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CONTENTS

THE GLORY OF GOD IS INTELLIGENCE

Cover: Cretaceous coals near Castle Gate, Utah.

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CONTENTS

Sedimentary Environment of the Cretaceous Ferron Sandstone near Caineville, Utah*

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ABSTRACT.—The upper part of the Ferron Sandstone Member of the Mancos Shale, in the northeastern part of the Henry Mountain basin, records the foundering of a deltaic complex which had prograded into the Mancos Sea during middle Carlile (Turonian) time.

Excellent three-dimensional exposures and 53 measured sections in an area covering approximately 5 km^2 provided data for the study.

The shales in the lower part of the studied interval were deposited on the siltstone which capped river channel deposits at the top of the massive lower sandstone of the member. This transition was produced as a major distributary system shifted away from the area. However, sediment brought in by smaller channels and splays maintained an unstable balance for a time which allowed the formation of two thin coal seams and three carbonaceous shale horizons. A northeasterly flowing distributary then temporarily occupied the area. The abandonment of this distributary allowed the formation of the relatively thick (70 cm) upper coal. However, subsidence eventually outpaced peat accumulation, and flooding occurred. An influx of sediment from the southeast kept the southern part of the area from being flooded for a time, but ultimately it too subsided beneath the transgressive Mancos Sea.

INTRODUCTION

Location

The study area is located 10 km east of Caineville, in Wayne County, Utah, along the cuesta held up by the Ferron Sandstone (fig. 1). The map area covers approximately 5 km^2, mostly within sections 13, 14, 23, 24 of T. 28, R. 9. The overlying Blue Gate Tongue of the Mancos Shale has been largely stripped back, leaving excellent exposures of the Ferron beds. Small gullies cut through the cuesta at nearly right angles and provide three-dimensional exposures for the study.

Access is via Utah 24, either from Caineville, 10 km to the west, or from Hanksville, 20 km to the east. A maintained gravel road provides access from the highway to the more northern parts of the study area, and roads and trails cross through the southern part.

Previous Work

Gilbert's (1877) classic study of the Henry Mountains was the first significant geologic investigation of the study area. He described the general stratigraphy and included the sandstone above the Tununk Shale as the Tununk Sandstone. Lupton (1916) described the geology of Castle Valley, paying particular attention to the coal beds of the Ferron Sandstone. He named the Ferron Sandstone and correlated it with nearby sections, including the one described by Gilbert south of the San Rafael Swell, near the Henry Mountains. Spieker and Reeside (1925) reviewed the geology described by Lupton and included it in a regional setting. They proposed a Middle Coloradoan (Carlile) age for the Ferron Sandstone. In later reports (1946, 1949) Spieker discussed the orogenic history of the Wasatch Plateau and eastern Utah and concluded that the Ferron Sandstone could not be definitively correlated to any single orogenic pulse to the west because, faunally, the Allen Valley Shale in Sanpete County was the westward equivalent of the Ferron beds and, in effect, cut the latter sandstone off from the contemporary conglomerates to the west. He therefore envisioned the Ferron Sandstone as a peninsular or coastal sandstone body separated from the Sevier uplift to the west by a north-northeasterly trending embayment of the Mancos Shale.

C. B. Hunt (1946) described the geology of the Henry Mountain region and distinguished the sandstone, shale, and coal in the upper part of the Ferron from the sandstone with thin beds of shale in the lower part. He noted that the sandstones grade eastward and disappear into the Mancos Shale (Hunt and others 1953). Cobban and Reeside (1952) correlated the Cretaceous rocks of the western interior of the U.S. and assigned a Middle Carlile (Turonian) age to the Ferron Sandstone. Katich (1953) postulated a source area to the west or southwest on the basis of transport directions as indicated by cross-bed dip directions. Katich (1954) correlated the Ferron Sandstone with the Funk Valley Formation of the Wasatch Plateau and the Tununk Shale with the Allen Valley Shale. Davis (1954) separated the Ferron Sandstone in Castle Valley into an upper and lower sequence and suggested that the

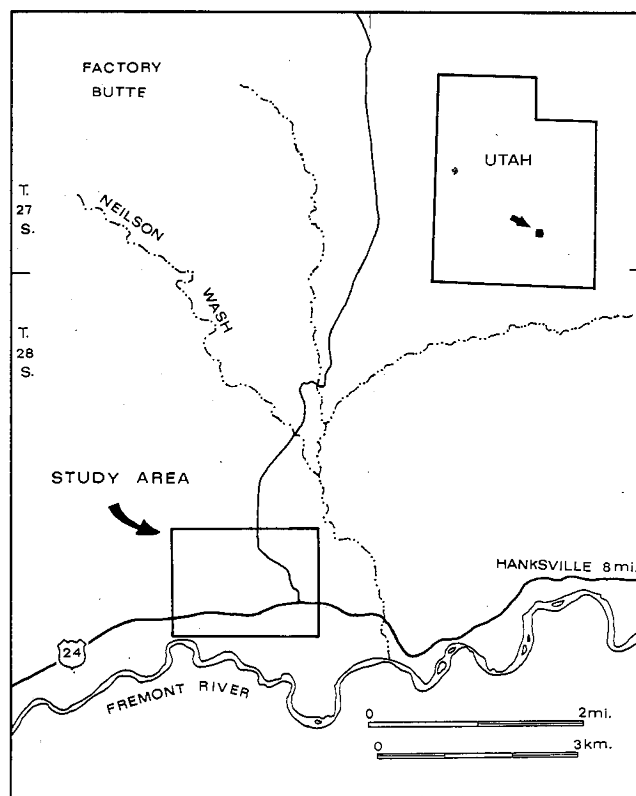

FIGURE 1.—Index map.

*A thesis presented to the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree Master of Science, December 1978. Thesis chairman: J. Keith Rigby.

source area for the lower part was to the northwest while that for the upper part was to the southwest. Knight (1954) carried out a preliminary study of heavy minerals in the Ferron Sandstone from localities in Castle Valley and near Caineville and concluded that there are no readily apparent mineral zones in the Ferron Sandstone which can be used in correlation, and that the sediments were derived from several independent source areas and deposited in different sedimentary realms.

Sarmiento-Soto (1957) zoned the Mancos Shale on the basis of microfossils and concluded that the lower portion of the shale was deposited in deeper water than was the upper, and that the Ferron Sandstone represented a shallow-water interval. Gray and others (1966) correlated selected Ferron coal seams on the basis of pollen assemblages and identified abundant fern spores and angiosperm pollen. Other palynormorphs were extremely limited. Unusual coprolites from the lower portion of the Ferron Sandstone in east central Utah were studied by Balsley (1969) and Balsley and Stokes (1969), who concluded that they were produced by octopuslike organisms, indicating a nearshore marine environment for the lower portion of the Ferron Sandstone.

Cotter (1971) described the characteristics of the river system which must have provided the sediment for the Ferron Sandstone in Castle Valley. The deltaic nature of the Ferron beds was discussed by Hale (1972) who proposed the name Last Chance Delta for the rocks involved. Doelling (1972) and Doelling and Graham (1972) described the coal seams of the Ferron. May (1972) suggested that the Ferron might be Cenomanian rather than Turonian on the basis of palynomorph evidence. Cleavinger (1974) documented environments of deposition of the Ferron Sandstone in roadcuts along Interstate 70, 16 km southeast of Emery, Utah. He recognized open-marine, offshore, interdistributary bay, barrier-island, lagoon, and lower deltaic plain fluvial deposits in his area of study and concluded that these environments shifted rapidly in response to regression and transgression of the Mancos Sea. Further work by Cotter (1974, 1975a) documented the sedimentary results of the interplay between fair-weather processes and storm action, and (1975b) demonstrated the role of deltas in the formation of the Ferron Sandstone and its coals. He also (1976) documented that the Ferron Sandstone of the San Rafael Swell was produced by two separate deltaic systems. The Last Chance Delta prograded towards the northeast into what is now Castle Valley, and the lower, thin, sheetlike nearshore and offshore units in the north were derived from the Vernal Delta which was centered in northeastern Utah. Maxfield (1976) zoned the Mancos Shale on the basis of foraminifera. He suggested that deltaic construction was responsible for a local regression and that the later transgression of the Mancos Sea over the Ferron beds began in the north, with the Henry Mounain area being covered later.

Methods

A preliminary map of the outcrops of the three coal beds which exhibit the greatest lateral continuity was produced by walking out each unit and plotting the outcrop on enlarged aerial photographs. This provided a framework for locating the most favorable outcrops for measuring sections and for later detailed mapping.

Fifty-three sections were measured to provide control for establishing the vertical and lateral relationship of the rock bodies (fig. 2). A fence diagram (fig. 3) illustrating this relationship was constructed and, because of the rapid facies changes involved, field-checked in order to incorporate detail not attainable using measured sections alone.

The area was also mapped at a scale of 1:5,000, using enlarged aerial photographs and a base map enlarged to the same scale (fig. 4). Paleogeologic maps of selected horizons were also made in the field. They were prepared on the same enlarged base map and compared with aerial photographs and the fence diagram. Such a three-dimensional compilation allowed a detailed description of the rock units and the sequence of events related to their formation.

Acknowledgments

The author wishes to express special appreciation to J. K. Rigby for encouragement and assistance, both in the field and during manuscript preparation. The assistance of J. L. Baer, who served on the committee and read the manuscript, is also appreciated. J. R. Bushman also read the manuscript. W. D. Tidwell helped identify some of the fossil plants. Malcom Rogers of Teasdale, Utah, and John Johnson of the Atlas–Dirty Devil Mining Company provided helpful information about the study area. My parents let me borrow their camper for some of the fieldwork. Special thanks also go to my wife and our field crew (Judy, Jeanie, Bonnie, and Wade) for their help and support. A grant by Gulf Oil Company helped defray expenses of the study.

GEOLOGIC SETTING

The study area is located on the eastern flank of the northern part of the Henry Mountain structural basin. Rocks in the area dip gently to the west, in contrast to the steeply dipping beds of the North Caineville reef, which form the western flank of the structure 10 km to the west.

Drainage is into the Fremont River which meanders through a valley immediately south of the study area. Erosion of the present topography has been controlled, in large part, by rock types and gentle structure in the area. The more resistant sandstones generally cap the ridges or small hills, and shale and mudstone form the slopes and valleys. Evidences of stream piracy and changes in drainage patterns are clearly apparent. For example, the drainage which initially emptied into Nielsen Wash has been captured by a stream flowing southwestward into the Fremont River.

Erosion appears to be the major geologic process operating at present, although at no time during the fieldwork in 1977 and 1978 was water flowing in any of the streambeds. Occasional flash floods are produced by sudden summer showers and lack of vegetation on the unprotected clay soil, over large collecting areas. These floods probably provide the only instances when water flows along the streambeds. Armored mud balls in some of the stream beds indicate significant sedimentary load and water volume at times. Scarcity of vegetation facilitates geologic investigation.

The Ferron Sandstone rests conformably and gradationally upon the Tununk Shale Member of the Mancos Shale and is in turn overlain gradationally by the Blue Gate Shale Member. The Mancos Shale represents sediments deposited during a major marine transgression of the Upper Cretaceous. Within the overall transgressive-regressive sequence, however, several episodes of transgression and regression are evident. Wiemer (1960) documented four major transgressive-regressive cycles in Coloradoan and Montanan rocks of the Rocky Mountain area and suggested that subsidence or tectonic control was more important in these cycles than sediment supply. The Ferron Sandstone represents the earliest regressive pulse following movement of the Mancos (Tununk) Sea across east central Utah (Cotter 1976).

Documentation and description of the depositional environments associated with this regressive to transgressive sequence, in particular the transgressive phase, are the principal purposes of this study.

LITHOLOGIES

Sandstone

Sandstone units exhibit a range of grain sizes, compositions, structures, and lateral and vertical expression, but the bulk of the sandstone is a tan-weathering, medium-grained, quartz sandstone. It is convenient to divide the sandstones into three major types for description: (1) the lower massive sandstone, (2) sandstones interbedded with mudstone and coals between the lower sandstone and the upper coal, and (3) the sandstone above the upper coal.

The lower massive sandstone is a gray to buff, medium-grained, porous quartz sandstone. The quartz grains are well sorted and generally subangular to subrounded. Scattered dark mineral grains occasionally produce a slight salt-and-pepper texture, and limonite staining is very common. This unit generally weathers to a tan color, but red, brown, yellow, and very light gray beds are also common. The lower sandstone is the thickest and laterally most extensive sandstone in the study area. It grades into the underlying Tununk Shale. Siltstone and sandstone layers at the contact became coarser and thicker upward until the massive sandstone was produced. There is a prominent interbedded shale marker zone near the top of this unit. This shale is not present in some outcrops but thickens and

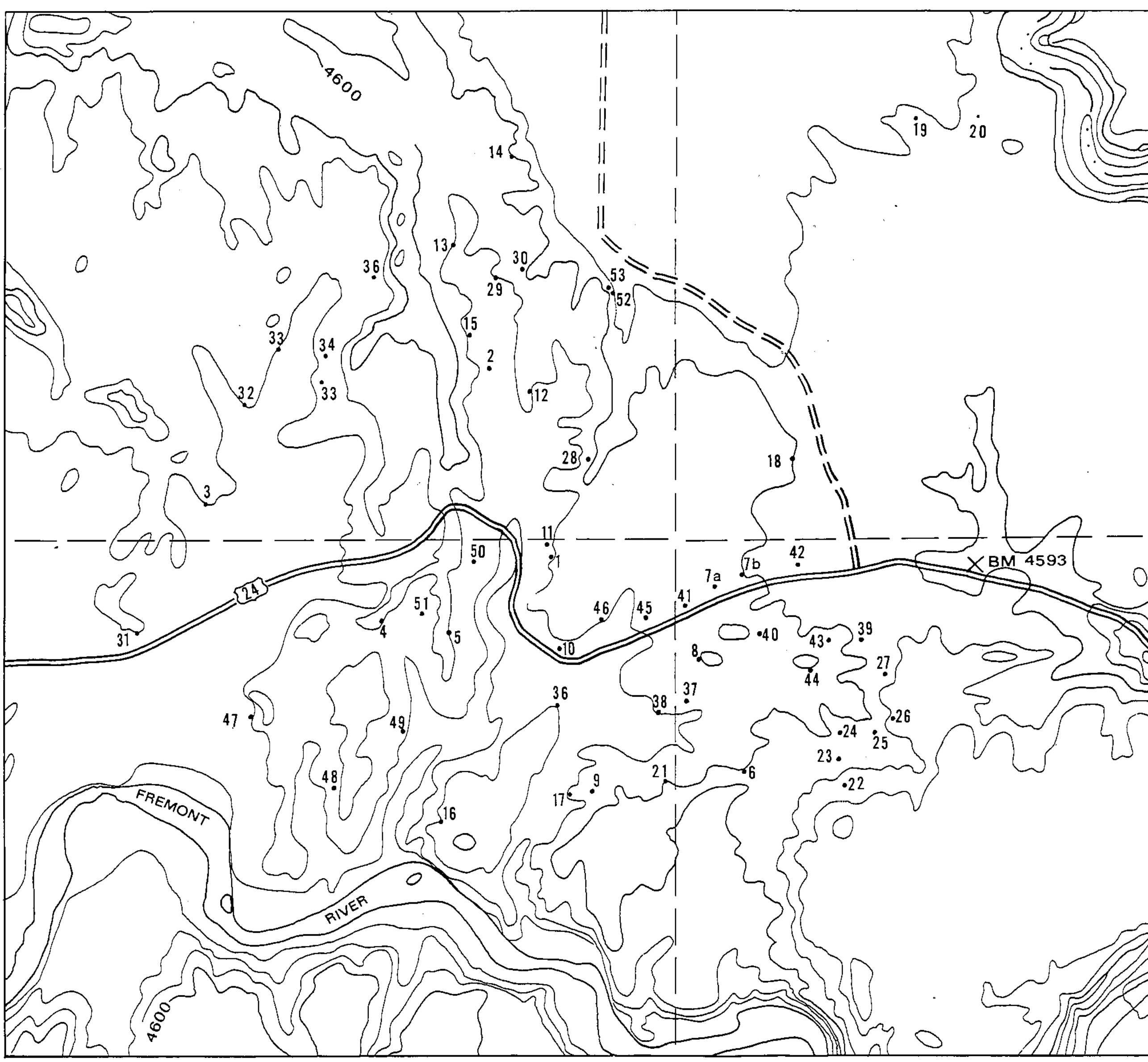

FIGURE 2.–Map showing location of measured sections on USGS Factory Butte 15-minute quadrangle base map.

coarsens to produce several feet of mudstone and carbonaceous shale elsewhere. At some localities this shale thickens at the expense of the overlying sandstone which interfingers into the finer sedimentary layers and disappears.

Spherical red concretions, ranging from 3 to 30 cm in diameter, are locally abundant, as are impressions of wood fragments. The upper portion is also extensively bioturbated. Heavy mineral lenses, which weather a dark brown, are occa-

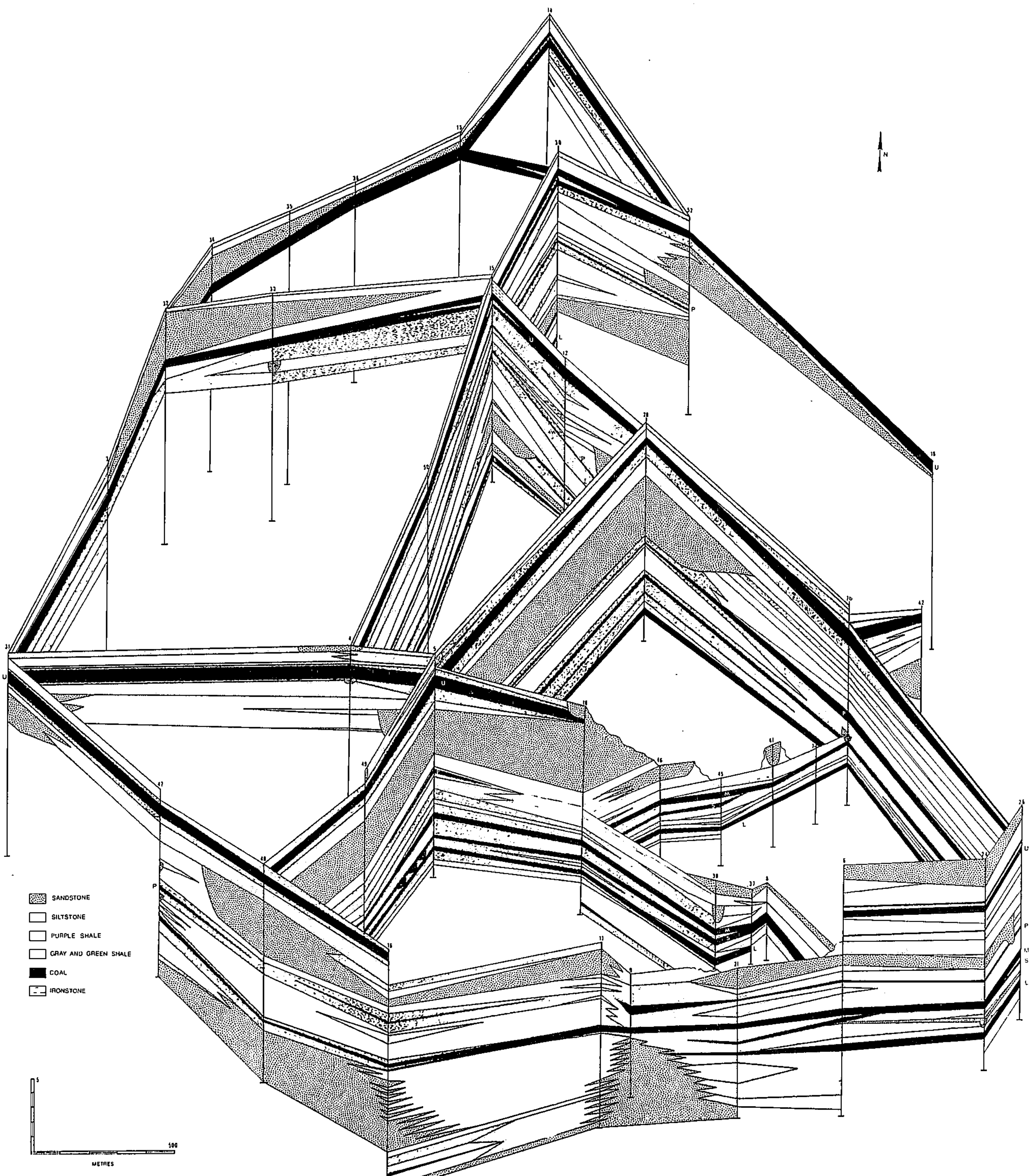

FIGURE 3.–Fence diagram illustrating stratigraphic relationships within study area. Vertical exaggeration 50x. U–Upper coal, P–Purple marker unit, M–Middle coal, S–"Stray" coal, L–Lower coal.

sionally present, but are not abundant or thick and are limited to the zone above the shale marker zone.

Sandstones above the massive basal unit and below the upper coal are lenticular and of limited areal extent. They can be divided into two general types on the basis of lithology and outcrop characteristics. The first type is a thin (usually less than 60 cm thick) unit, easily recognized when mapping. It is a very fine sandstone composed of quartz with abundant dark minerals and locally significant amounts of clay. Siderite is often present as well. Color varies from olive green to red brown on a weathered surface. The color appears related to underlying strata, for the olive green color predominates above green shale, and the red brown color is dominant over ironstone layers. Sandstones of this type are found scattered throughout the interval between the massive lower sandstone and the upper coal zone. They are often current laminated at the top and may show evidences of small channels, or they may be sheetlike laterally. Intensely bioturbated or rooted localities are common. In most cases, they thin and wedge out laterally.

The second type of this kind of sandstone is generally thicker bedded, 60 cm or thicker, and is also easily recognized when mapping. These are medium-grained, well-sorted, quartz sandstones which weather tan and in general are similar to the lower massive sandstone. These units generally fine upward and are often capped with a silty unit which may be either orange and soft or light gray weathering and rich in organic matter. These beds often contain concretions and wood impressions, and some of the best petrified wood from the area came from one such unit. Bioturbation or rooting is often intense near the top. Grit and gravel may be found scattered in the lower part. It is also common for the channel sandstone bodies to depress underlying sediments, occasionally resulting in the development of small faults there (fig. 5). The lower contact is usually sharp and may show sole markings in good exposures. The upper contact is usually gradational. These units may fine laterally into a siltstone, wedge out under a siltstone, or terminate abruptly against shales or siltstones. A definite trend of elongation is another of their distinctive characteristics.

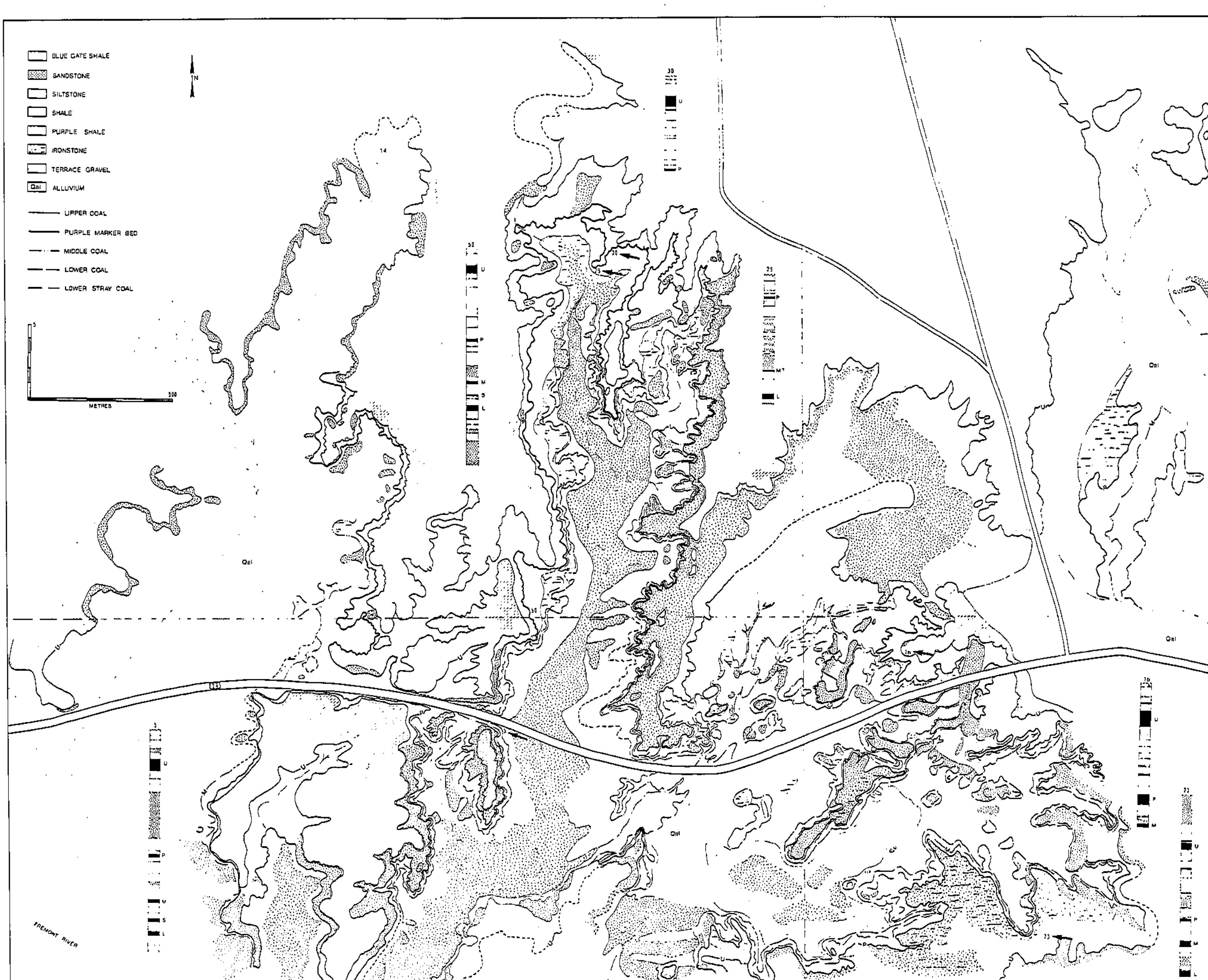

FIGURE 4.—Geologic map of study area. Parts of selected measured sections are included to illustrate detail since many areas of map show only dominant lithology. "Stray" coal outcrop omitted for lack of space. It essentially parallels middle coal outcrop.

FIGURE 5.–Small normal fault offsetting middle coal beneath thick channel sand near measured section 25. Slickensides are visible where fault plane is exposed. Fault probably developed as result of differential compaction and subsidence caused by weight of sandstone above.

Siltstone

Siltstone beds are commonly associated with sandstone units and are of three major types: (1) yellow and orange gray to light gray, (2) purple, and (3) green gray. Yellow orange to light gray siltstone beds often cap the basal sandstone and some of the larger sandstone units higher in the section. The siltstone beds are usually much more extensive laterally than the associated sandstone units. The yellow color is derived from limonite staining and is particularly obvious when excavated, but, because of the extremely soft nature of these rocks, they weather quickly and are often covered by slopewash from units above. The lower contact is gradational, and sandstone lenses are often interbedded with these siltstone beds.

Purple siltstone units are also usually soft and at times form covered slopes, but occasionally they form a slightly steeper slope or a poorly expressed ledge. These units weather light gray on the surface, but a freshly broken surface shows the purple tinge and abundant plant fragments in a fine quartz and clay matrix. The purple siltstones are found interbedded with fine sandstone layers at the top of the lower sandstone but are not laterally extensive at this level. Higher in the section, they are more widespread and often fine upward into shale or mudstone. Root traces are common.

Green gray siltstone beds are less abundant than the purple siltstone and often grade into it. Although not abundant, plant fragments are occasionally observed in the green gray units. Also, some greenish weathering siltstones are light purple on a fresh surface, indicating a gradation. Transition from gray to green to purple is common, both laterally and vertically, and is usually simply a gradual color change without a distinct boundary. Purple siltstone beds generally interfinger with the yellow orange to light gray siltstone units so that a distinct boundary is discernable.

Mudstone

The argillaceous rocks are divided into purple, green, and gray units, partly because of the ease of tracing these units in the outcrop and partly because it was hoped that the colors would be significant. As with the siltstones, these variously colored units often grade from one to another or from shale to siltstone.

The most significant characteristics of the purple mudstones are the abundance of plant fragments and the color variation. The color varies from red brown to purple, with yellow streaks of jarosite more abundant as the organic content and fissility increase. Coals or carbonaceous shales are associated with the purple shales, and in only two cases were coals found on a substrate other than purple shale. The purple shales may be blocky weathering, like the green gray mudstones, but they become very fissile near the top, especially under the coal. In general, as the organic content increases, the fissility increases in these rocks. Slickensides, similar to those observed by the writer in the fireclays of the eastern Carboniferous coals, are also common. In general, the purple shales strongly resemble West Virginia and Pennsylvania fireclays in color, texture, organic content, and slickensides. A major difference, however, is the lack of obvious root traces in the Ferron shales. This is probably the result of differences in vegetation since the easily identifiable *Stigmaria* traces are not present in the Ferron.

The purple mudstones produce a purple outcrop that is readily recognizable, but in some cases these rocks may also produce a white or light gray outcrop. The purple-outcrop-producing units are usually fissile shales with a high content of organic matter and dark red brown to purple color on a fresh exposure. One unit of this lithology, approximately 5 m below the upper coal, is one of the most readily recognizable and extensive units in the mapped area. It has an average thickness of over 100 cm, is very dark and fissile, and occasionally has a carbonaceous shale in the middle or upper part. The white-weathering purple mudstones are usually not fissile and are lighter colored on fresh surfaces.

The purple shales probably represent soils developed in areas of extensive plant growth, and were, at least at times, subaerial or above the water table (Dunbar and Rodgers 1957). The more fissile shale is probably sediment deposited at the top of such a soil zone which, along with plant material, helped produce the fissility noted at the top of such units.

The green and gray mudstones have much less organic material and are usually blocky in outcrop. Plant fragments and evidences of rooting are also rare. These mudstones range from gray to green, but a gray green color is most frequently encountered, except in the Blue Gate Member, above the upper coal, which is usually gray. Fresh surfaces are especially difficult to differentiate, and sometimes the weathered surface is the primary basis of identification.

A shark tooth and abundant fish scales were found immediately above the upper coal in the Blue Gate Member, and the gray and green shales below the coal provided a few small phosphatic fragments which appear to be fish scales.

Coal and Carbonaceous Shale

The coal seams range in thickness from thin, isolated stringers of coal to extensive beds 80 cm thick. The coal beds appear to have a high ash content and frequently grade into bone and carbonaceous shale. In many exposures, gypsum filling is found in the cleat or in a layer at the base of the coal, and abundant yellow streaks of jarosite are often found in the lower portions of some of the coals.

There are three significant coal seams. The thickest and uppermost coal is referred to informally as the upper coal in this study and corresponds to the Upper Coal Zone of Doelling (1972). It is also the most uniform coal seam in the area and ranges in thickness from 40 to 80 cm, except for measured section 10 where it is cut out. Most exposures show about 70 cm of coal. The coal becomes dirty in measured section 42, but otherwise this bed is the cleanest of the coal seams present. Gypsum is commonly found in the cleat or in a layer at the base of the coal. In some of the measured sections, at measured section 31 in particular, a definite sulfur odor is produced as the coal is excavated, indicating high sulfur content.

The middle coal is located stratigraphically approximately 7 m below the upper coal. It varies from 0 to 50 cm thick and grades from coal through bone to carbonaceous shale. It often has a gypsum layer at the base or within the lower 10 cm of the coal seams, and jarosite streaks are common.

The lower coal varies in thickness from 0 to 50 cm and like the middle coal varies from coal through bone to carbonaceous shale within the mapped area. It occasionally has a gypsum layer at the base, and yellow streaks of iron sulfate are abundant in most exposures, helping to distinguish it from the other coal seams. Both the middle and lower coal beds fall into what Doelling (1972) referred to as the Lower Coal Zone.

There is a stray lenticular coal that occurs between the middle and lower coals in several measured sections. It is extremely variable and is a split from the middle coal above it. Another thin, discontinuous coal occurs locally about 2 m below the lower coal, but it is limited areally and is predominantly a carbonaceous shale.

Doelling (1972) recorded that the coals of the Henry Mountain field have been classified as high volative B bituminous and give the following average proximate analysis: moisture–5%, volative matter–35.3%, fixed carbon–42.9%, ash–15.3%, sulfur–2.85%, and Btu/lb.–11575. This would indicate that these coals are high ash, high sulfur, and moderately high Btu.

Other Rock Types

Gypsum is present as crack fillings in all other lithologic units, as well as being found in distinct layers in the shales and beneath coals. It occasionally forms clumps in some layers, resembling the accumulation of salts formed around vegetation. Selenite plates as long as 25 cm are relatively common. A widespread, but thin (3 cm), layer of gypsum resembling light brown satin spar is found above the upper coal.

Ironstone is abundant, particularly associated with green shales. A mappable ironstone zone immediately above the distinctive purple shale in the upper part of the section shows some lateral continuity. Ironstone is found in layers 3–15 cm thick or in concretionary masses as large as 1 m in diameter. Generally, the concretionary masses weather rapidly and fracture or crumble, leaving only fragments in a pile. Several concretions have poorly preserved petrified wood or plant debris in their cores, and most of the fossils found in the member are of the same material.

Several large barite crystals were found at the top of the orange siltstone interval above the lower sandstone at measured section 1 (fig. 2).

FOSSILS

Plant fragments are abundant, but most are not identifiable. The purple shales are particularly rich in plant fragments. These fragments indicate that reedlike vegetation was most abundant. A seed cone 1 cm long was found in an ironstone outcrop between measured sections 16 and 36. A *Protophyllocladus*-like leaf fragment was found in the ironstone above the middle coal at measured section 7b.

Several poorly preserved wood fragments were collected near measured section 52, but alteration to hematite and limonite has destroyed internal structure and prevents identification. The log preserved in the upper coal near measured section 51 retained most of its internal structure although slightly compressed (fig. 6). It is an angiosperm, resembling *Paraphyllanthoxylon. Paraphyllanthoxylon* has been collected from Upper Cretaceous deposits in Arizona (Tidwell 1975, p. 139).

Abundant phosphatic fish scales are found in the gray shales above the upper coal in most localities. A shark tooth was collected from the slopewash above the upper coal at measured section 12.

DEPOSITIONAL SIGNIFICANCE OF OBSERVED UNITS

Sandstone

Most of the sandstone bodies in the area are channel-fill deposits. This is indicated by the general geometry of the sandstone lenses, the well-oriented cross-bedding, point bar deposits, upward decrease in grain size and bed thickness, local basal conglomerates, evidence of scour, and the elongate map pattern of the deposits. All the above are characteristic of fluvial deposits, as described by Pettijohn and Potter (1965). Further, the adjacent levee and swamp deposits fit well into a channel-fill interpretation for these sandstones.

A lobate sequence of alternating siltstone and sandstone in the NE ½ of sec. 23 (fig. 4) is probably a channel mouth deposit, formed as a channel moved out into an interdistributary bay which had developed over a swamp or marsh. Study of the Ferron Sandstone along the western side of the Henry Mountain basin has documented thick fluvial sandstones there (Rigby 1978 pers. comm.). The upper part of the lower massive sandstone in the present study area represents similar deposits. Sandstone lenses above this lower unit are also predominantly channel-fill sandstones.

Transport directions were determined with the use of elongation and cross-bedding relationships, which indicate that currents in seven of the mapped channels flowed toward the northeast, eleven toward the east, and four toward the north or northwest. The average transport direction is northeast and suggests regional depositional slope, but, since the area is small,

FIGURE 6.–*Paraphyllanthoxylon*-like log preserved in upper coal seam at measured section 51.

local subsidence and depositional factors may have played a part in determining the location and direction of some of the channels.

Some of the channel-fills are highly sinuous, in particular those which do not terminate within the mapped area and probably represent through-flowing, meandering streams. Others, less sinuous, usually terminate within the study area, probably related to crevasses or avulsion.

The thick sandstone above the purple marker zone is elongate, but locally reaches a thickness of over 5 m (fig. 7). It probably developed as a major river changed courses and flowed into a trough, but then changed courses again. The latter shift probably occurred when the temporary advantage of the trough-controlled channel was eliminated—as if it were filled with sediments.

The sandstones above the upper coal are extremely bioturbated, reflecting the rapid encroachment of the sea over them. They appear to have been final pulses of coarse terrigenous sediment into the area, immediately prior to submergence beneath the Mancos Sea.

Siltstone

The siltstones, in particular the yellow orange and purple siltstones, are predominantly natural levee deposits. Their position above and laterally adjacent to the sandstone units, intense rooting and burrowing, and the oxidized nature of the sediment support this conclusion, as suggested by Coleman (1976, p. 34) for similar deposits elsewhere. The interfingering of organic mudstones with silty mudstones and the gradual fining upward from the coarser channel sandstone may also indicate natural levee deposits as suggested in an idealized sequence by Reinick and Singh (1973, p. 246).

Some thin sheets of siltstones are probably the outer edge of splays since they are gradational with associated sandstone channels, such as below the middle coal in the vicinity of measured section 45 (fig. 2).

Gray and Green Mudstone

Gray and gray green mudstones represent sediment deposited under a variety of conditions. Shale of the Blue Gate Member of the Mancos Shale is generally a gray marine shale or mudstone which weathers light gray to tan in most exposures. However, the shales in the Ferron Sandstone interval vary in color from gray to gray green to light purple, excluding the dark red and purple shales. This variation, with the absence of fish scales, shark teeth, and mollusks, indicates that perhaps marine influence was minimal during deposition of many of these units.

MacCarthy (1926) concluded that most sediment color is determined by iron compounds and documented the colors produced by ferric, ferro-ferric, and ferrous ions in sediments. He stated that ferrous minerals impart little color to the rock, ferric minerals are red or yellow, and hydrous ferro-ferric minerals are blue, mixtures of ferro-ferric and ferric ions produce greens, and mixtures of ferro-ferric and other ferric minerals are purple.

Within such a framework, the gray sediments in the study were probably deposited under reducing conditions or low iron concentrations. The gray green units were deposited under less reducing conditions, and the purple units under oxidizing conditions. Diagenesis and weathering may have obscured some original characteristics, but the field relationships appear to support such a differentiation based on colors. The transition upward from gray to red or purple shale is well shown in most sections, and is particularly striking in the siltstone units beneath the upper coal in measured sections 13 and 16. This change indicates a shift to higher EH conditions. The upward transition from purple or red siltstone and shale to gray or gray green units is well shown in measured sections 24 and 25. This change indicates a shift toward low EH conditions.

Gypsum is commonly found in the purple or gray shales and siltstones and much less frequently in gray green shales. However, ironstone concretions are common only in the gray green shales. This finding is probably an indication of the brackish nature of the environment under which the gray green shales were deposited relative to the shallow-marine environment under which the gray shales developed, and the high rate of evaporation in the marshes where the purple shales accumulated. On the basis of observed field relations, the gray units probably represent predominantly marine conditions, while the gray green mudstones were probably deposited in brackish areas cut off from free access to marine influences.

Purple Shale

Research on the origin of the fireclays or seat earths of Carboniferous coals has been extensive and has produced a variety of conclusions. For example, Weller (1930) stated that at least intermittent subaerial exposure was necessary for formation of the soil-like seat earths and fireclays. Huddle and Patterson (1961), on the other hand, showed that all kinds of seat earths could have formed in swamps. Moore (1968) provided evidence to show that the locus of formation of these types of sediments lay within a region of broad, relatively flat fresh or brackish shallow water. Regression or sediment buildup would have been accompanied by an advance of hydrophytic vegetation, followed in succession by a higher xerophytic flora. Roots and rhizomes would have been incorporated in muds and vegetation established although clastic sedimentation continued. At this point, the environment became acidic, and leaching allowed the formation of kaolinite and the removal of iron. Sedi-

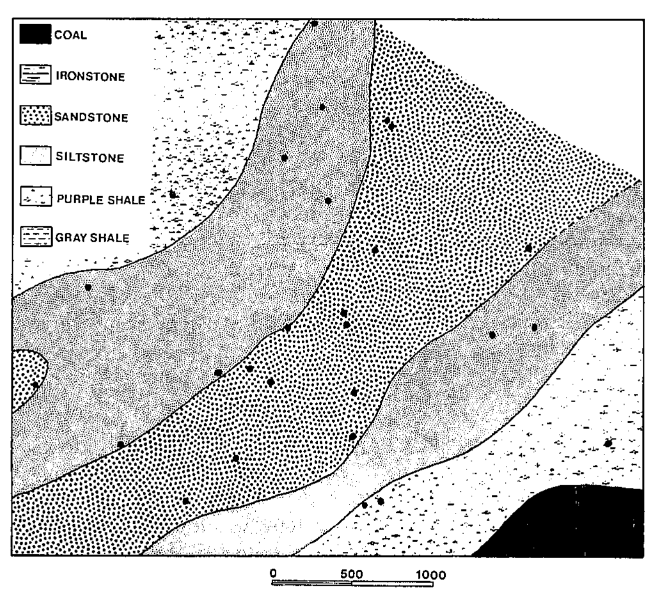

FIGURE 7.—Large sandstone above purple marker unit. Map shows sandstone channel-fill flanked in turn by siltstone, purple shale, and coal.

ments of this stage are highly organic and often slickensided following compaction due to dewatering and decay of roots. This represents the establishment of a base level condition, and the region would have been critically balanced with regard to drainage. Standing water became stagnant and the pH below 3.5 to 4.0. The last deposited sediment would be bedded and would contain abundant organic matter, which would be preserved, for low pH reduces microbiological activity. The critical balance relative to drainage is indicated by local interbedded marine deposits.

From this stage, if conditions of pH, water, and organic accumulation were maintained, peat would be formed. Lack of correlation between thicknesses of the coal seam and associated seat earth is a result of this succession of events and the delicate balance necessary to maintain any particular stage.

The shale beneath the coal beds in the study area appears to fit the model proposed by Moore (1968) very well. In general, the purple shale grades upward from mudstone, which becomes more rooted until a zone of slickensides and abundant organic material occurs. A thin fissile zone of shale with coal streaks may occur above the rooted rocks. Some coal beds show a sharp transition from clay to coal, and others grade from shale through carbonaceous shale to dirty coal. This difference demonstrates the effect produced by even small amounts of sediment during peat development.

Purple shale is also found locally above the coals, indicating a shift back to conditions of sediment influx, although vegetation was not eliminated. Prominent purple shale zones without coals, or with only carbonaceous shale zones in the middle of the bed, are examples of the process that did not go to completion, as for example the purple marker unit in the NW ½ of sec. 24.

Two sequences of environments and sediments are possible in these shales, according to the model proposed by Moore (1968). In one, the vegetation advances, producing typical red purple shale. Stagnation and low pH conditions are reached, and organic deposits begin to form. An influx of fresh water and fine sediments, however, raises the pH and introduces sediment to the area again, perhaps to be inundated by the sea or covered by coarse sediments brought in as splays or as channel fills at a later time. Such a sequence of events would result in formation of a purple shale above a coal or carbonaceous shale.

In the other sequence, subsidence may be sufficiently rapid to allow flooding of the area by the sea and would produce an abrupt change from carbonaceous shale or coal to gray marine shale.

Rocks associated with the lower coal and "stray" coal above it usually follow the first sequence. The middle coal shows evidence of deposition, following the pattern of the first sequence in most localities, except for an area through the center of the mapped area which was evidently flooded during deposition. The purple marker horizon (fig. 2) is perhaps the best example of deposition resulting from the first sequence. These beds show a general transition from purple shale to carbonaceous shale and then back to purple shale again, except for the trough through the center of the area where a carbonaceous shale was not deposited in some localities (fig. 3). The upper coal in the south follows the first sequence, as well, but most of the northern part was apparently flooded by the sea, thus following the pattern of the second sequence. It seems that a gradual transition from peat deposition through increased influx of sediments to marine dominance is more common than an abrupt change to marine sedimentation, probably because flooding is a result of slow subsidence which allows fine clastic sediments to move into vegetated areas. The weight of such clastic sediments over the peat may then actually increase local subsidence by compacting the underlying peat.

Coal and Carbonaceous Shale

Identifiable fossils are rare in the study area. On the basis of plant fragments found immediately beneath the coal seams, however, the vegetation was reedlike in nature. These plants may have been a pioneer assemblage, however, with trees growing later as an upper story. A small, poorly preserved knot was found in carbonaceous shales of the purple marker unit at measured section 7 and was associated with abundant reedlike impressions. This relationship suggests that trees were probably present or nearby during peat formation in at least some localities. Vitrain bands in the coals also indicate the presence of woody tissue.

Huddle and Patterson (1961) suggested that the plants which grew in the available substrate were the same kind that contributed to the formation of Carboniferous coals. If this is also true for the Ferron coal seams, reedlike plants would make up the bulk of the coal since such plants are most commonly found in the shales both above and below the coal, indicating a marsh rather than swamp environment for the coals in the study area. Gray and others (1966) identified abundant fern spores and angiosperm pollen in the Ferron coal beds of Castle Valley, and a similar assemblage may be present in the study area.

The coal beds in the area are composed of relatively high sulfur coals with abundant jarosite which may have formed as the result of the oxidation of pyrite in a relationship similar to that between jarosite and pyrite noted by Young (1976, p. 8) in coals of the Blackhawk Formation in the Book Cliffs.

The origin of sulfur in coals has been debated for decades, with proposals ranging from precipitation as organic sulfur to reactions between iron present in subsoil water and H_2S derived from organic material being suggested as the means by which the sulfur accumulated. Yorovskii (1960) convincingly proposed that sulfates derived from seawater may be responsible for much of the sulfur in coal. He suggested that (1) sulfates of seawater are the chief source of sulfur that give rise to FeS_2; (2) fresh water containing iron is the second essential component; (3) possible ingress of ferruginous solutions throughout the whole period of coal formation, where the roof consists of limestone or sandstone, affects the process; (4) intensity of reducing conditions, including bacteria, is important; and (5) reaction (acidity or alkalinity) of the medium coalification affects the process and amount of sulfur present.

The coals of the study area fit the model of Yorovskii (1968) well in that they are relatively high-sulfur coals, and the abundance of iron and calcium sulfate is readily apparent. A possible illustration of the effect of ferruginous solutions where the roof consists of sandstone is found beneath the upper sandstone, west of measured section 23. In this location, the sandstone overlies approximately 2 m of mudstone and shale above the upper coal. The color of the fracture staining grades from red immediately below the sandstone through orange to yellow immediately above the coal. This may be an illustration of iron-bearing solutions from the sandstone above interacting with sulfur in the sediments below, following the model proposed by Yorovskii (1968). It may be that iron is a critical factor necessary to fix the sulfur, during both peat formation and diagenesis.

A relationship between the incursion of seawater and increased sulfur content is also noted in some coals of Pennsylvania (George Pedlow III 1975 pers. comm.).

Eighteen samples from the middle coal were analyzed for sulfur. They were taken from the upper 5 cm at measured sections 5, 6, 7a, 7b, 9, 10, 11, 12, 16, 17, 21, 36, 38, 39, 41, 46, 49, and 50 (fig. 8). These sections and this coal bed were chosen because of the variability of rock types overlying and underlying the coal seam. The samples were gravimetrically analyzed by Rocky Mountain Geochemical Corp. The results showed a range from 0.77% to 2.29% sulfur, but a relationship to lithologies above or below was not conclusively demonstrated.

The highest sulfur values are in coals capped by sandstone and ironstone (measured sections 7a, 50). This finding agrees with the model suggested by Yorovskii (1974). However, the second and third lowest sulfur values are also found in coals capped by sandstone and ironstone (7b, 11). The difference may be that the high-sulfur coal (7a) is capped by purple shale then ironstone while the low-sulfur coal (11) grades upward to purple shale, then through gray shale to ironstone. Further, the sandstone rests directly on the low-sulfur coal (7b) while the high-sulfur coal (50) is capped by green shale, then sandstone.

Measured sections with silt or sand immediately above or below the coal generally have a higher sulfur content, but exceptions (measured sections 6, 7b, 10) are common. Gray silt and shale over the coal are associated with sulfur values of 1.34% or above. Green shales are generally found above coal with sulfur content of 1.05% or lower. Purple shales above or below the coal seem to have no relationship with sulfur content since they are found associated with low, moderate, and high sulfur values.

These data were plotted (fig. 8) and compared with the middle coal isopach and the paleogeologic maps of overlying and underlying strata. However, no conclusive relationship could be demonstrated.

Appendix 2 shows sulfur values for other samples taken from the lower part of the coal beds. The value for measured section 6 is nearly double that for the top of the bed, as recorded in Appendix 1, an indication that significant variation may exist vertically within a coal bed. The sandstone of measured section 7b appears to have cut out the coal, probably affecting the sulfur values for the sample since it would not be from the upper part of the coal like the other samples.

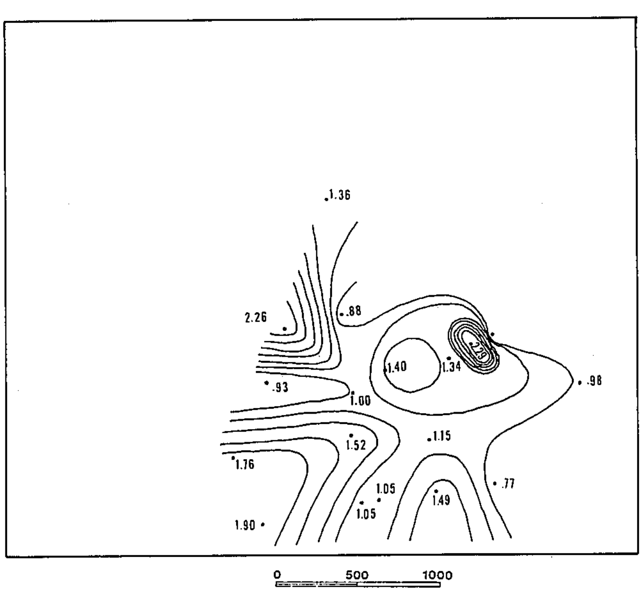

FIGURE 8.–Sulfur concentration map for middle coal. Values are percent sulfur, and complete section of studied strata is represented.

The difference in sulfur content between coal showing prominent yellow jarosite streaks and coal without streaks is shown for the upper coal. The difference is as might be expected, but appears to be a minor factor in this case.

The amount of uranium in the coal being mined north of Factory Butte is probably partly the result of concentration of uranium solutions by reaction with humic acid from the peat. Such concentration occurs following the death of the plants, when lignin is transformed to insoluble humic acid which in turn concentrates uranium from dilute solutions in natural waters and sediments. Szalay (1964) described this process, which involves leaching of uranium salts from granite and other uranium-bearing rocks. Such leaching generally produces solutions of 100 mg uranium per ton of water. Sorption of the uranium by humic acids of peat involves an enrichment factor of 10,000 to 1 and produces a concentration of 100 to 1000 grams of uranium per ton of organic matter. Secondary mineralization may then take place under the influence of local chemical environments. Concentrations up to 0.02% in coal being mined north of Factory Butte fall within the 0.1–.01% range observed by Szalay.

Ironstone

Most ironstone units in the study area are structureless and fracture readily into small pieces that weather dark red to nearly black. Three types of ironstone are recognizable: (1) elongate concretions lying roughly parallel to the bedding, (2) small, more nearly spherical concretions, (3) discontinuous sheets.

The elongate concretions are thought to be the result of decay of logs buried under stagnant, acidic conditions, under which siderite or other iron-bearing minerals are precipitated around and in the log. Much of this process is accomplished by iron-bearing groundwater solutions following burial (Degens 1965, p. 125).

In most cases, the original organic material is completely removed, leaving a structureless concretion which breaks apart into many small fragments when exhumed later by erosion. Decay prior to burial and flattening following burial help to destroy the original structure. However, a few well-preserved logs are present in a shale parting in the large sandstone in the SE ¼ of sec. 14, where this unit goes to the subsurface. Evidently decay was inhibited by relatively quick burial, and structure of the original wood was partially preserved as the ironstone developed around and in the woody tissue. Figure 9 shows a flattened log protruding from shales beneath a sandstone ledge. Fragments of the log have weathered out and are in the foreground. Although the log has been flattened, its external appearance is preserved and the woodlike texture is obvious. The ironstone staining does not extend more than 2 or 3 cm beyong the log into the surrounding mudstone.

Another flattened log is shown in figure 10. It lacks obvious woodlike texture. However, it is exposed on the opposite side of the small outcrop pictured, and its loglike shape shows clearly. In this case, decay was probably more extensive and preservation was intermediate between the well-preserved logs and the completely structureless concretions.

Figure 11 shows a small branch surrounded by a thick ironstone accumulation. This example suggests that only a

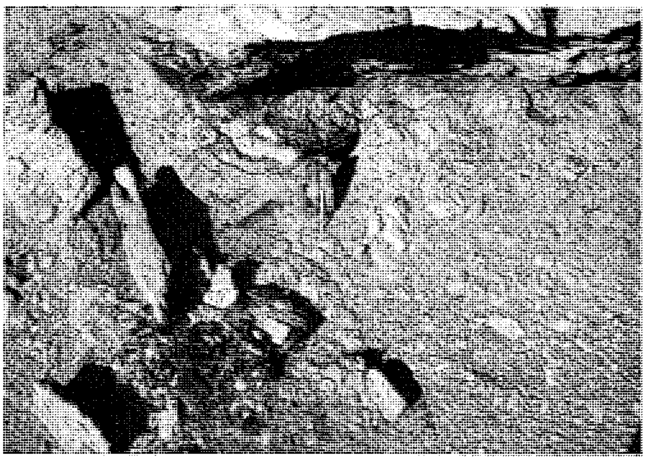

FIGURE 9.–Portion of flattened log protruding from green shales below sandstone ledge near measured section 52.

FIGURE 11.–Large ironstone mass with small limb in its core. Arrow indicates undisturbed fragments of limb; scattered fragments in right foreground. Illustrates extent to which decaying matter may affect surrounding rocks.

small nucleus of organic matter may be sufficient to initiate a large concretion.

Normal appearance of the majority of elongate ironstone concretions of the study area is shown in figure 12. Two knots are preserved in this particular instance, however. Knots such as these are occasionally preferentially preserved, probably because they were generally harder than surrounding wood and perhaps more resistant to bacterial action.

These concretions may have formed by having decay-produced ammonia lower the pH in the immediate vicinity of the logs after their burial in a manner proposed by Degens (1965, p. 125). However, Hemingway (1968) states that CO_2, produced during the early diagenetic stages of both the coal and fine-plant debris in the sediments, and bacterial actions are more significant than ammonia in the formation of nodular and bedded bodies.

The second or subspherical type of concretion is generally found on the outcrop only as a small heap of ironstone fragments, which generally occur with similar heaps or with the elongate concretions discussed above at the same horizon. They are commonly found in green mudstone immediately above beds of organic red brown or purple shale and vary from approximately 15 to 60 cm in diameter. They may be related to organic decay like the logs mentioned above, and they may have precipitated in and around stumps which were inundated and later buried by sediment. Although all concretions of this type in the study area are structureless, a locality approximately 1.5 km to the northeast contains three identifiable in situ stumps in one of these layers. Nearby concretions are structureless, as usual, and two of the stumps are poorly preserved. One stump is well preserved, however (fig. 13), although composed of the same ironstone material.

FIGURE 10.–Pen rests on flattened log similar to that in figure 9, but woodlike structure is lacking. Represents intermediate form of preservation between well-preserved logs like that in figure 9 and majority of logs, which are structureless.

FIGURE 12.–Small mound of ironstone fragments shows appearance of majority of ironstone concretions in area. Pens indicate knots preferentially preserved.

FIGURE 13.–In situ stump northeast of study area. Two poorly preserved stumps and numerous structureless concretionary masses are found at this horizon in immediate vicinity.

The third type of ironstone deposit, the lenses, are thought to be the result of precipitation or flocculation of solutions rich in iron. Organic matter was probably involved in this process since a few ironstone layers do contain plant fragments. One layer in particular, near the transition into an associated sandy siltstone lens above the middle coal at measured section 7, has extensive plant fragments. These fragments may have been transported into the stagnant water and deposited there, forming a large portion of the sediment. Other factors besides organic decay were probably also involved.

These units are generally found in green mudstones and are locally stratigraphically equivalent or grade into thin sandstone lenses or the end of small channel-fill sandstone bodies (fig. 14). At several horizons, particularly immediately above the middle coal, ironstone is associated with thin, laterally extensive, sandstone layers overlying a green shale. They may represent sand carried into stagnant bodies of water that contained abundant dissolved iron compounds. The latter were possibly precipitated by contact with seawater in the manner described by Krauskopf (1967, p. 261). The gray mudstone often found above this ironstone horizon may be an indication of more nearly marine conditions following this flooding.

Ironstones give some indication of the environment since they are likely to be produced in warm humid climates with abundant vegetation, which produces a low EH and pH in surface water and groundwater. They also are common in environments without abundant clastic sediment, such as in a restricted basin or arm of the sea (Krauskopf 1967, p. 263).

Ironstone layers in the study area probably developed in lakes or possibly brackish bays where organic debris was abundant. The gradational nature of the contact between some of the sandstone bodies and the ironstones indicates that occasionally small streams or floods brought sediment into these low-lying areas. Ironstone layers above coal beds or carbonaceous shale in some areas is thought to record drowning of the peat-forming vegetation and subsequent deposition of iron from the stagnant waters. Only in measured section 41 is an ironstone layer found immediately below a coal seam. It suggests that, while it may be common for a peat-forming swamp or marsh to be drowned or otherwise transformed into a stagnant dead pond, vegetation usually did not immediately reoccupy such an area. Following the filling of such an area by clastic sediments, however, vegetation may be reestablished, producing an upward sequence of ironstone, gray shale, and purple shale, as shown very well below the upper coal in measured section 23 (fig. 3). Such a pattern may be related to water depth or other factors, but was probably related to the toxic nature of the water. The stratigraphic pattern is probably also related to the usual sequence of events in which sediment influx and vegetation offset susbsidence. When sediment influx wanes, subsidence eventually outpaces peat development, and ponds tend to develop in areas sinking faster than surrounding areas. These sags or basins would tend to be centers of ironstone accumulation.

The intriguing ironstone concretions of the Ferron Sandstone are probably a result of environmental concentration rather than exceptionally abundant iron supply. It is interesting to note, however, that in Late Turonian marine sediments from Montana to Kansas, conspicuous ferruginous concretions are locally abundant (Reeside 1957).

ECONOMIC POSSIBILITIES

Coal

Coal is the most promising natural resource of the area. Several prospects and small mines for local demand are found in the Henry Mountain field, but all have been abandoned (Doelling 1972). Atlas–Dirty Devil Mining Company, however, opened a new strip mine in June 1978, 13 km north of the study area, with plans to produce 400,000 tons of coal per year from the Ferron beds. A 7-year operation is projected on the basis of proven reserves held by the company. The lowest coal bed in their holdings is the thickest, ranging from 90 cm to 550 cm thick, but the thinner seams above are also recovered during the mining operation. The coal is shipped by truck to Green River, Utah, and from there it is shipped by unit train to the Moapa power plant in southern Nevada. The coal con-

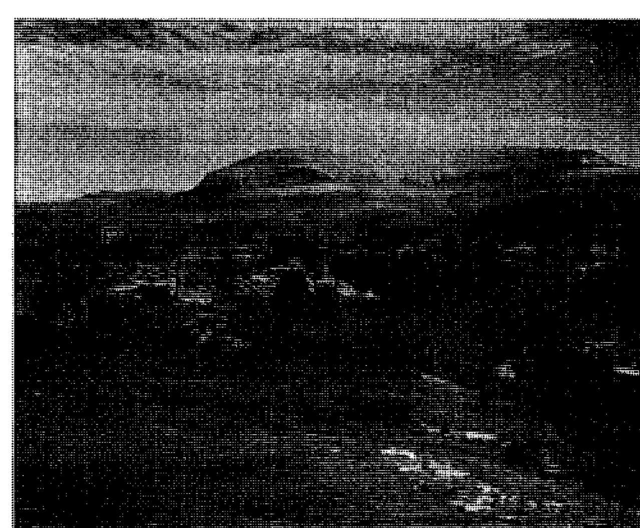

FIGURE 14.–Sandstone (left center) and laterally equivalent ironstone horizon (right center) illustrates transition from sandstone to ironstone commonly found in study area. U–Upper coal, P–Purple marker unit, M–Middle coal, L–Lower coal.

tains approximately 0.2% uranium, which is not economically recoverable from the coal, but recovery from the ash might be possible (John Johnson 1978 pers. comm.).

Coal development is not likely in the study area because the beds are much thinner and of poor quality. The upper coal bed locally thickens to 90 cm and on the basis of surface expression is covered by 450 cm or less cover under an area of approximately 2.5 km^2 west of the study area.

The trend of the thick coal being mined by Atlas–Dirty Devil Mining is northeast-southwest, following the trend of the Caineville Reef, so the coals of the study area may thicken to the northwest. Mancos Blue Gate Shale toward North Caineville Mesa is too thick and precludes economical strip mining. Underground mining of the thin and relatively poor quality coal would probably not be practical, even with thicker seams.

The Factory Butte NW Quadrangle, which includes the property operated by Atlas–Dirty Devil Mining Company and the study area, is estimated to have 45,000,000 tons of coal, with 22,750,000 tons in seams over 45 cm thick (Doelling 1972).

Uranium

As mentioned above, approximately 0.02% uranium occurs in the Ferron coal being mined north of Factory Butte, and it might be recoverable from the ash after the coal is burned.

Several uranium claims to the east and northeast of the study area are held by Mr. Malcom Rogers of Teasdale, Utah. He has commenced a drilling program to evaluate the massive sandstone and the shales immediately above it for uranium. It is the opinion of the writer that economic deposits of uranium will not be found in the Ferron Sandstone in the vicinity of the study area, with the possible exception of recovery from coal ash, as mentioned above.

The water well drilled for the mine operation north of Factory Butte encountered the Morrison Formation 274 m below the Ferron Sandstone, and thus exploration of the Morrison Formation, which has produced uranium in other localities, would be unlikely in the study area.

Oil and Gas

Records of exploration for oil and gas show that the nearest wells 11 km to the northwest, 22 km to the southwest, 20 km to the southeast, and 16 km to the east were dry holes although all were completed to the Mississippian. The nearest producing wells are (1) 32 km to the northeast in Emery County, producing from the Moenkopi Formation; (2) 25 km to the northwest, also producing from Moenkopi beds; and (3) 32 km to the southwest, producing from the Kaibab Limestone (10 BOPD–later abandoned). This record, coupled with the history of 60 additional dry holes and no additional producers for all of Wayne County, does little to stimulate further exploration. Further, the study area is located in a syncline, which makes it one of the least attractive prospects.

The Ferron Sandstone is an oil and gas producer to the north near Clear Creek and Ferron. Although the Ferron Sandstone appears to be porous and shows one occurrence of dead oil in the SE ¼ of sec. 14, it will not be a producing horizon in the immediate vicinity of the study area because it crops out. The only possibilities are updip pinchouts of a sandstone, similar to the large sandstone in the center of the study area. Most of the linear sandstone bodies show a northeast trend and could pinch out up on the eastern flank of the syncline. However, lack of sufficient cover in the immediate vicinity and lack of any record of production from such sandstone units in other nearby areas makes this an unlikely prospect.

The Dakota Sandstone would be a possibility only if an isolated patch of Dakota Sandstone were buried along the eastern flank of the structure. There is evidence that the Dakota Sandstone pinches out to the north and south and thins in the subsurface several miles to the west (Hunt and others 1953, Lawyer 1973). This would leave the remote possibility that the Dakota Sandstone might also pinch out in a lobate manner which would allow the development of updip stratigraphic traps along the eastern flank of the structure. The Mancos Shale and other units penetrated by the water well mentioned above are badly fractured, so an effective trap may not exist even if the pinchouts are present.

Titanium

Potentially commercial deposits of titanium-bearing black sandstone lenses in the Ferron Sandstone and Straight Cliffs Sandstone are located in Emery, Garfield, and Kane counties (Adams 1964). However, the dark heavy-mineral lenses present in the study area are small and widely scattered and are not considered to be an economic resource.

Jet

"Jet is a black variety of brown coal, compact in texture, and taking a good polish" (Dana and Ford 1949, p. 779). The most important source of jet in North America is in the Henry Mountains, on the northwest flank of Mt. Ellen (Dash 1964). However, the only occurrence of jet in the study area is one log found in the upper coal (fig. 6), samples of which are hard and black and take a good polish.

Gravel

Road material has been obtained from gravel-capped small hills in the southern end of the study area. These gravels were apparently deposited by the Fremont River when it was at a higher level than at present. Much of the available gravel has been excavated for use in constructing Utah 24. Local demand for gravel will probably be sporadic in the future, so the supply should meet the demand. For example, the access road into the Atlas–Dirty Devil Mine was constructed using these gravel deposits.

DEPOSITIONAL HISTORY

Depositional history was determined primarily by correlation of the fence diagram with maps prepared in the field for twelve selected horizons. This correlation permitted a detailed reconstruction of events. However, five sources of error were encountered which may have affected some of the conclusions: (1) Some units are locally buried or missing because of erosion, particularly complicating correlation because many of the units are lenticular. (2) Channel-fill deposits occasionally cut out lower units, complicating interpretation of depositional sequence. (3) The lenticular nature of units precludes correlation of simply connecting similar lithologies between measured sections on a fence diagram. Sandstone units are especially susceptible to this problem since most are channel-fill deposits but could be correlated to look like sheets of sand. Further, since exposures are usually better below sandstone outcrops, the tendency to preferentially select these sites for measuring sections compounds the problem. (4) Thickness variations complicate the interpretation of events and lateral relationships. For example, the upper coal in measured section 6 rests on a thin purple shale unit over a thick gray shale unit. However, the upper coal in nearby measured section 23 rests on a thick purple shale over a thin gray shale. Lithologically, this is very easily correlated, but trying to establish a time or depositional correlation is more difficult. (5) Sedimentary structures, in particular cross-beds, are generally indistinct, partly because of adjustment during compaction and dewatering following deposition.

Notwithstanding these possible sources of error, the following sequence of events was determined for the study area:

The lower massive sandstone was not studied in detail since this study was limited to the transgressive beds above it. However, the general coarsening upward sequence from the Tununk Shale Member below to the studied interval is most likely a prodelta-delta front-distributary mouth bar sequence overlain by point-bar and channel-fill sediments deposited as the system prograded seaward.

An orange white siltstone caps this sandstone in most parts of the study area, and it fines upward in the southeast quarter into a purple shale which locally becomes carbonaceous, recording the establishment of a well-vegetated marsh over the older channel-fill and levee deposits. The carbonaceous shales probably developed in an area which had limited sediment influx.

The gray and gray green shales and siltstones above this carbonaceous shale indicate that here subsidence was faster and flooding occurred while the area to the east probably remained a well-vegetated marsh. The flooding permitted a new channel system to move into the more swiftly subsiding area near the center of the study area. From the limited evidence present, it seems that streams modified initial bay-fill deposits in this sequence since point bar and channel-fill deposits are present at measured sections 12 and 49, respectively. Apparent removal of older units further supports this interpretation. The bulk of the sandstone associated with this event was probably deposited in the west central part of the study area. Shales and siltstones of measured section 49 may be channel-fill deposits younger than the seemingly equivalent shales to the east (fig. 15).

The lower coal is of variable quality and thickness (fig. 16). It is present over the entire study area except for the southwest corner. After deposition of the coal, an influx of fine clastic sediments produced the purple shales above the coal. Several small channels developed and left channel-fill deposits. Small channels near the southwest part of the area carried sediment eastward, finally flaring out, then wedging out near section 5 (fig. 17). These small sandstone lenses were probably the edges of small splays from a large channel to the southwest. The larger channel developed a lobate deposit (fig. 17) into a swamp where the peats of the lower coal were being deposited. The northern lobe of this deposit is relatively small and terminates in the outcrop, but the middle and southern lobes extend eastward into the subcrop. The location of this deposit was probably determined in part by the sandstone lying below the lower coal to the north. Northwestward trending channels later entered from the southeast (fig. 18). These channels produced a thin sheet of silt and sand near the center of the area. They probably represent crevasse channels and splays from a larger channel to the south.

Amount of subsidence was evidently offset at this time by the thickness of sediments brought into the area, for organic-rich sediments continued to accumulate. Locally, a thin carbonaceous shale and coal developed where the critical balance allowed peat formation. This formed the "stray" coal encountered in some sections (fig. 19).

The middle coal is thickest in the central and southeastern parts of the area (fig. 20), roughly over the location of the channel-fills and thin sandstone which were deposited over the lower coal. This may be related, in part, to less compaction of the substrate.

Coal thickness is difficult to analyze since a variety of factors are involved. The substrate or buried topography may control the rate of subsidence and the amount or type of vegetation which develops (figs. 21, 22). The interaction of swamp and marsh with unvegetated ponds is very complex, as well, and affects the type and amount of peat produced. This inter-

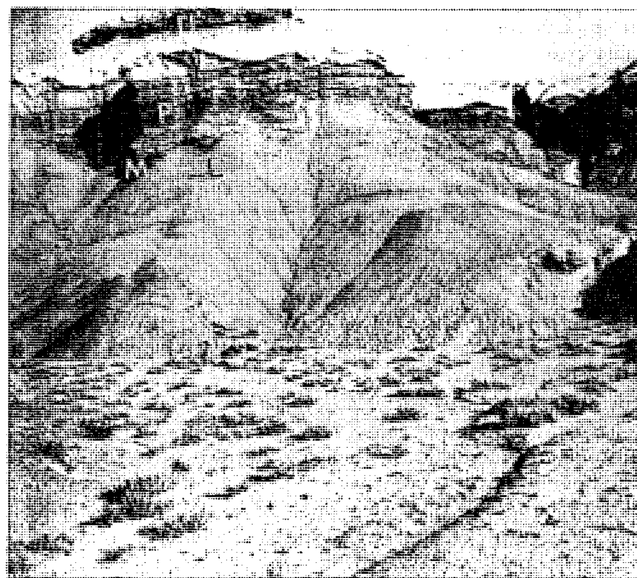

FIGURE 15.–Abandoned channel filled with organic rich siltstone and shale at measured section 49. Channel sandstone (point bar) wedges out near center of photograph. Deposit located at western end of linear depression which marks position of abandoned channel.

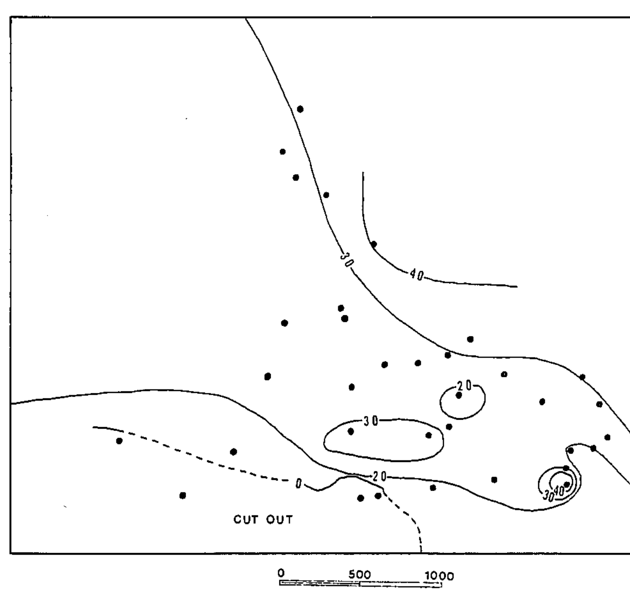

FIGURE 16.–Lower coal isopach. Thickness in centimeters.

action is illustrated by recent deposits in Louisiana (Frazier and Osanik 1964) and in Florida (Spackman and others 1964). The introduction of clastic sediment may produce carbonaceous shales of varying thickness and may affect total seam thickness and quality.

The zone from the middle coal to the base of the purple marker unit is an extremely varied and complex mixture of rock types, both laterally and vertically, indicating a wide variety of subenvironments which changed with time. In most measured sections, there is a gradual upward change from purple shale immediately above the coal to gray shale—an indication of an influx of sediment with continued plant growth for a time before flooding. Measured sections 17 and 36 have gray or green shales immediately above the coal, indicating that these localities were more quickly flooded. Sections 12, 15, and 49 have siltstone or sandstone units overlying or cutting out the coal (fig. 23).

A major influx of sand occurred in the northern part of the

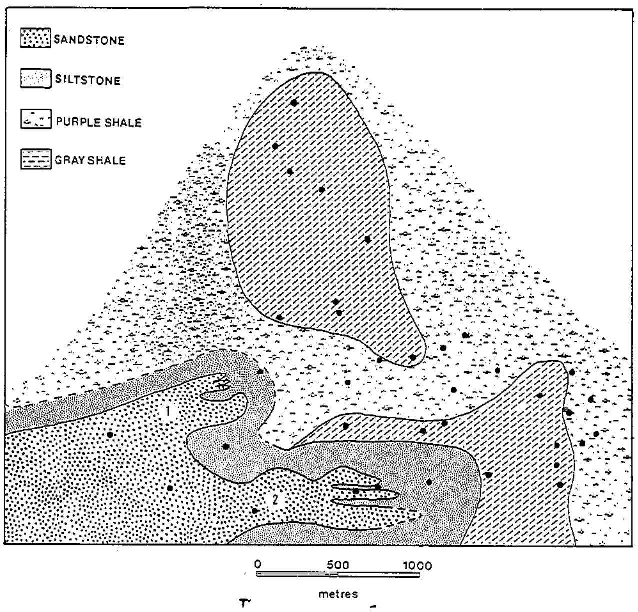

FIGURE 17.—Large channel above lower coal, which is cut out by sandstone at (1), but only overlain by thin sandstone sheet at (2).

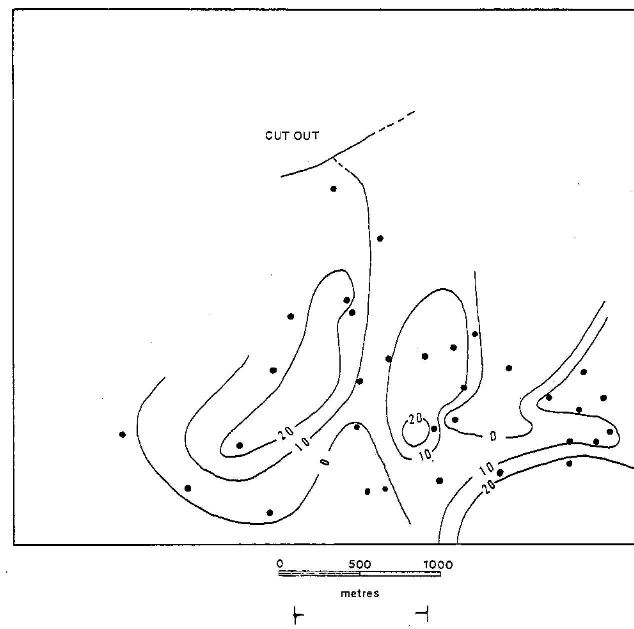

FIGURE 19.—"Stray" coal isopach. Thickness in centimeters. It joins with middle coal at O isopach except where it is cut out in southwest corner. Primarily a carbonaceous shale.

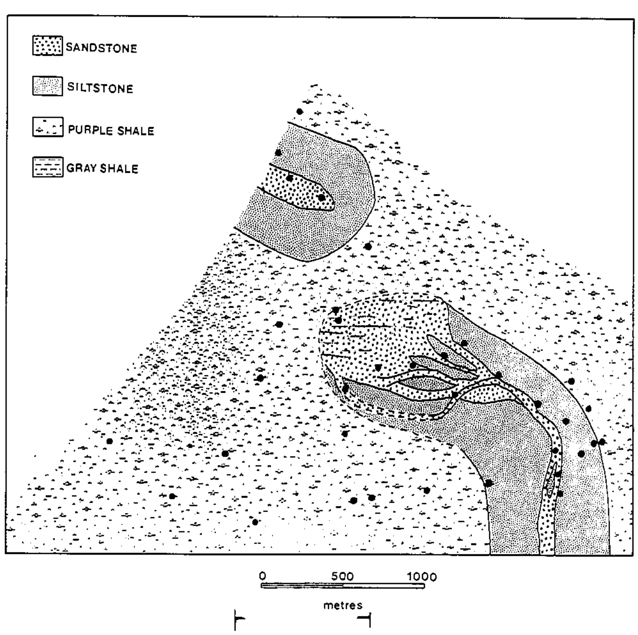

FIGURE 18.—Sandstone channel-fill and splay above lower coal.

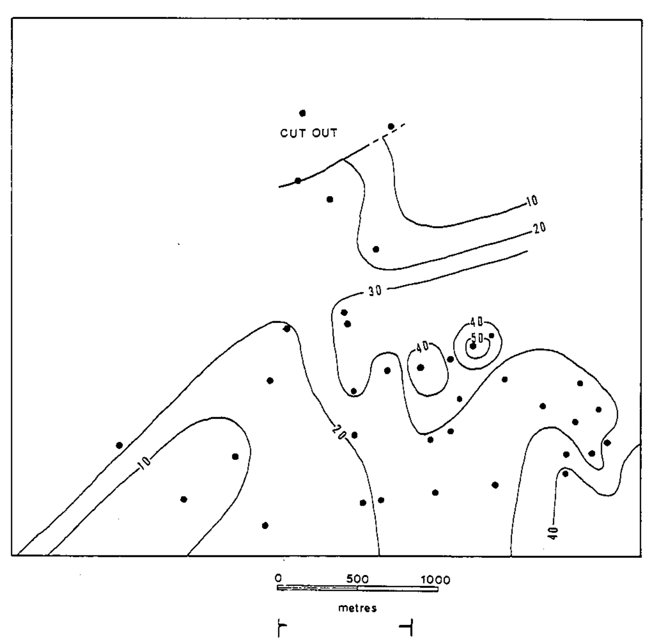

FIGURE 20.—Middle coal isopach. Thickness in centimeters.

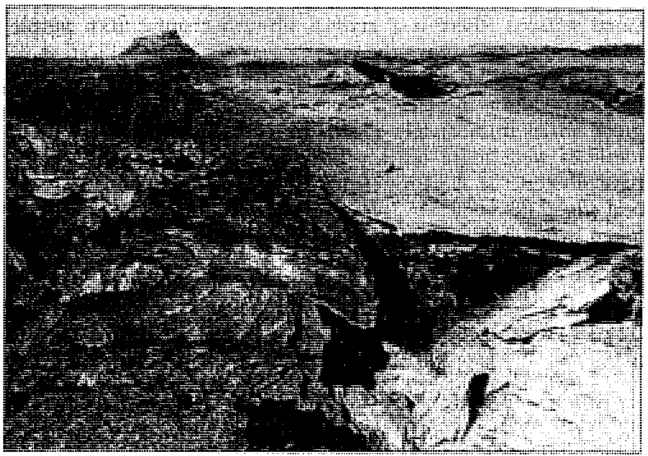

FIGURE 21.—Small channel fill sandstone east of measured section 40. Channel is narrower where it passes through large sandstone body than where flanked by shales.

area during this time (fig. 24). Cross-bedding and elongation of channel-fills indicate an easterly flow direction for the more prominent channels. Green siltstone with interbedded thin sandstone and ironstone layers occurs above these sandstone channel-fills and indicates that the area was probably covered with water after channel deposition. This sandstone and ironstone layer covers most of the northern half of the study area and is overlain in most localities by green or gray mudstones or thin siltstones. This relationship indicates that subsidence was greater than sediment accumulation and suggests, as well, that the sandstone may have even accelerated subsidence and compaction by loading. The sandstone units generally fine upward into the purple shale of the prominent purple marker unit. The general pattern shows that continued sedimentation filled the area, and vegetation established a firm foothold.

A separate channel sandstone and associated natural levee which entered from the south (fig. 24) clearly shows the transition from sandstone to ironstone that is common in the area at most horizons. In this case, as in most cases, a small channel-fill thins and widens where ironstone content increases until the horizon is predominantly ironstone. This pattern probably represents small channels emptying into bodies of water in which iron had accumulated.

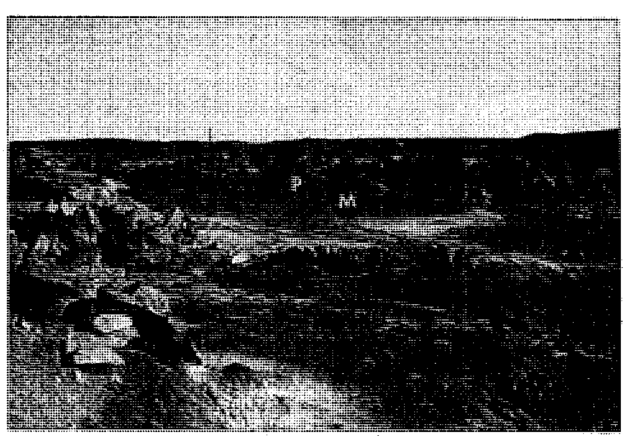

FIGURE 22.—View eastward from measured section 40. Middle coal (dark band—M) of small ridge in center of photograph illustrates development of local sags and highs. Such local variations are common in study area and generally reflect control exerted by buried topography and lithologies. These variations in turn exert control on present drainage patterns. Portion of sandstone channel-fill shown in figure 21 in center foreground.

The southern part of the study area generally remained more stable than the central and northern parts. Over it, the interval between the middle coal and the prominent purple marker unit is an unbroken sequence of purple shale, indicating that, although there was an increase in clastic sedimentation, conditions did not change much. Absence of ironstone in the southern part also suggests that the area was reasonably well drained at this time.

Thickness of beds between the middle coal and the purple marker unit is generally 1.5 m or less where the organic-rich sedimentation continued. They are approximately 2 m thick where vegetation was evidently flooded but then later reestablished, and more than 2 m thick where sandstone and siltstone are abundant. This difference in thickness is further evidence that the localities that subsided enough to inhibit vegetation were indeed topographic lows that had to be filled with more sediment than adjacent sites before vegetation could be reestablished.

In this study, it was noted that coarser sediments, in particular large sandstone bodies, tend to thicken an interval. This difference is probably the result, in part, of greater compaction of finer sediments following deposition. However, the original depositional framework may also help produce it. Splays and levees of large channels tend to produce thicker and topographically higher deposits, so the thickness would be different even before differential compaction. This difference would be especially noticeable if a river moved into a topographic low that was subsiding rapidly and then developed channel and levee deposits which eventually produced a topographic high.

The extensive purple marker bed records the abundance of vegetation over most of the area at that time. Presence of very

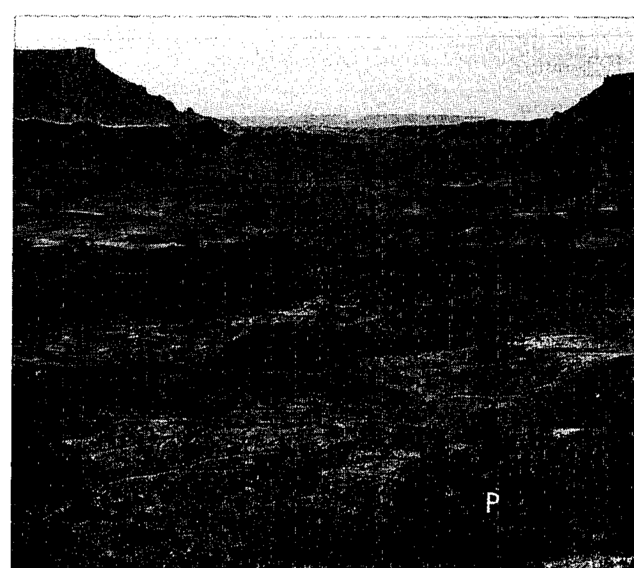

FIGURE 23.—View northward from measured section 12 showing ironstone-capped sandstone channel-fill deposits which cut out middle coal. Purple marker unit (P) is dark band in lower right corner. Narrow dark band in background is outcrop of upper coal (U).

little carbonaceous shale in the north and parts of the south (fig. 25), however, indicates that these areas may have been higher or more effectively drained than the center of the area. East of the center of the mapped area, a thick carbonaceous shale was deposited, but a sequence of purple and green mudstone with ironstone developed in the southwest. This distribution documents a transition from relatively high or well-drained marsh or levee, through swamps, to a pond or inlet of

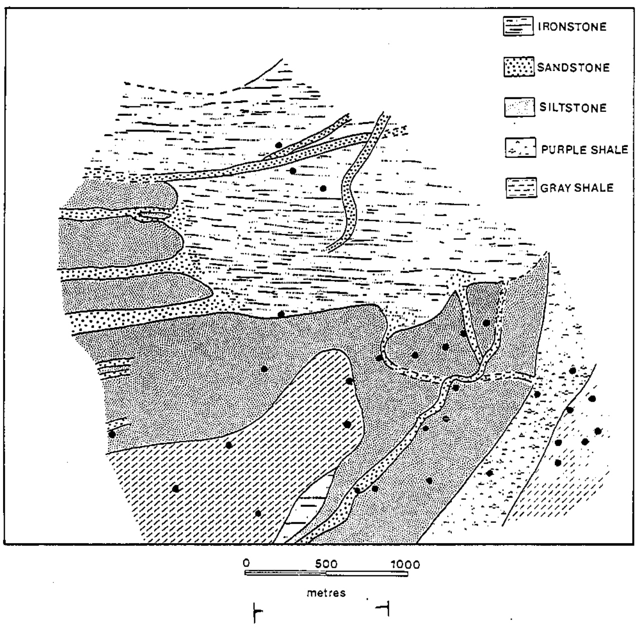

FIGURE 24.–Interval between middle coal and purple marker unit. Sandstone channel-fills are in extensive siltstone sequence and terminate in most widespread ironstone deposit of study area. Ironstone in northern part overlies sandstone channel-fill deposits.

open water restricted to a southwest-northeast trending trough. This trough began to develop after deposition of the peat of the middle coal, and continued past the development of the purple marker unit.

A complex sequence of flooding and pulses of coarse sediment then developed. In the southern half of the study area, ironstones above the carbonaceous shales of the purple unit indicate temporary flooding. However, as subsidence continued, channels developed and entered early from the southeast (fig. 26). The channel which entered from the southeast meandered toward the center of the area, then turned northward. Two crevasses developed from one of the meander loops. The northern crevasse channel spread sand and silt over the center of the area. The other crevasse channel produced an elongate sheet of sand toward the southwest. These sandstone sheets do not grade into ironstones as similar deposits do elsewhere–an indication that these sheets developed in a relatively well-drained locality. Following this, the main flow of water shifted to the east for a time, although a small stream still flowed through the old channel (fig. 27). At this time, a sheet of sand was deposited over much of the southeast part of the area by small streams from the southwest. Some outcrops also indicate contemporary transport from the southeast, as well. The large stream reoccupied the old channel (fig. 27) with modification, and a thick levee sequence developed along its flanks, covering the sands which had just been deposited.

A system of small channels next entered from the western edge of the area, depositing sediment into the northeasterly trending open pond trough which had continued to this time (fig. 27).

At this stage a large channel entered from the southwest and flowed northeastward along the trough (fig. 7), eroding down to the purple unit in some places. The new channel was probably the result of a course change in a major river to the south. However, deposits produced by this event may not ex-

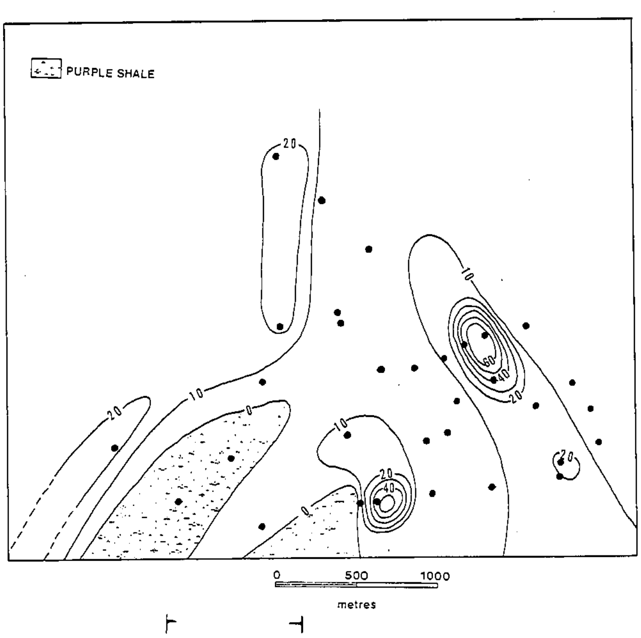

FIGURE 25.–Purple marker unit isopach which shows thickness of carbonaceous shale in centimeters. Equivalent purple shales are indicated where a carbonaceous shale is not present.

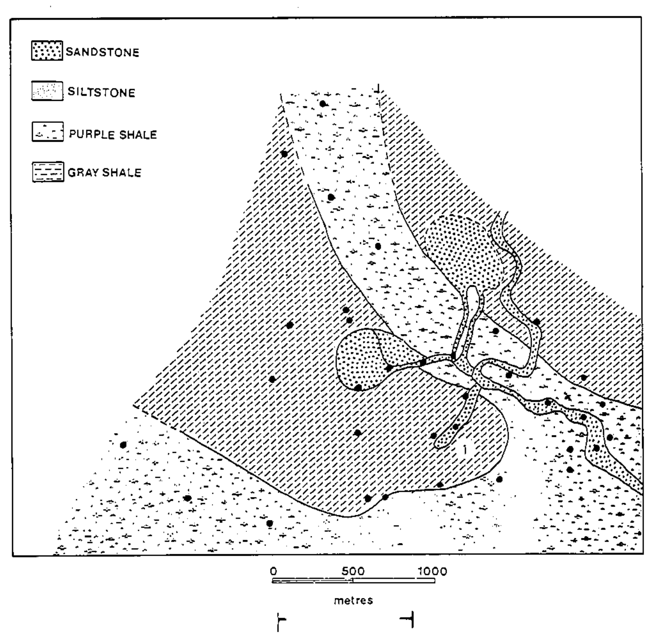

FIGURE 26.–Early sequence of small channels above purple marker unit showing three small splays or crevasses. 1–Coarsening upward bay-fill sequence.

tend to the northeast much beyond the study area because they are not recognizable in exposures approximately 1 km to the northeast. The channel-fill sandstone also shows thinning and fining where it goes to the subsurface in northernmost exposures. Natural levee siltstones are commonly found adjacent to and capping this unit. Some measured sections, section 5 for example, suggest that not only did this channel cut down through existing sediments, but that subaqueous levees may have developed next to it and as sediment accumulated, subaerial natural levees developed. The sandstone is limited to a distinct channel, but the associated levee deposits of yellow orange siltstone, or less commonly of gray or purple siltstone, are found throughout the map area except in the southeast corner. The widespread deposition indicates the significant influence of this event. The fining-upward sequence at the top of the unit documents the eventual abandonment of this channel and its gradual infilling, at first by increasingly finer sediments and eventually by peat.

Laterally equivalent beds demonstrate the sediment variation next to a major channel. Measured sections adjacent to the sandstone body show equivalent beds to be siltstone which is commonly limonite stained. Sections farther to the southeast show purple shales, carbonaceous shales, and even some ironstone lenses. This lithologic gradation shows transition from channel, to levee, to backswamp conditions. Continued sedimentation eventually resulted in formation of a purple shale over most of the area, probably during and following the final stages of deposition of the large channel. The channel was eventually abandoned. The resulting absence of clastic sediment allowed peat formation, and subsidence became a major factor in sediment patterns. The deposition of the thick, uniform upper coal seam (fig. 28) at this time suggests that one of the most stable periods in the history of the area followed this massive influx of sediments.

It is interesting to note that the upper coal is a split seam in the southeast and northwest corners of the study area, perhaps because of compaction of the underlying shales and sediment influx, or perhaps because the area was closer to a source of sediment. In either case, vegetation remained the dominant factor, as indicated by abundant plant fragments in these intervening shales.

Peat deposition was evidently terminated when the northern half of the area was flooded by the Mancos Sea. Gray or gray-purple shale was deposited above the upper coal seam. The southern part of the area remained covered by abundant plant growth, although development of purple shales record an increase of clastic sediments. These shales grade upwards into gray or gray-purple shales and siltstones, documenting the gradual change to marine conditions. Abundant gypsum at this level may indicate shallow water with high evaporation rates as in a model like that proposed by Reinick and Singh (1973, p. 252). Sandstone and siltstone are commonly found at this transition to marine deposition. Sandstone bodies above the upper coal (fig. 29) are located on both flanks of the large sandstone channel below the upper coal, showing that what had been a trough became a high or at least a more slowly subsiding locality.

Hunt and others (1953) regarded similar sandstones west of the Henry Mountains as transgressive, reworked shoreline sandstone produced by the Mancos Sea. The sandstones at this horizon in this study are highly bioturbated and lack the levee deposits associated with many of the sandstones in the sequence below. They were probably reworked by the sea as the area was flooded. However, this sandstone in the northwest part of the area shows a current direction to the northeast as well as vestiges of a silt cap which may indicate that, although these sandstone lenses were reworked by the Mancos Sea, at least some of them may represent final pulses of sand brought into the rapidly submerging bays by streams as the Mancos Sea advanced. However, unlike earlier phases in Ferron deposition, advance of the sea continued, and the fish-bearing marine sediments of the Blue Gate Shale accumulated over the buried deltaic deposits.

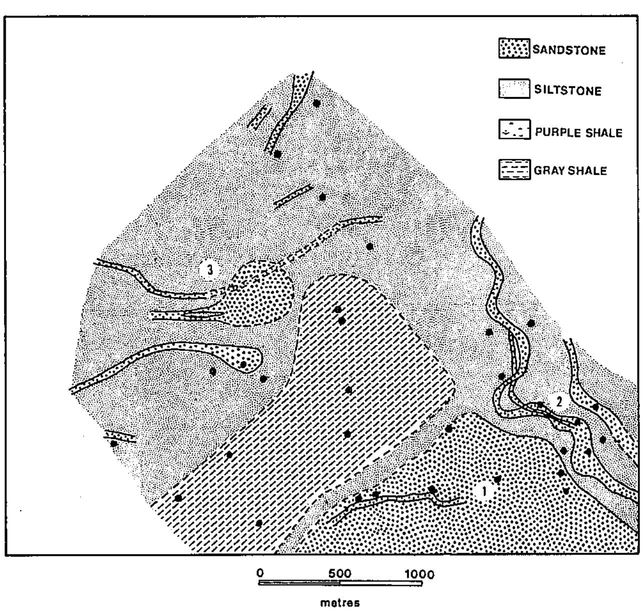

FIGURE 27.—Later sequence of small channels above purple marker unit: 1—Widespread thin sheet of fine sandstone. 2—System of northwesrerly trending channel-fills which cut into underlying units. 3—System of small northeasterly trending channel-fills and splays.

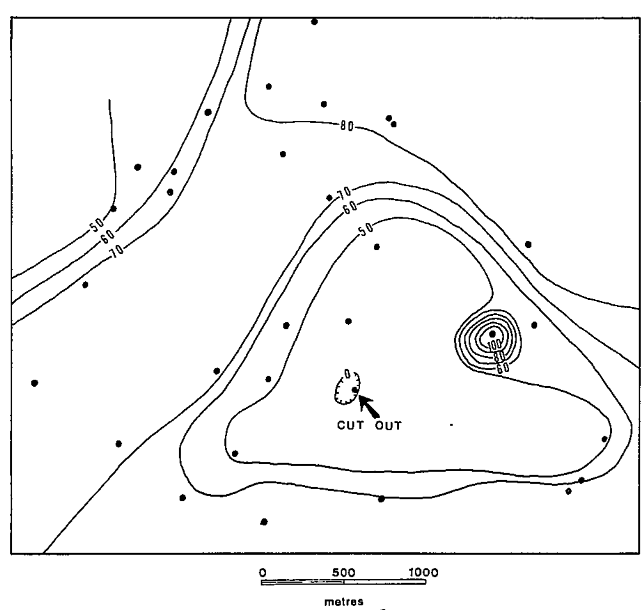

FIGURE 28.—Isopach of upper coal. Thickness in centimeters. Note correlation with levee deposits of figure 7.

OBSERVATIONS

Perhaps the most striking feature of this sequence is the manner in which the locus of deposition shifts from locality to locality at succeeding horizons. Sandstone bodies illustrate this particularly well. A good example is deposition of sandstone in the northwestern and southeastern parts of the area over the purple marker unit (figs. 2, 27). This sandstone is followed by deposition of a thick, extensive sandstone unit in the trough between these two areas (fig. 7). However, sandstone lenses above the upper coal occur on the flanks of this buried sandstone body (fig. 29). Similar shifting of deposition has been noted in other Cretaceous sequences although on a different scale (Asquith 1974), in a Carboniferous sequence (Ferm and Cavaroc 1968), and in modern deposits (Coleman 1976).

The transition from orange white siltstone through purple siltstone to purple shales into the levee sequence is also commonly encountered in the study area. In the case of the large distributary below the coal, this transition included a carbonaceous shale at the outer edge of the sequence.

COAL QUALITY AND THICKNESS

A direct relationship of coal quality and thickness with any particular overlying or underlying lithology is difficult to establish in this study, except for channel sandstones which occasionally cut out parts of a seam. Purple shales are, with only one exception, present under the coal seams, but a direct relationship between coal and shale thickness is not apparent.

However, attention to the depositional framework helps to explain coal thickness and quality in some cases. The upper coal is thinnest directly over the large sandstone body, but thickest immediately adjacent to it, and thinner away from it. Perhaps the levee zone was subsiding more than over the channel sand, thus accumulating more peat, but not so much as to be flooded by clastic sediments. For example, areas to the northwest and southeast have prominent shale splits developed in the seam. Thickness of the carbonaceous shale in the purple marker unit is less conclusive, but it appears to be locally thicker over the splay and channel sandstone. The middle coal is likewise thicker above a splay sandstone. Above splays and small channels seems to be a favorable environment for peat formation, although the coal seams do not develop directly on the sandstone without an intervening shale unit. Large channels seem to be less favorable.

Thickness of the coal is apparently determined by how effectively and how long the critical balance necessary for peat accumulation can be maintained. A sandstone or siltstone layer below the peat-forming zone may be a stabilizing factor in some cases, particularly if subsidence is an active process.

The great variety of relationships between coal seams and substrates is illustrated in a report by Wanless and others (1964), which included examples similar to those mentioned above.

At least some subsidence may be related to compaction of underlying sediments, which may be a long-term process, as shown, for example, by the sagging of the large sandstone unit into a mudstone and shale-filled trough in the lower sandstone in the southwest corner of the area. This deformation appears to be the result of compaction following deposition of the sand.

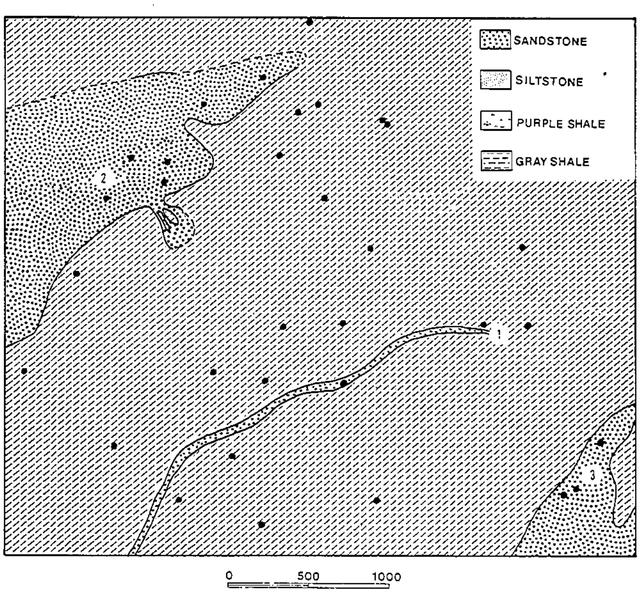

FIGURE 29.—Interval above upper coal and below Blue Gate Shale Member. Long, linear channel fill in center (1) was deposited prior to larger sandstone bodies to northwest (2) and southeast (3).

CONCLUSION

Ferron Sandstone in the studied area represents deposits produced within a large delta complex. The upper part of the member was deposited in a deltaic complex after the major distributary system had changed location or diminished significantly in volume. Subsidence was matched by deposition of peat and clastic sediments derived from splays and channels for a time, but eventually the area was submerged beneath the Mancos Sea.

The Mississippi delta, although perhaps overworked as a model, provides one of the better examples of the environments represented by the rocks of the study area. The close correlation of the lithologic relationships noted in this study and the relationships found in the West Bay bay fill (Coleman 1976) and other parts of the Mississippi delta (Frazier and Osanik 1964) illustrate the similarities of the two depositional systems. Although the detailed small-scale scope of the present investigation precludes an effective comparison of overall Ferron Sandstone depositional framework with the entire Mississippi delta complex, the vertical and lateral relationships noted in this study resemble similar vertical and lateral relationships within the Mississippi complex.

APPENDIX 1

Middle Coal Sulfur Analysis

Section Number	Sulfur %
5	0.93
6	0.77
7a	2.29
7b	0.91
9	1.05
10	1.00
11	0.88
12	1.36
16	1.90
17	1.05
21	1.49
36	1.52
38	1.15
39	0.98
41	1.34
46	1.40
49	1.76
50	2.26

APPENDIX 2
Sulfur Analysis at
the Base of Selected Coals

Section Number		Sulfur %
6	Lower Coal	1.40
31	Upper Coal	1.66
6	Middle Coal	1.42
13	Upper Coal	1.53
5	Upper Coal	1.44

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