computed for each zone of total thickness. The results are shown in table 5.

TABLE 5.—*Average percent of total coal in beds of indicated thickness in areas with given total coal thickness*

Total thickness of coal in area (ft)	Average percent of total coal		
	Beds 2–5 feet thick	Beds 5–10 feet thick	Beds >10 feet thick
0–10	67	33	----------
10–20	33	38	29
20–30	24	38	38
30–40	16	27	57
40–50	20	20	60
50–60	15	17	68
60–70	15	13	72
>70	11	16	73

The amount of coal in the formation was determined from the average total thicknesses shown in figure 21. This map was combined with the overburden map (fig. 27), and the area of each zone of total thickness was measured by planimeter in each of the depth categories. The resulting areas in square miles were multiplied by the average total thickness in feet of coal in each area. The figures thus obtained were the square mile-feet of coal in each area. These figures were multiplied by the weight per square mile-foot of subbituminous coal (1,132,560 tons) to obtain the total tonnage of coal within the respective areas. The totals were then multiplied by the percentage figures given in table 5. The final products are the tons of coal present in beds of indicated thickness within zones of given total thickness under each category of overburden. The above computations were made separately for areas in Colorado and New Mexico to facilitate the possible use of these results in future State estimates of resources. In these computations no allowance was made for the dip of the beds. Especially along the northern margin of the basin where the coals dip steeply to depths greater than 3,000 feet, the dip would have the effect of increasing the area of the coal bed and so its total tonnage.

The results of the computations just described are given in table 6. Table 7 summarizes the data in more compact form. As a result of this study, it was determined that approximately 6,250 square miles within the area of the San Juan Basin is underlain by coal beds of the Fruitland Formation and that the beds contain an aggregate of about 200 billion tons of coal. Owing to the regional nature of this study and the methods used in estimating the coal resources, the results are considered to be "inferred by zone" rather than "measured" or "indicated" as defined by Averitt (1961).

TABLE 6.—*Fruitland Formation coal resources in millions of short tons under indicated overburden, arranged by States according to bed thickness and total coal thickness*

Coal thickness (ft)		Area underlain (square miles)		Coal resources by bed thickness, in millions of short tons				
Range	Average	Colorado	New Mexico	Thickness of beds (ft)	Colorado	Mew Mexico	Total	Combined tota
				Overburden: 0–500 feet				
0–10	5	32. 0	184. 0	2–5	121. 4	698. 1	819. 5	1, 223. 1
				5–10	59. 8	343. 8	403. 6	
10–20	15	11. 5	230. 0	2–5	64. 5	1, 289. 4	1, 353. 9	4, 102. 7
				5–10	74. 2	1, 484. 8	1, 559. 0	
				>10	56. 7	1, 133. 1	1, 189. 8	
20–30	25	13. 0	145. 5	2–5	88. 3	988. 7	1, 077. 0	4, 487. 8
				5–10	139. 9	1, 565. 5	1, 705. 4	
				>10	139. 9	1, 565. 5	1, 705. 4	
30–40	35	8. 0	92. 5	2–5	50. 7	586. 7	637. 4	3, 983. 7
				5–10	85. 6	990. 0	1, 075. 6	
				>10	180. 7	2, 090. 0	2, 270. 7	
40–50	45	3. 5	3. 0	2–5	35. 7	30. 6	66. 3	331. 3
				5–10	35. 7	30. 6	66. 3	
				>10	107. 0	91. 7	198. 7	
50–60	55	2. 0	----------	2–5	18. 7	------------	18. 7	124. 6
				5–10	21. 2	------------	21. 2	
				>10	84. 7	------------	84. 7	
60–70	65	2. 0	----------	2–5	22. 1	------------	22. 1	147. 2
				5–10	19. 1	------------	19. 1	
				>10	106. 0	------------	106. 0	
70+	70+	3. 0	----------	2–5	26. 2	------------	26. 2	237. 9
				5–10	38. 1	------------	38. 1	
				>10	173. 6	------------	173. 6	
Totals		75. 0	655. 0	All beds	1, 749. 8	12, 888. 5	14, 638. 3	14, 638. 3
				Overburden: 500–1,000 feet				
0–10	5	5. 0	76. 5	2–5	19. 0	290. 2	309. 2	461. 5
				5–10	9. 3	143. 0	152. 3	
10–20	15	26. 5	196. 0	2–5	148. 6	1, 098. 8	1, 247. 4	3, 780. 0
				5–10	171. 1	1, 265. 3	1, 436. 4	
				>10	130. 6	965. 6	1, 096. 2	
20–30	25	13. 5	201. 0	2–5	91. 7	1, 365. 9	1, 457. 6	6, 073. 4
				5–10	145. 3	2, 162. 6	2, 307. 9	
				>10	145. 3	2, 162. 6	2, 307. 9	
30–40	35	12. 0	57. 5	2–5	76. 1	364. 7	440. 8	2, 754. 9
				5–10	128. 4	615. 4	743. 8	
				>10	271. 1	1, 299. 2	1, 570. 3	
40–50	45	4. 5	2. 5	2–5	45. 9	25. 5	71. 4	356. 8
				5–10	45. 9	25. 5	71. 4	
				>10	137. 6	76. 4	214. 0	
50–60	55	1. 5	----------	2–5	14. 0	------------	14. 0	93. 4
				5–10	15. 9	------------	15. 9	
				>10	63. 5	------------	63. 5	

TABLE 6.—*Fruitland Formation coal resources in millions of short tons under indicated overburden, arranged by States according to bed thickness and total coal thickness*—Continued

Coal thickness (ft)		Area underlain (square miles)		Coal resources by bed thickness, in millions of short tons				
Range	Average	Colorado	New Mexico	Thickness of beds (ft)	Colorado	Mew Mexico	Total	Combined total
Overburden: 500–1,000—Continued								
60–70	65	1.5		2–5	16.6		16.6	110.4
				5–10	14.3		14.3	
				>10	79.5		79.5	
70+	70+	3.0		2–5	26.2		26.2	237.8
				5–10	38.0		38.0	
				>10	173.6		173.6	
Totals		67.5	533.5	All beds	2,007.5	11,860.7	13,868.2	13,868.2
Overburden: 1,000–2,000 feet								
0–10	5		479.0	2–5		1,817.4	1,817.4	2,712.5
				5–10		895.1	895.1	
10–20	15	15.0	593.0	2–5	84.1	3,324.5	3,408.6	10,329.0
				5–10	96.8	3,828.2	3,925.0	
				>10	73.9	2,921.5	2,995.4	
20–30	25	31.5	339.0	2–5	214.1	2,303.6	2,517.7	10,490.3
				5–10	338.9	3,647.4	3,986.3	
				>10	338.9	3,647.4	3,986.3	
30–40	35	19.0	39.0	2–5	120.5	247.3	367.8	2,299.1
				5–10	203.4	417.4	620.8	
				>10	429.3	881.2	1,310.5	
40–50	45	13.0	10.5	2–5	132.5	107.0	239.5	1,197.6
				5–10	132.5	107.0	239.5	
				>10	397.5	321.1	718.6	
50–60	55	4.0		2–5	37.4		37.4	249.2
				5–10	42.4		42.4	
				>10	169.4		169.4	
60–70	65	2.5		2–5	27.6		27.6	184.0
				5–10	23.9		23.9	
				>10	132.5		132.5	
70+	70+	6.0		2–5	52.3		52.3	475.7
				5–10	76.1		76.1	
				>10	347.3		347.3	
Totals		91.0	1,460.5	All beds	3,471.3	24,466.1	27,937.4	27,937.4
Overburden: 2,000–3,000 feet								
0–10	5		92.0	2–5		349.1	349.1	521.0
				5–10		171.9	171.9	
10–20	15		345.0	2–5		1,934.1	1,934.1	5,861.0
				5–10		2,227.2	2,227.2	
				>10		1,699.7	1,699.7	
20–30	25	24.0	269.0	2–5	163.1	1,827.9	1,991.0	8,296.0
				5–10	258.2	2,894.3	3,152.5	
				>10	258.2	2,894.3	3,152.5	
30–40	35	122.0	234.0	2–5	773.8	1,484.1	2,257.9	14,111.7
				5–10	1,305.7	2,504.4	3,810.1	
				>10	2,756.6	5,287.1	8,043.7	
40–50	45	156.0	143.0	2–5	1,590.1	1,457.6	3,047.7	15,238.6
				5–10	1,590.1	1,457.6	3,047.7	
				>10	4,770.4	4,372.8	9,143.2	
50–60	55	94.0	60.0	2–5	878.3	560.6	1,438.9	9,592.8
				5–10	995.4	635.4	1,630.8	
				>10	3,981.6	2,541.5	6,523.1	
60–70	65	29.5	20.5	2–5	325.8	226.3	552.1	3,680.8
				5–10	282.3	196.2	478.5	
				>10	1,563.6	1,086.6	2,650.2	
70+	70+	16.5	2.5	2–5	143.9	21.8	165.7	1,506.3
				5–10	209.3	31.7	241.0	
				>10	954.9	144.7	1,099.6	
Totals		442.0	1,166.0	All beds	22,801.3	36,006.9	58,808.2	58,808.2

TABLE 6.—*Fruitland Formation coal resources in millions of short tons under indicated overburden, arranged by states according to bed thickness and total coal thickness*—Continued

Coal thickness (ft)		Area underlain (square miles)		Coal resources by bed thickness, in millions of short tons				
Range	Average	Colorado	New Mexico	Thickness of beds (ft)	Colorado	Mew Mexico	Total	Combined total
				Overburden: 3,000–4,000 feet				
0–10	5		33. 5	2–5		127. 1	127. 1	189. 7
				5–10		62. 6	62. 6	
10–20	15		103. 0	2–5		577. 4	577. 4	1, 749. 8
				5–10		664. 9	664. 9	
				>10		507. 5	507. 5	
20–30	25		234. 0	2–5		1, 590. 1	1, 590. 1	6, 625. 5
				5–10		2, 517. 7	2, 517. 7	
				>10		2, 517. 7	2, 517. 7	
30–40	35	34. 0	398. 0	2–5	215. 6	2, 524. 3	2, 739. 9	17, 124. 3
				5–10	363. 9	4, 259. 7	4, 623. 6	
				>10	768. 2	8, 992. 6	9, 760. 8	
40–50	45	48. 5	276. 0	2–5	494. 4	2, 813. 3	3, 307. 7	16, 538. 2
				5–10	494. 3	2, 813. 3	3, 307. 6	
				>10	1, 483. 1	8, 439. 8	9, 922. 9	
50–60	55	55. 0	161. 0	2–5	513. 9	1, 504. 3	2, 018. 2	13, 454. 8
				5–10	582. 4	1, 704. 9	2, 287. 3	
				>10	2, 329. 7	6, 819. 6	9, 149. 3	
60–70	65	20. 0	213. 0	2–5	220. 9	2, 352. 0	2, 572. 9	17, 152. 6
				5–10	191. 4	2, 038. 4	2, 229. 8	
				>10	1, 060. 1	11, 289. 8	12, 349. 9	
70+	70+	40. 0	86. 0	2–5	348. 8	750. 0	1, 098. 8	9, 989. 2
				5–10	507. 4	1, 090. 9	1, 598. 3	
				>10	2, 314. 9	4, 977. 2	7, 292. 1	
Totals		197. 5	1, 504. 5	All beds	11, 889. 0	70, 935. 1	82, 824. 1	82, 824. 1
				Overburden: 4,000+ feet				
0–10	5			2–5				
				5–10				
10–20	15			2–5				
				5–10				
				>10				
20–30	25		6. 0	2–5		40. 7	40. 7	169. 9
				5–10		64. 6	64. 6	
				>10		64. 6	64. 6	
30–40	35		17. 0	2–5		107. 8	107. 8	673. 9
				5–10		182. 0	182. 0	
				>10		384. 1	384. 1	
40–50	45		8. 0	2–5		81. 5	81. 5	407. 7
				5–10		81. 5	81. 5	
				>10		244. 7	244. 7	
50–60	55		12. 5	2–5		116. 8	116. 8	778. 7
				5–10		132. 4	132. 4	
				>10		529. 5	529. 5	
60–70	65		14. 0	2–5		154. 6	154. 6	1, 030. 6
				5–10		134. 0	134. 0	
				>10		742. 0	742. 0	
70+	70+			2–5				
				5–10				
				>10				
Totals			57. 5	All beds		3, 060. 8	3, 060. 8	3, 060. 8

DEVELOPMENT

Approximately 30 known mines and prospect drifts have been excavated in Fruitland coal beds; the majority of these were small truck mines, which were operated briefly for local markets. The coal from them could not compete successfully for broader markets with the higher quality coal produced from the Menefee Formation of the Mesaverde Group in the same areas. As of 1968, the very large Navajo strip mine of the Utah Construction and Mining Co. on the Navajo Indian Reservation in New Mexico is the only mine known by the authors to be currently producing coal from the Fruitland Formation. The output from this mine is used to fuel the steam-operated power plant of the Arizona Public Service Co. near Kirtland, N. Mex.

The locations of most known Fruitland mines are shown in figure 19; some of the data about these mines is tabulated in table 8.

TABLE 7.—*Coal resources of the Fruitland Formation*

[In millions of short tons]

Overburden (ft)	Total coal in beds of indicated thickness			Total
	2-5 feet	5-10 feet	>10 feet	
0-500	4, 021. 1	4, 888. 3	5, 728. 9	14, 638. 3
500-1,000	3, 583. 2	4, 780. 0	5, 505. 0	13, 868. 2
1,000-2,000	8, 468. 3	9, 809. 1	9, 660. 0	27, 937. 4
2,000-3,000	11, 736. 5	14, 759. 7	32, 312. 0	58, 808. 2
3,000-4,000	14, 032. 1	17, 291. 8	51, 500. 2	82, 824. 1
4,000+	501. 4	594. 5	1, 964. 9	3, 060. 8
Total	42, 342. 6	52, 123. 4	106, 671. 0	201, 137. 0

TABLE 8.—*Production and dates of operation of coal mines in the Fruitland Formation*

[N.D.A., no data available]

Number in figure 10	Name of mine	Period of operation	Total production (tons)
1	Archuleta	N.D.A	N.D.A.
2	Talian	1913-15	7, 637
3	Columbine	1938-56	10, 596
4	Cooper	N.D.A	N.D.A.
5	Triple S	1941-51	5, 348
	Shamrock No. 1	1928-36	3, 916
	Shamrock No. 2	1937-41	2, 398
6	Morning Glory	1930-36	4, 207
7	Palmer	N.D.A	N.D.A.
8	Blue Jay	1935-44	3, 135
9	Love	N.D.A	N.D.A.
10	Excelsior (3 shafts)	1927-38	3, 914
11	Schutz (2 shafts)	N.D.A	N.D.A.
12	Prospect pit	N.D.A	N.D.A.
13	Unknown	N.D.A	N.D.A.
14	do	N.D.A	N.D.A.
15	do	N.D.A	N.D.A.
16	La Plata	1893-1902	5, 447
17	Unknown	N.D.A	N.D.A.
18	Mormon	N.D.A	N.D.A.
19	Fort Lewis	1943-49	1, 395
	Henderson	N.D.A	N.D.A.
20	Soda Spring	1928-47	5, 218
21	Cinder Butte (Pruitt?)	N.D.A	N.D.A.
22	New Mexico (Kempton)	1928-45	10, 361
23	Bill Thomas (Morgan)	1931-47	7, 521
24	Jones	?-1918?	N.D.A.
25	Prospect drift	N.D.A	N.D.A.
26	Marcelius (Caudell?)	1924-38	10, 318
27	Blanchard	N.D.A	N.D.A.
28	Black Diamond (Christenson), (3 mines?).	1918-33(?)	N.D.A.
29	L. W. Hendrickson	1929-30(?)	N.D.A.
30	Utah Construction and Mining Co. Navajo (strip).	1963-	[1] 19, 490, 600
31	Prospect drift	N.D.A	N.D.A.

[1] To August 2, 1970.

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