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# Deltaic Coals of Ferron Sandstone Member of Mancos Shale: Predictive Model for Cretaceous Coal-Bearing Strata of Western Interior[1]

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## ABSTRACT

**The Upper Cretaceous Ferron Sandstone Member of the Mancos Shale, the coal-bearing unit of the Emery coalfield in central Utah, shows accumulation of clastic sediments in a lobate, river-dominated deltaic system that existed along the western shoreline of the Interior Cretaceous seaway during late Turonian time. Five cycles of deltaic sedimentation, each containing one major coal bed or coal zone, are represented. A clear genetic relationship exists between the geometries of the major coal beds of the Emery field and the geometries of the delta-front sandstone units with which they are associated. The thicker part of each coal bed extends from the vicinity of the landward pinch-out of the associated delta-front sandstone landward to a distance of about 10 km. This genetic relation forms the basis of a predictive model that can be used in designing more cost-effective exploration programs in coal-bearing strata of Cretaceous age in the Western Interior.**

## INTRODUCTION

A substantial gap exists between capabilities and common practices in the science of coal geology. The basic tasks of the coal geologist typically are (1) to design drilling and coring programs that, in combination with existing data, adequately evaluate areas of interest; (2) to supervise the drilling programs and the collection of data and coal samples; (3) to compile and interpret data to establish coal bed continuity, thickness, coal quality, and minable reserves; and (4), when a particular area warrants, to cooperate with mining engineers in the planning of a mine. This procedure has been applied effectively for many years, but it has one major shortcoming—little or no attention is paid to the relations between the coal beds and their enclosing strata. If the strata are studied at all, it is to determine physical properties that affect mining. A great deal of valuable information has remained unutilized.

In recent years, depositional models relating the paleoenvironmental histories of coal beds and associated strata have been effectively and profitably applied in mine planning (Horne et al, 1978). The principal value of the models is that they are predictive. Areas of potentially dangerous roof conditions, areas where coal beds are likely to thin or split, and, to a lesser extent, coal quality and chemistry all can often be predicted with even a limited amount of drill hole data. These predictions can be utilized in both advanced-stage drilling and mine planning. Unfortunately, most tract evaluation and mine-planning programs do not include development and application of depositional models. This will undoubtedly change in coming years, as increasing demand for coal, wider use of multiple seam mining methods, mining to greater depths as shallow reserves are depleted, and increasing concern for mine safety all increase the desirability of more efficient and cost-effective methods in tract evaluation and mine planning.

It is the premise of this paper that depositional models can also be effectively applied in coal exploration. The predictive model presented here has been developed for the Upper Cretaceous Ferron Sandstone Member of the Mancos Shale, the coal-bearing unit of the Emery coalfield in central Utah. I believe that the model will prove to be applicable to much of the coal-bearing strata of Cretaceous age in the Western Interior United States, although modification will be necessary for its application to areas characterized by different styles of sedimentation. Some possible modifications are discussed.

## EMERY COALFIELD, UTAH

The Emery coalfield (Fig. 1), with total coal resources

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The results of this study were first presented at the AAPG annual meeting, Houston, Texas, in 1979.

Stratigraphic studies of the Ferron Sandstone Member and its coal beds were conducted primarily during the summers of 1976-78. Michael Hannigan, Debra Hannigan, Richard Phillips, and Steven Goolsby all rendered capable assistance in the field.

A large quantity of subsurface data from the Emery coalfield was made available by The Consolidation Coal Co. The conclusions drawn here would not have been possible without access to these data; special thanks to William Eastwood and Edwin Kuhn for their help in its acquisition. Additional subsurface data were provided by Gerald Vaninetti, Utah Power and Light Co., Salt Lake City, and Mark Wilkerson, Atlantic Richfield, Denver. Anna Langer compiled much of the subsurface data and assisted in its interpretation.

of approximately 1.3 billion metric tons (Lupton, 1916; Doelling, 1972), is one of the smaller coalfields in the Rocky Mountain region. It combines various characteristics that make it ideally suited for a study relating the geometries of coal beds to their paleoenvironmental settings: (1) natural exposures of the Ferron Sandstone Member in the Emery area are superb (Fig. 2), permitting detailed stratigraphic study and paleoenvironmental reconstruction; (2) the structural strike of the area is at a high angle to the depositional strike of the Ferron, making it possible to describe complex interfingering of marine and nonmarine facies in the direction of depositional dip; (3) all major coal beds and some associated rocks contain layers of altered volcanic ash that can be correlated and used as isochronous surfaces in paleoenvironmental reconstructions; and (4) the area has been extensively drilled by the coal industry.

## METHODOLOGY

Of primary importance in this study was the delineation of the stratigraphic framework of the Ferron Sandstone Member in the Emery coalfield, specifically, the recognition and mapping of the major cycles of sedimentation. The nearly continuous outcrops of the Ferron were studied along a distance of 40 km parallel with the structural strike. The actual outcrop distance studied, considering the numerous canyons and smaller irregularities of the outcrop, totals about 70 km. Smaller areas within the coalfield and selected stratigraphic intervals within the Ferron were chosen for more detailed stratigraphic study. The purpose of these studies was to relate, in as much detail as the outcrops would afford, several major coal bodies to their paleoenvironmental settings within the depositional cycles. The results of these studies are reported elsewhere (Ryer and Langer, 1980; Ryer et al, 1980; Ryer, 1981a). A large amount of proprietary drill hole and corehole data was made available by the coal industry. These data were interpreted and combined with the general and specific stratigraphic models to provide a sound, three-dimensional picture of the Ferron Sandstone Member and its coal beds. Finally, all data were integrated to produce the predictive model.

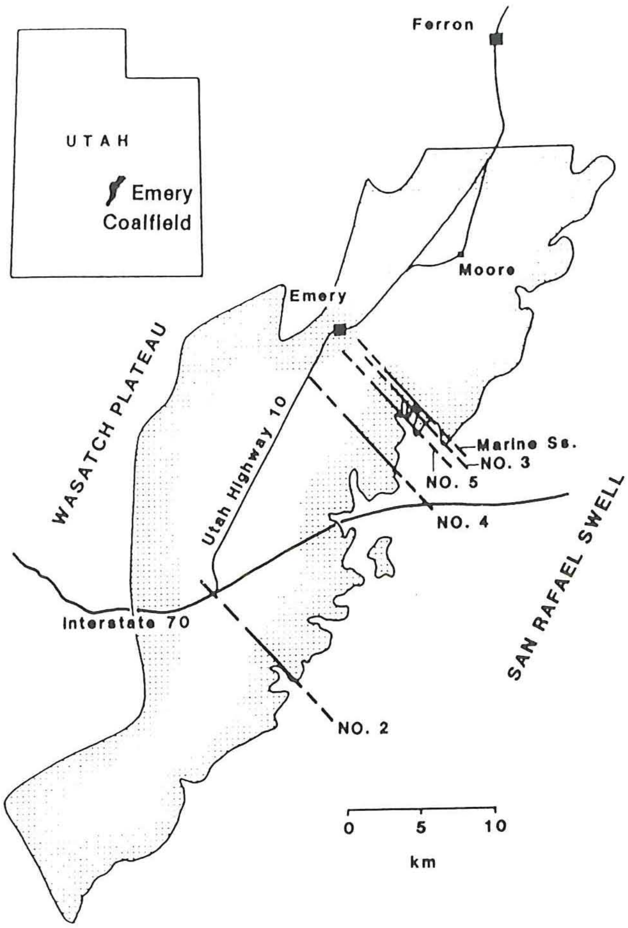

**FIG. 1—Outline of Emery coalfield. Southeast edge of coalfield is outcrop of Ferron Sandstone Member; northwest edge approximately coincides with eastern escarpment of Wasatch Plateau. The coalfield is defined at its northeast edge by approximate seaward limit of coal in Ferron and at its southwest edge by covering of Ferron by Tertiary volcanic rocks. Also shown are locations of landward pinch-outs of delta-front and marine sandstones discussed in text. (Outline of coalfield from Doelling, 1972.)**

## FERRON SANDSTONE MEMBER

### Stratigraphic Setting

The Ferron Sandstone Member accumulated during late Turonian time in a suite of deltaic paleoenvironments along the western shoreline of the vast Interior Cretaceous epeiric seaway. The seaway (Fig. 3), which occupied the interior of the North American continent during latest Early Cretaceous and most of Late Cretaceous time, connected waters of the proto-Caribbean on the south with those of the Circumboreal sea on the north and, at times of maximum development, stretched from western and central Utah eastward to Missouri and Iowa (Williams and Stelck, 1975). West of the Interior Cretaceous seaway, in southeastern Nevada, western Utah, and southern Idaho, a mountainous region, the Sevier orogenic belt, was repeatedly thrust-faulted and uplifted throughout Cretaceous time (Armstrong, 1968). Erosion of Paleozoic strata and, later, granitic basement rocks in the Sevier orogenic belt during Late Cretaceous time produced immense quantities of clastic sediments, which were shed eastward to accumulate in the Rocky Mountain geosyncline. The thickest Upper Cretaceous sections occur in a pronounced foreland basin that extended from central Utah northward into southwestern Wyoming (McGookey, 1972). The Emery area lies on the southeastern flank of this foreland basin.

The western shoreline of the Interior Cretaceous seaway underwent a series of major transgressions and regressions during Late Cretaceous time (Kauffman, 1977). The regressions are represented by eastward-thinning and generally eastward-fining wedges of clastic

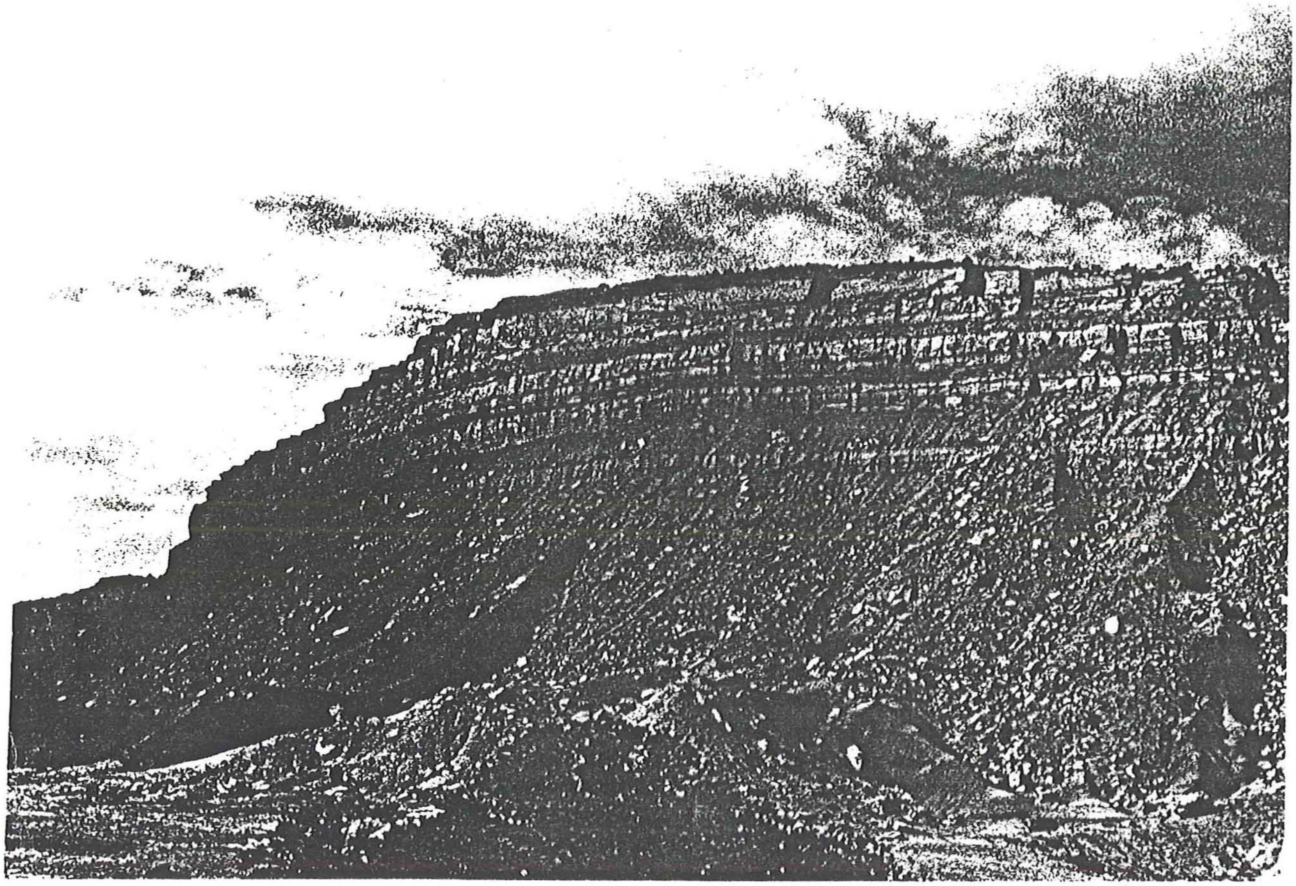

**FIG. 2—Exposures of Ferron Sandstone Member east of Emery, Utah. Delta-front sandstone units form prominent ledges.**

sediments from the Sevier orogenic belt; the transgressions are represented by westward-thinning tongues of marine mudstone and shale. The Ferron Sandstone Member constitutes the earliest of these major Upper Cretaceous clastic wedges in central Utah (Fig. 4). The Emery coalfield is situated at the distal end of the wedge, where the Ferron interfingers with and pinches out eastward into mudstones of the Mancos Shale.

### Stratigraphy and Paleoenvironments

The stratigraphy of the Ferron Sandstone Member was first described by Lupton (1916) in his comprehensive study of the coal resources of the Emery field. Lupton's coal resource data have been updated and revised by Doelling (1972). Davis (1954) and Katich (1954) recognized the Ferron as a deltaic deposit, recording accumulation of sediment derived from an area located southwest of the Emery coalfield. They also noted that the Ferron Sandstone Member in central Utah is not a single genetic unit. In addition to the deltaic complex, typified by exposures in the Emery coalfield, the Ferron includes a slightly older, stratigraphically lower sequence of intensely bioturbated, predominantly horizontal planar-laminated sandstone and siltstone that is best developed north of the Emery field. Cotter (1975a, b, 1976) has elucidated this relation. Hale

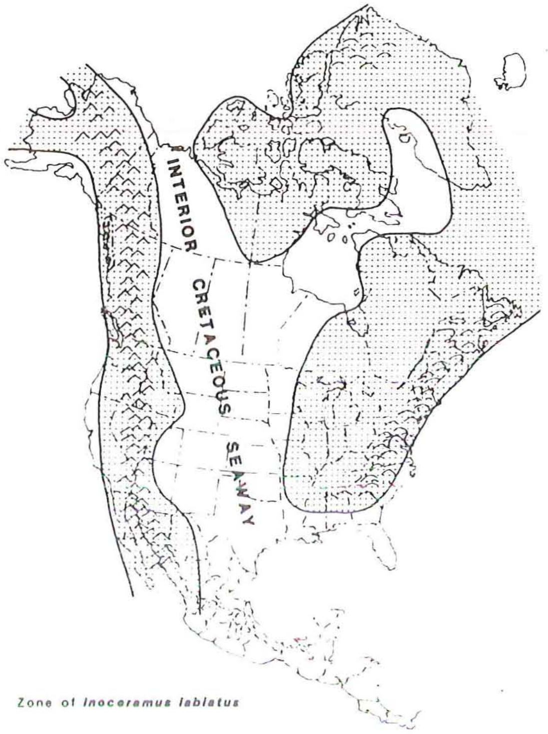

FIG. 3—Paleogeography of Interior Cretaceous seaway of western North America at peak transgression in early Turonian time. (Modified from Williams and Stelck, 1975.)

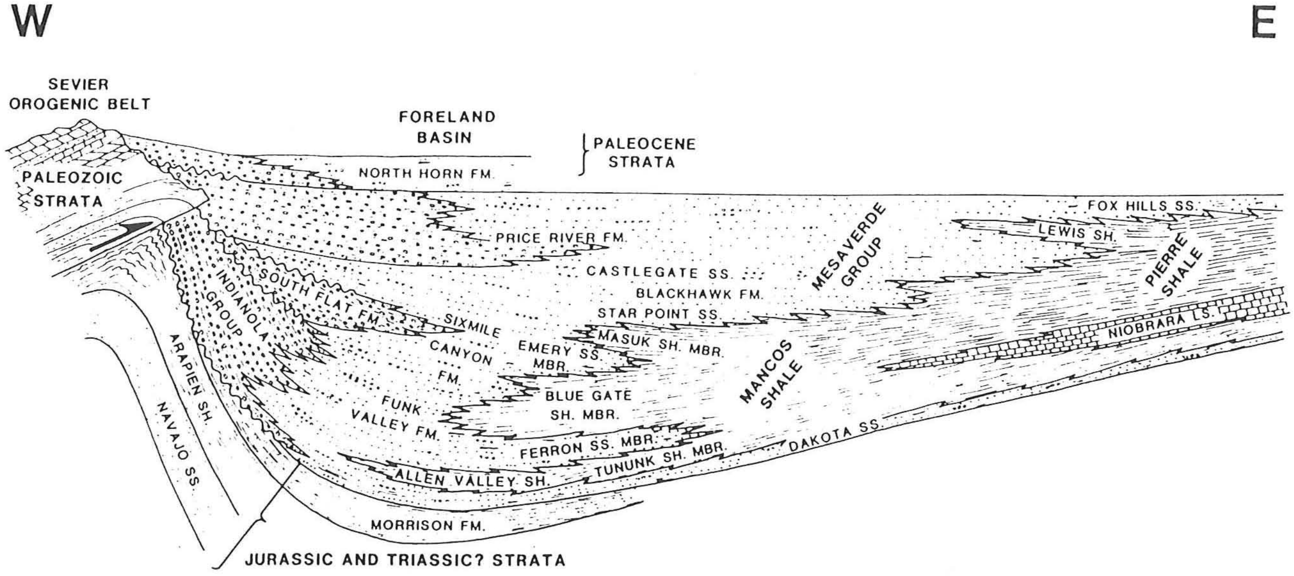

**FIG. 4—Diagrammatic, restored west-east cross section of Cretaceous strata extending from western Utah to western Colorado. (Modified from Armstrong, 1968.)**

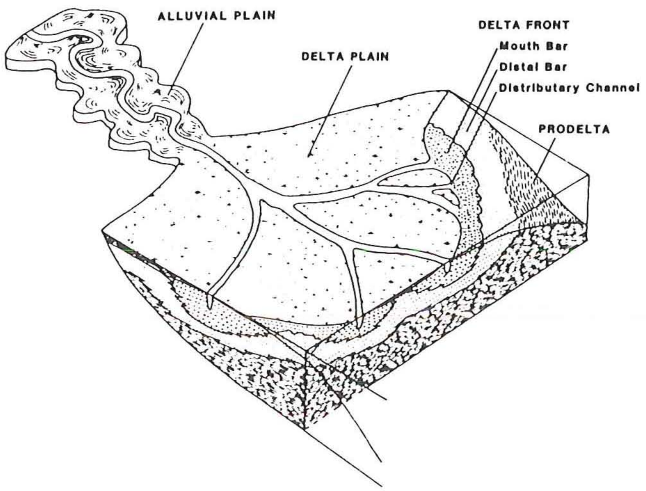

**FIG. 5—Facies of lobate, river-dominated delta. (Modified from Fisher et al, 1969.)**

(1972), utilizing subsurface data from oil and gas tests, published a regional interpretation of the depositional history of the Ferron Sandstone Member. The Emery coalfield is in the southernmost part of Hale's study area.

The Ferron Sandstone Member in the Emery coalfield is the product of episodic northeastward progradation of a lobate, river-dominated deltaic system. Broadly defined facies in a deltaic system of this type are shown in Figure 5. As a delta progrades seaward, the more landward facies come to overlie the more seaward facies in a progradation sequence. An idealized progradational sequence for the Ferron Sandstone Member is shown in Figure 6.

Cotter (1975a) described the deltaic facies of the Ferron Sandstone Member in considerable detail and compared them with analogous facies of several modern deltas. Inasmuch as my observations and interpretations agree with Cotter's, a detailed redescription of the facies of the Ferron here is unwarranted. The following is a brief description of facies (Fig. 6), emphasizing those features that substantiate the interpretation of the Ferron as a river-dominated, lobate deltaic system.

*Prodelta*—Prodelta deposits of the Ferron consist of interbedded mudstone and very fine to fine-grained sandstone (Fig. 7). The number and thickness of sandstone beds increase upsection. The sandstone beds are generally planar laminated and have abrupt lower contacts that commonly display evidence of minor erosion. Long-crested oscillation ripples and ripple drift lamination are commonly present in the upper parts. Bioturbation in the prodelta facies is generally sparse. The most common burrow types are *Ophiomorpha* and *Thalassinoides*.

*Delta front*—The laterally continuous, cliff-forming sandstone units of the Ferron Sandstone Member (Fig. 2) accumulated in the delta-front environment. The units consist of very fine to medium-grained sandstone with minor interbeds of mudstone and typically range from about 15 to 25 m in thickness. Though the thickness of a particular delta-front sandstone changes only gradually along the outcrop, the sequence of sedimentary structures in the sandstone may change dramatically over short distances. These rapid lateral changes are related to the proximity of contemporaneous distributary channels within the deltaic system.

At most localities, the delta-front sandstones can be divided into distal bar and distributary mouth bar subfacies. Deposits of the distal bar consist of very fine to fine-grained, planar-laminated sandstone with minor interbeds of mudstone. Some hummocky cross-stratifi-

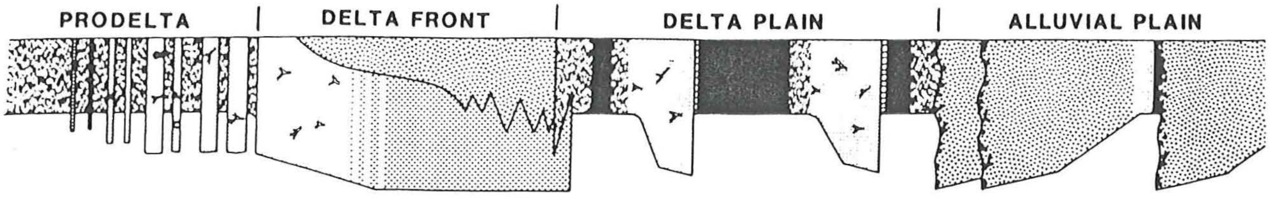

**FIG. 6—Idealized progradational sequence for Ferron Sandstone Member.**

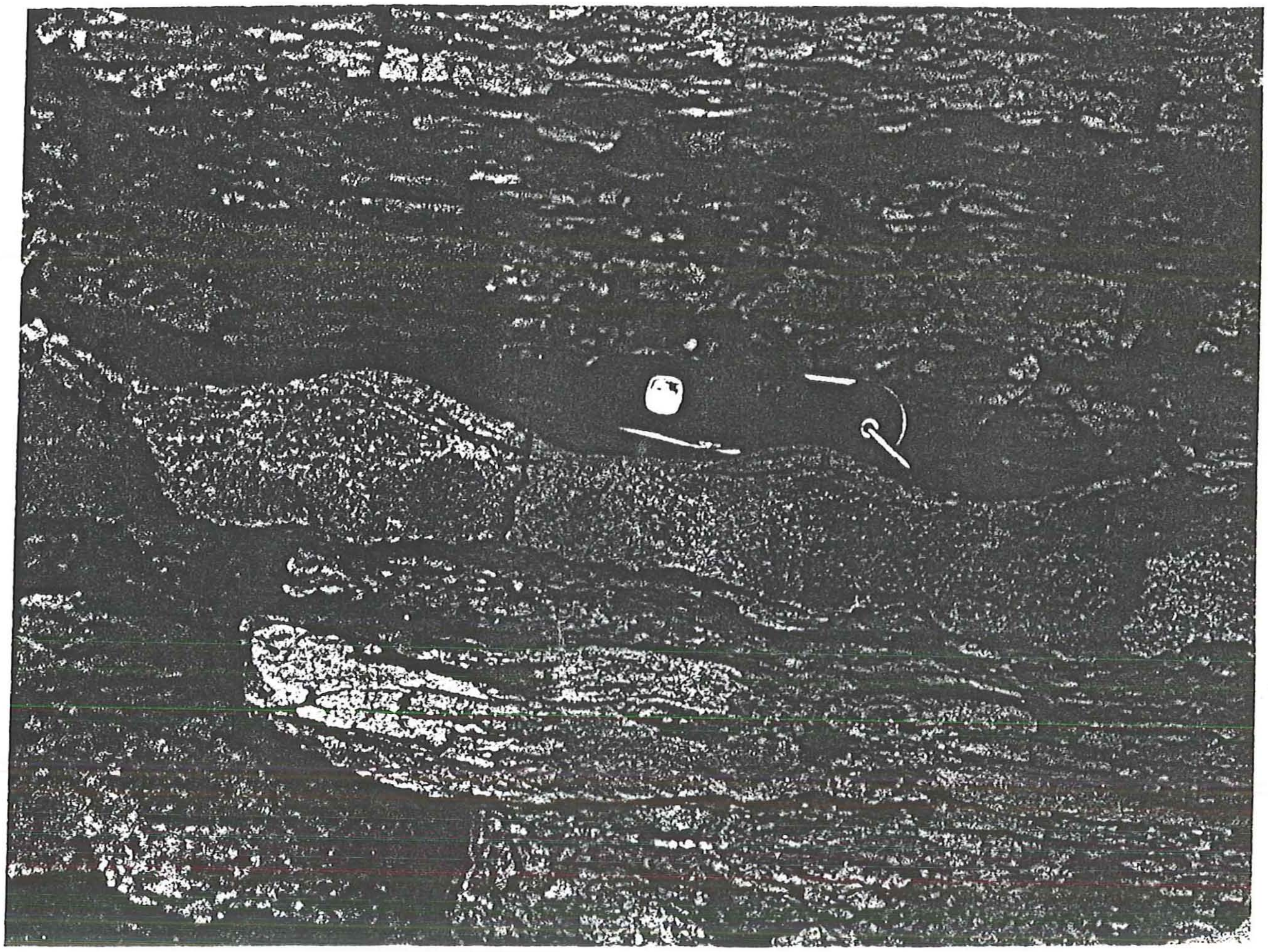

**FIG. 7—Interbedded sandstone and mudstone of prodelta facies. Sandstone bed at middle of photo displays oscillation ripples.**

cation is present; bioturbation is sparse. Bedding planes dip gently seaward. Very fine to medium-grained sandstones of the distributary mouth bar are characterized by trough cross-stratification. Transport directions are variable but are generally seaward. Biogenic structures are rare. Just seaward of active distributary channels, the distributary mouth bar deposits are thicker than normal and display large, complicated cut and fill structures (Fig. 8). The delta-front sandstones are locally cut by distributary channels (Fig. 9). The largest distributary channel observed on the outcrop was 15 m deep and about 100 m wide. Following abandonment, the distributaries were filled with trough cross-stratified sandstone, interbedded sandstone and mudstone, or carbonaceous mudstone.

*Delta plain*—The delta-plain facies of the Ferron includes a variety of subfacies. Most distinctive are extensively bioturbated mudstones and siltstones deposited in brackish water bays. These deposits commonly contain oysters, corbiculid, corbulid, and mytilid bivalves, and a variety of gastropods. The bay deposits are commonly capped by upward coarsening crevasse splay sequences of laminated siltstone and ripple drift cross-laminated sandstone. The tops of the splay sequences are commonly root penetrated and overlain by carbonaceous shale or coal. The major coal beds of the Emery coalfield are associated with the delta-plain facies though, as discussed later, the areas of peat accumulation may later have become isolated between river channels of the alluvial plain as the deltaic system prograded. Abandoned fills of nonsinuous distributary channels are common in the delta-plain facies. The channel fills are plano-convex lens shaped in section perpendicular to the direction of flow and may be filled with sandstone, siltstone, or shale. Flanking the channels are levee deposits consisting of bioturbated, very fine-grained sandstone and siltstone.

*Alluvial plain*—The alluvial-plain facies is characterized by fining-upward sequences of coarse to very fine-grained sandstone that record accumulation of sediment on the point bars of meandering river channels (Fig. 10). The sandstones of the point bar sequences are trough cross-bedded. At the bases of the channels are lag deposits composed of chips and pebbles of claystone and some carbonized logs. The size of the bed load material becomes coarser in the most landward part of the deltaic system, where the channels commonly contain coarse sandstone with granules of quartz and chert. The point bar sequences range up to about 12 m in thickness. Thicker fluvial sandstone units, up to about 30 m thick, are the result of vertical stacking of point bar sequences. Laterally migrating channels have eroded much or all of the preexisting delta-plain facies in some areas. There, alluvial channel sequences may rest erosionally upon a delta-front sandstone unit. Also present in the alluvial facies are levee deposits and beds of mudstone, carbonaceous shale, and coal deposited in flood basins. The coal beds of the alluvial facies are generally thin and laterally discontinuous.

*Transgressive deposits*—Progradation of the Ferron deltaic system was interrupted several times by transgressions of the shoreline. Associated with the erosional surfaces developed during these transgressive episodes are transgressive lag deposits. These deposits vary greatly in character and are thin or absent at most localities. The thickest transgressive unit observed on the outcrop reaches 2 m in thickness and is shown in Figure 11. It directly overlies the C coal bed of the Emery coalfield and is overlain by prodelta deposits of the next delta cycle. The unit consists of intensively bioturbated, poorly sorted, silty sandstone. Fragments of coalified peat, eroded from the underlying C coal bed, are abundant in the lower part. Logs bored by *Teredo*-like bivalves are also present. Numerous sand-filled burrows extend downward from the base of the deposit into the top of the coal bed. Locally, the erosional surface beneath the transgressive deposit descends to the level of a layer of altered volcanic ash contained in the C coal bed (the "thick" parting described by Ryer et al (1980). Here, rotated and partly rounded blocks of kaolinitic claystone from the altered ash layer are incorporated into the base of the transgressive lag. Other transgressive deposits consist of planar laminated, moderately bioturbated, very fine to medium-grained sandstone. In most places, the transgressive deposits consist of only a few centimeters of poorly sorted, intensely bioturbated sandstone. Volumetrically, they form an insignificant part of the Ferron Sandstone Member.

The outcrop of the Ferron Sandstone Member is approximately parallel with the depositional dip; the width of the outcrop belt, parallel with the depositional strike, reaches a maximum of only about 4 km. As a result, it is impossible to distinguish the shapes of individual delta lobes within the Ferron deltaic system. A variety of evidence, however, can be used to determine the basic geometry of the deltas.

1. Bioturbation within the prodelta and delta-front facies is generally sparse, indicating that rates of sediment accumulation were sufficiently rapid to preclude complete homogenization of sediment by the burrowing infauna.

2. Shoreface sequences (Clifton et al, 1971; Howard and Reineck, 1972, 1981), the result of sedimentation along wave-dominated coastlines, are rare in the Ferron, being only locally present in the southernmost part of the Emery coalfield. Wave energy, however, was sufficient to produce laterally continuous delta-front sheet sands.

3. The delta-front sandstones of the Ferron consist primarily of distal bar and mouth bar deposits and are

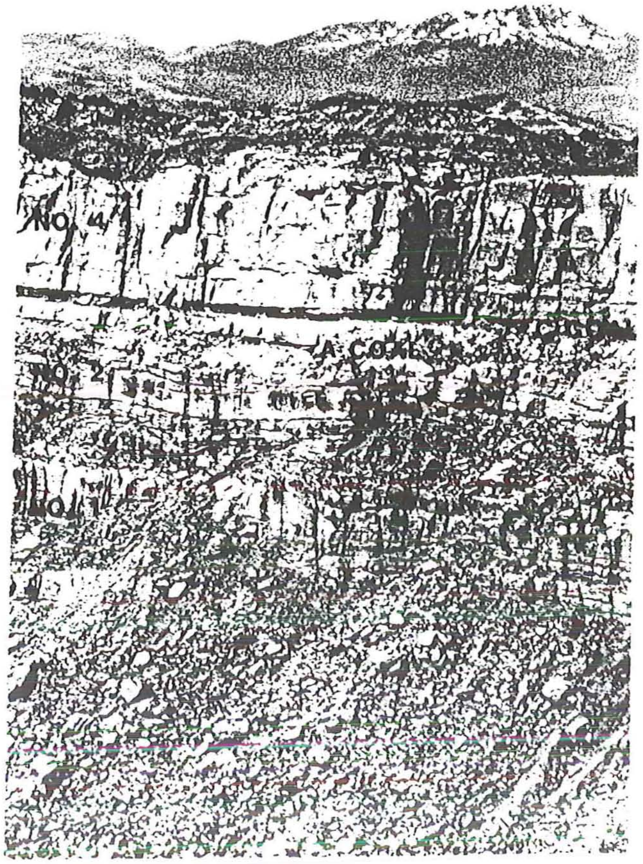

FIG. 8—Exposure of Ferron Sandstone Member southeast of Emery shows Nos. 1, 2, and 4 delta-front sandstones, plus A and C coal beds of Emery coalfield. No. 2 delta-front sandstone displays complicated cut and fill structures characteristic of mouth bar deposits seaward of active distributaries. Small distributary channel filled with mudstone cuts top of No. 4 delta-front sandstone.

cut by nonsinuous distributary channels.

4. The delta-plain facies contains many nonsinuous distributary channels and the deposits of brackish water bays. Though the development of brackish water bays suggests tidal exchange of water, there is no evidence for strong tidal influence.

5. The alluvial-plain facies consists primarily of the deposits of meandering river channels.

These criteria are all consistent with those of modern lobate, river-dominated delta systems (Galloway, 1975; Coleman, 1976).

As is evident from the preceding discussion, the Ferron Sandstone Member consists not of a single prograded delta but of a series of deltaic systems stacked one above another. The basic cross-sectional geometry of each of the deltaic systems in the direction of depositional dip is shown in Figure 12. With the exception of the earliest system, which gradationally overlies the Tununk Shale Member, each deltaic system is underlain and overlain by erosional surfaces associated with preceding and succeeding transgressions. These prograded deltaic systems, each consisting of a series of coalesced delta lobes, plus their associated transgressive disconformities, define cycles of deltaic sedimentation. Cyclicity may be the result of autocyclic (Beerbower, 1964) processes within the fluvial-deltaic system, chief among them being the processes of river avulsion and delta switching. Cotter (1975a) cited the cyclic nature of progradation as further evidence that the delta was lobate and river dominated, thereby implying autocyclic control. Another possibility is that the transgressions are responses to episodic subsidence within the foreland basin.

Figure 13, a diagrammatic cross section of the Ferron Sandstone Member in the vicinity of the Emery coalfield, shows the basic stratigraphic framework of the Ferron (Ryer, 1981a, b). The Ferron consists of five major cycles of deltaic sedimentation. The delta-front sandstone units, which serve to define the cycles, are labeled numerically in ascending stratigraphic order. Each cycle includes one major coal bed or coal zone. Minor coal beds, most of which are locally developed rider coal beds associated with the major beds, are not shown in Figure 13. The coal beds are labeled alphabetically, in ascending stratigraphic order according to the scheme proposed by Lupton (1916). The I coal bed is split in a landward direction by a wedge of predominantly alluvial strata. The lower and upper

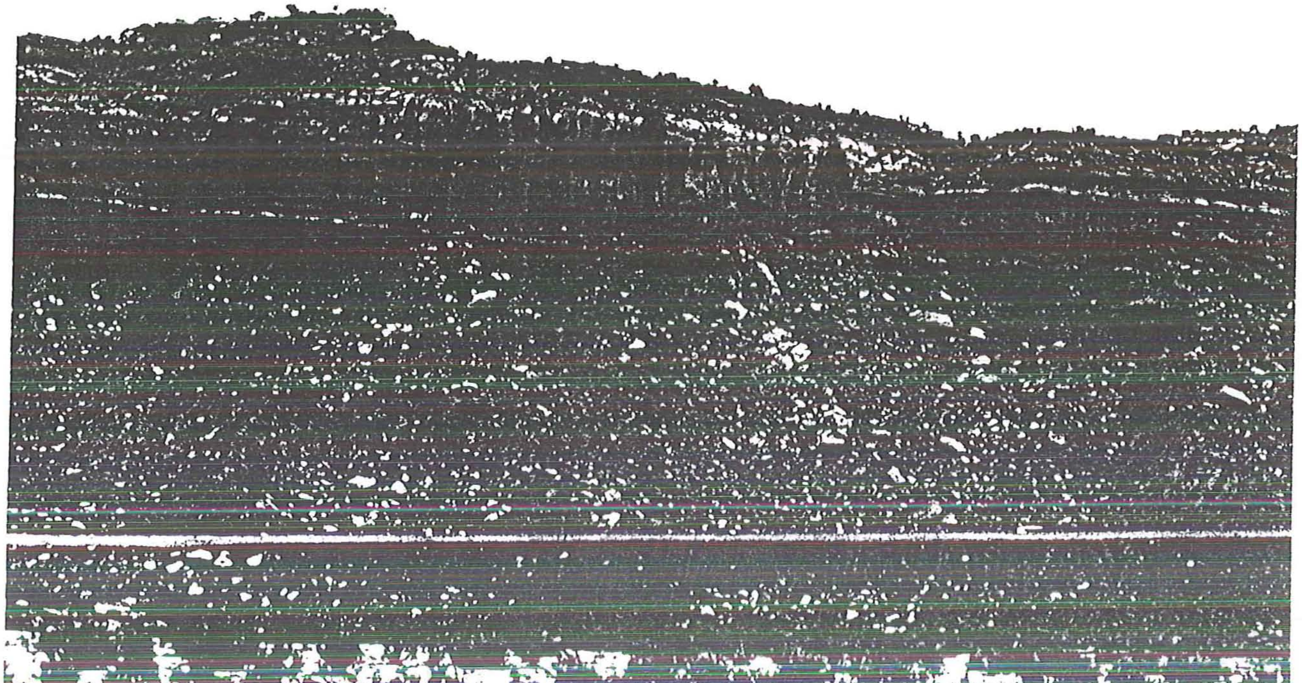

FIG. 9—Sandstone-filled distributary channel cutting No. 2 delta-front sandstone. Thin coal zone lies between No. 1 and No. 2 delta-front sandstones at this locality just south of Interstate 70.

subseams of the coal bed are designated $I_1$ and $I_2$, respectively.

Southwestward transgression of the sea across the top of the deltaic complex at the close of Ferron deposition was rapid but was interrupted by several brief periods of northeastward progradation of the shoreline. The progradational, shallow-marine sandstone units that accumulated at these times extend only a few kilometers seaward. Coal, generally in thin, localized beds, and carbonaceous shale are associated with these minor progradational events. One of these, the J coal bed (Fig. 13), is thick enough to be of economic value.

## LANDWARD PINCH-OUTS OF DELTA-FRONT SANDSTONES AND ESTABLISHMENT OF SHORELINE TRENDS

Each delta-front sandstone of the Ferron, together with its associated prodelta deposits, may be regarded as a unit having the general configuration of a parallelogram in a section parallel with the depositional dip (Fig. 12). Tracked in a landward direction, the prodelta, distal bar, and mouth bar deposits successively thin and pinch out against the erosional, disconformable surface that defines the base of the unit. The landward pinch-out of the delta-front sandstone against delta-plain or alluvial-plain deposits of the previous cycle marks the point of maximum transgression of the shoreline during the transgressive or delta-destructive phase that separated the two phases of deltaic progradation. Where the pinch-out of an individual delta-front sandstone unit can be observed at two or more localities along depositional strike on outcrops or recognized in the subsurface, the trend of the shoreline at maximum transgression can be established. The shoreline trends of the Ferron deltaic sandstones, recognized in this way, are approximately northwest, which agrees with the shoreline trend established for the area by regional study of the Ferron Sandstone Member and its lateral equivalents (Hale, 1972; paleogeographic maps, McGookey, 1972). The landward pinch-out of the No. 2 delta-front sandstone on an exposure in the southern part of the Emery coalfield (Fig. 1) is shown in Figure 14.

In areas where channels of the alluvial facies have eroded the upper parts of the delta-front sandstones, it is not possible to observe the landward pinch-outs, and their positions must be estimated. The landward pinch-out of the No. 4 sandstone on the outcrop is obscured in this way, and it was necessary to locate it approximate-

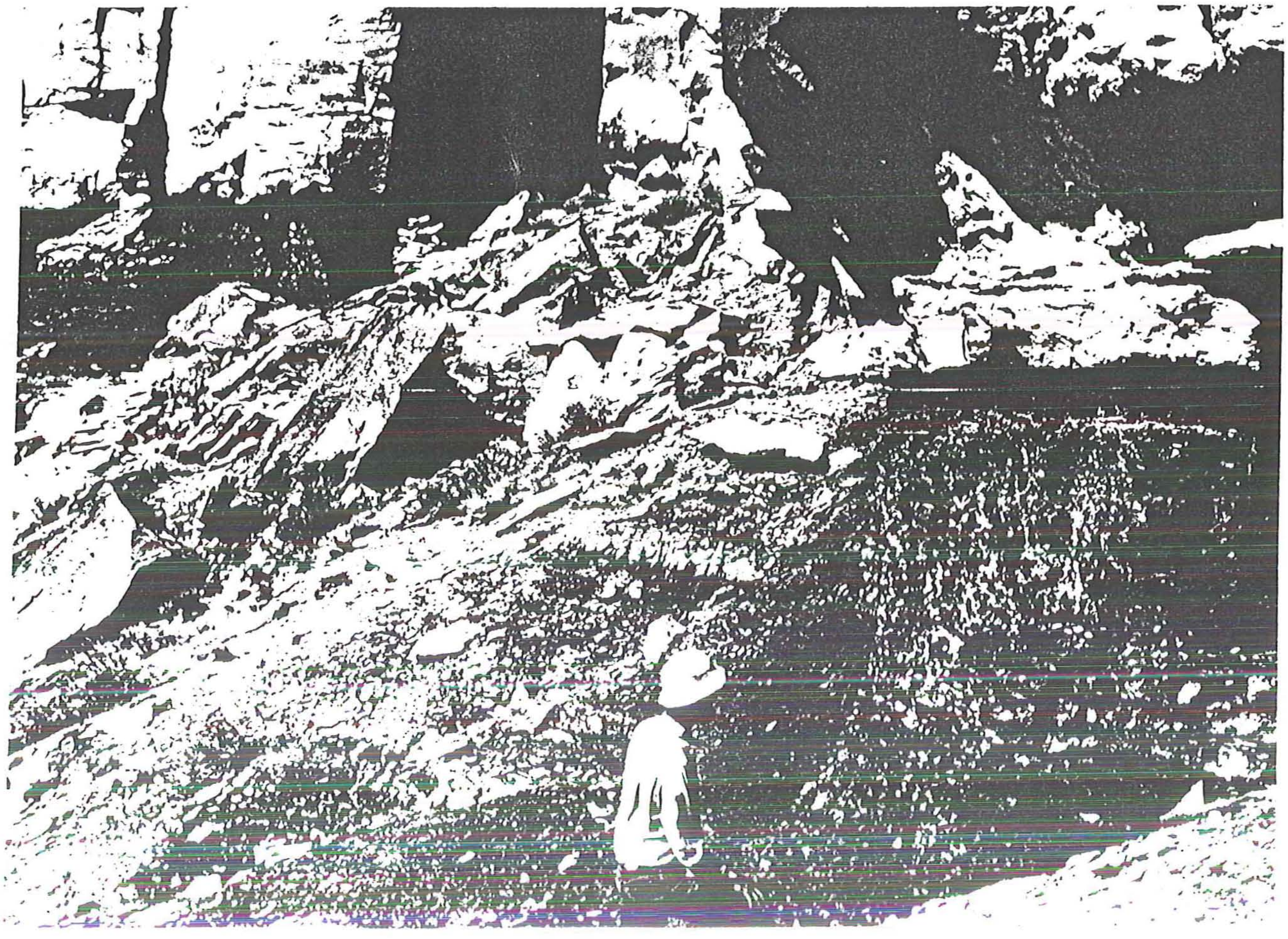

FIG. 10—Sandstone, representing active filling of meandering channel of alluvial facies, erosionally overlies bioturbated, carbonaceous siltstone of delta-plain facies.

ly. Fortunately, the trend of this pinch-out downdip from the outcrop could be defined using subsurface data.

## MAJOR COAL BEDS OF EMERY COALFIELD

A clear genetic relation exists between the geometries of the major coal beds of the Emery coalfield and the geometries of their associated delta-front sandstones. This relation is illustrated in Figures 15-19. The isopach maps in these figures were constructed using proprietary subsurface data augmented by outcrop measurements. To protect the confidentiality of the subsurface data, no information is shown that could be used to precisely locate the data points. These are total coal isopach maps, showing the thicknesses of the major coal beds, less any rock splits, plus the thicknesses of rider seams; they do not show minable seam thicknesses. Several thin, localized coal beds in the Ferron could not be related to any major coal bed with certainty, and therefore have not been included in the analysis. Their inclusion would not significantly alter the picture presented here. The coal beds are discussed individually in descending stratigraphic order. Though opposite to the order of deposition of the coal beds, this order of discussion allows progression from simpler to more complex situations.

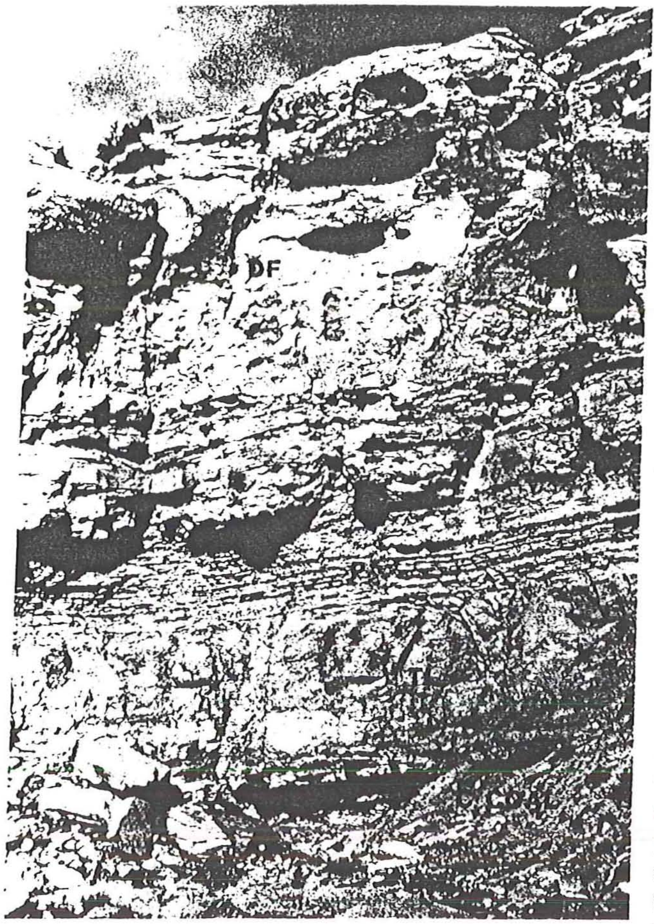

FIG. 11—Transgressive lag deposit (TL) overlies C coal bed with erosional contact. Prodelta (P) and delta-front (DF) deposits of No. 4 delta cycle overlie transgressive lag.

The J coal bed (Fig. 15) is the product of peat accumulation during one of the minor progradational events that interrupted the southwestward transgression of the sea across the Ferron deltaic complex. The coal bed only locally exceeds 2 m in thickness. The thicker part of the bed, "thicker" being arbitrarily defined as equaling or exceeding half the value of the greatest isopach line mapped on the bed, extends from a position approximately 3 km seaward of the landward pinch-out of the associated marine sandstone to a position approximately 11 km landward of the pinch-out. The body of thicker coal is elongate, the direction of elongation being nearly normal to the trend of the pinch-out of the marine sandstone.

The I coal bed (Fig. 16) is, economically, the most important bed in the Emery coalfield. It attains a maximum thickness of about 10 m. The thicker coal (greater than 5 m) occurs in an elongate body that extends from a distance of approximately 2 km to a distance of approximately 11 km landward of the landward pinch-out of the No. 5 delta-front sandstone. The elongation of the coal body, like that of the body of thicker J coal, is nearly normal to the trend of the pinch-out. The relation of the channel system that is indicated in the northeastern part of the area is unclear because the outcrops in the vicinity of the channel deposits have been disturb-

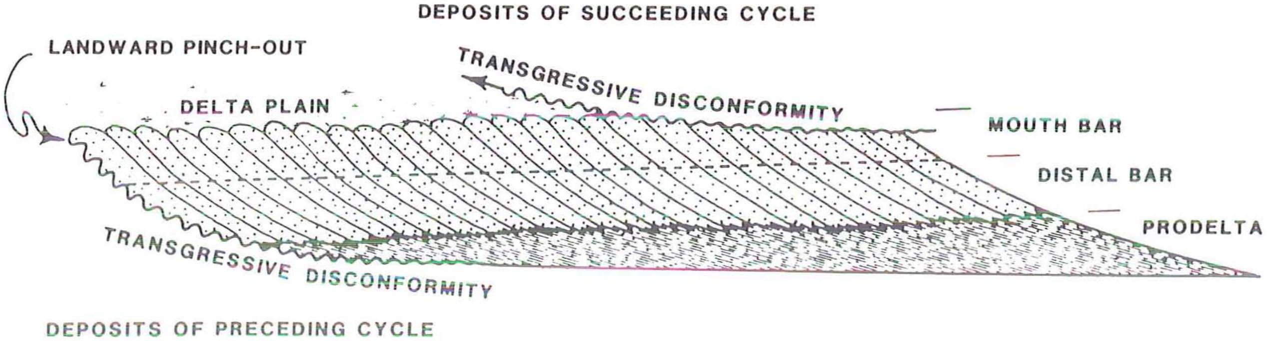

FIG. 12—Diagrammatic section, parallel with depositional dip, through deposits of deltaic cycle showing bounding transgressive disconformities and landward pinch-out of delta-front sandstone unit.

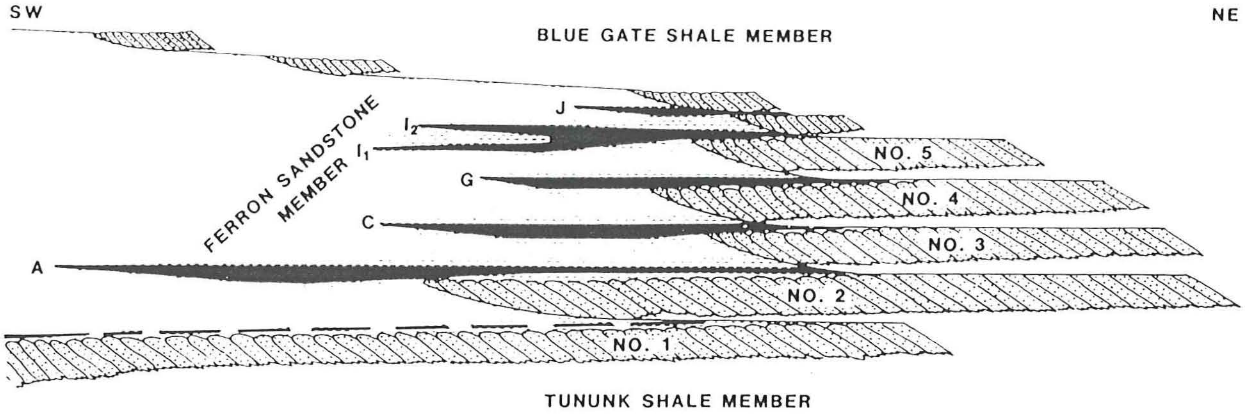

**FIG. 13—Diagrammatic cross section of Ferron Sandstone Member in vicinity of the Emery coalfield. Delta-front sandstone units are labeled numerically, major coal beds alphabetically. Undivided alluvial- and delta-plain deposits are indicated by horizontal dashed pattern.**

ed by natural burning of the I coal bed. It is probable that the channel system, which is represented by a series of stacked point bar sequences totaling 25 to 30 m in thickness, was at least partly contemporaneous with the swamp that produced the I coal bed. The channel system was abandoned prior to accumulation of the J coal bed.

The G coal bed (Fig. 17) only locally exceeds 2 m in thickness. The thicker (greater than 1 m) part of the coal bed extends from approximately 2 km seaward of the landward pinch-out of the No. 4 delta-front sandstone to at least 11 km landward of the pinch-out. If the thicker coal body has a direction of elongation, it is not apparent from the available data.

The C coal bed (Fig. 18) locally exceeds 6 m in thickness. The thicker part of the coal bed (greater than 3 m) extends from approximately 1 km landward of the landward pinch-out of the No. 3 sandstone to approximately 10 km landward of the pinch-out. The area of thicker coal parallels the trend of the pinch-out of the No. 3 sandstone but can be subdivided into two bodies by the convergence of the 3-m isopach lines in the north-central part of the mapped area. The shape of the northwesternmost of these two bodies cannot be clearly discerned because of the small number of drill holes that have penetrated it. Coal exceeds 5 m in thickness in two small areas within the well-defined southeasterly body. A line passing through these two areas of thickest coal intersects the trend of the pinch-out of the No. 3 sandstone at approximately a right angle.

The A coal bed (Fig. 19) is, by far, the most widespread of the coal beds in the Emery coalfield. This reflects the fact that the No. 2 delta-front sandstone, with which it is associated, has a much greater lateral extent parallel with the depositional dip than do the succeeding delta-front sandstones (Fig. 13). The coal bed locally exceeds 5 m in thickness. The thicker coal (shown in Figure 19 as coal exceeding 2 m in thickness, no 2.5-m contour having been mapped) occurs in three larger and one smaller bodies. One of the larger bodies is associated with the landward pinch-out of the No. 2 delta-front sandstone, following the pattern of the stratigraphically higher coal beds. This coal body extends from approximately 2 km seaward of the pinch-out to approximately 8 km landward of the pinch-out. As mapped in Figure 19, it is elongate perpendicular to the trend of the pinch-out of the No. 2 sandstone. The distribution of control points, however, is such that a different configuration is possible. The other two of the larger bodies of thicker coal occur between approximately 2 and 9 km seaward of the landward pinch-out of the No. 2 sandstone. The northernmost of these bodies is elongate at a high angle to the trend of the pinch-out; the other shows no elongation.

A zone containing carbonaceous shale and thin beds of coal is associated with the No. 1 delta-front sandstone. A maximum observed coal thickness of about 1 meter occurs in a bed in the southernmost part of the Emery coalfield. Lupton (1916) miscorrelated this coal bed with the A coal bed, which pinches out several kilometers to the north. The thin, localized coal beds of this zone were not isopached. No landward pinch-out of the No. 1 sandstone can be observed, the No. 1 sandstone being covered by Tertiary volcanic rocks at the south end of the outcrop of the Ferron Sandstone Member (Williams and Hackman, 1971).

## PREDICTIVE MODEL

A body of thicker coal is associated with each of the landward pinch-outs of the delta-front sandstones of the Ferron Sandstone Member in the Emery coalfield. The coal bodies extend about 10 km landward from the vicinities of the pinch-outs. This is also true for the minor marine sandstone unit associated with the J coal bed. This relation was used to construct the simple model shown in Figure 20. The model has predictive value in coal exploration: landward pinch-outs of the major delta-front sandstones within a deltaic complex can be located and their trends established; the probability is high that bodies of thicker coal will occur within belts that parallel these pinch-outs, each belt be-

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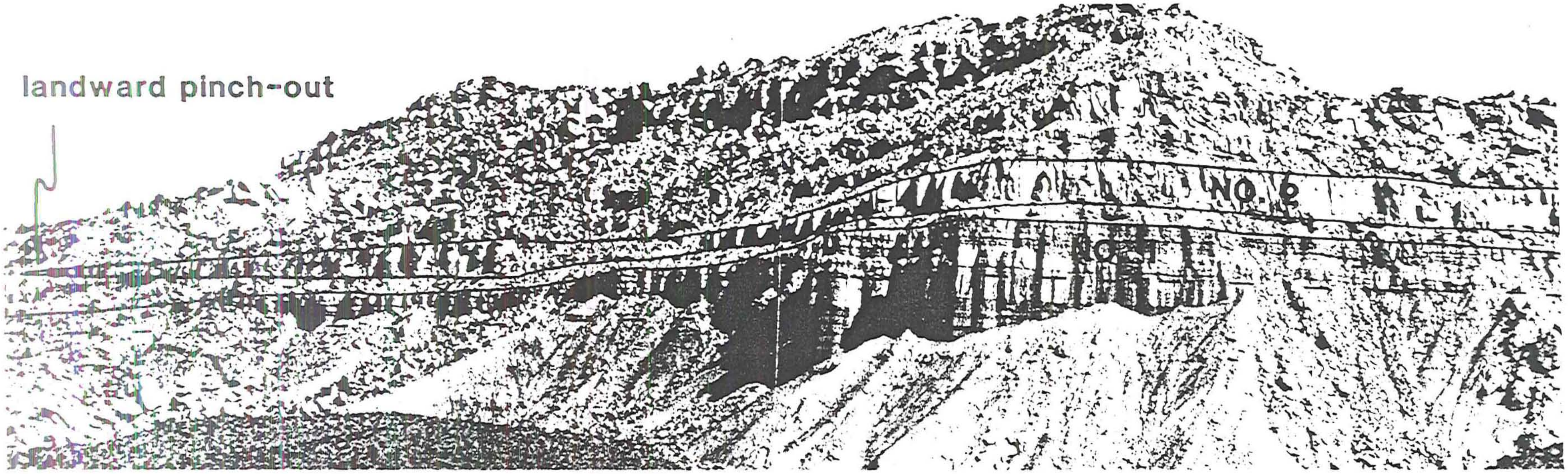

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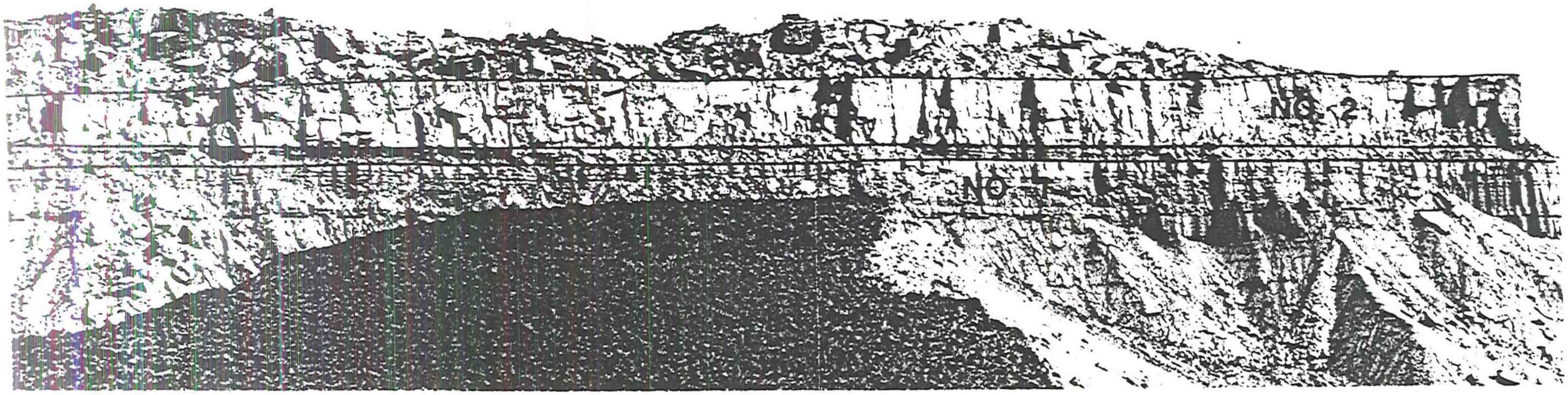

FIG. 14—Landward pinch-out of No. 2 delta-front sandstone of Ferron in southern part of Emery coalfield. Basal contact of No. 2 sandstone is erosional, resting on coal zone associated with No. 1 sandstone. Contact between No. 1 sandstone and underlying Tununk Shale Member is transitional.

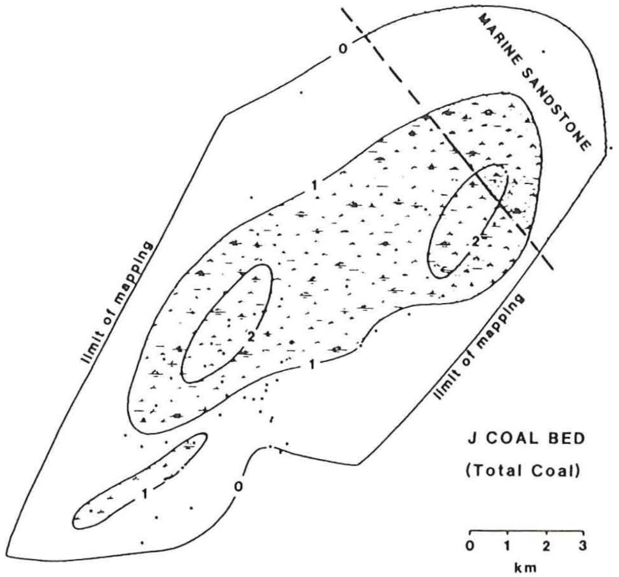

FIG. 15—Isopach map of J coal bed of Emery coalfield. In this and following figures: isopach lines are at 1-m intervals; north is toward top of figure, areas of thicker coal are indicated by swamp pattern, and landward pinch-out of associated marine sandstone or delta-front sandstone is indicated by northwest-trending line, which is solid in vicinity of outcrop. (Refer to Figure 1 for locations of pinch-outs.)

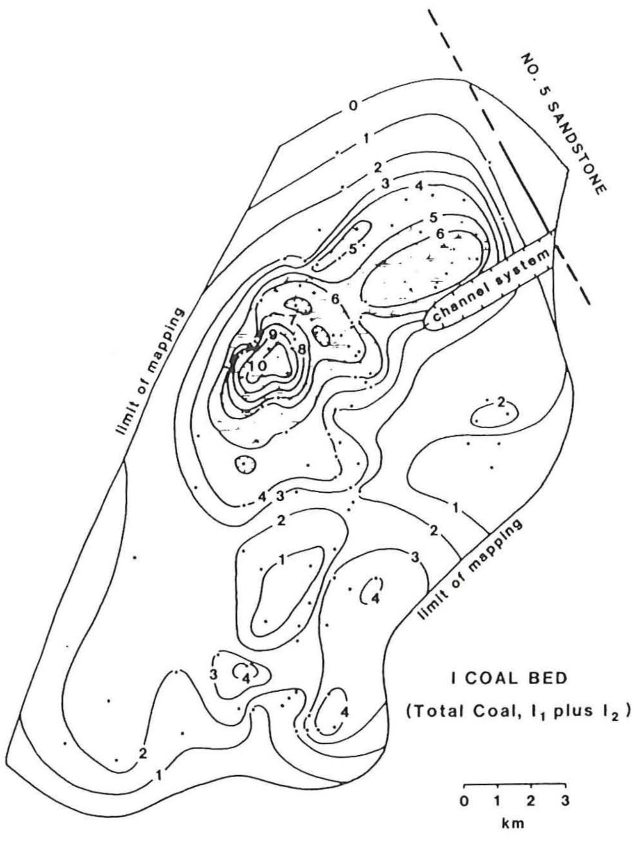

FIG. 16—Isopach map of I coal bed, the most economically important coal bed of Emery coalfield.

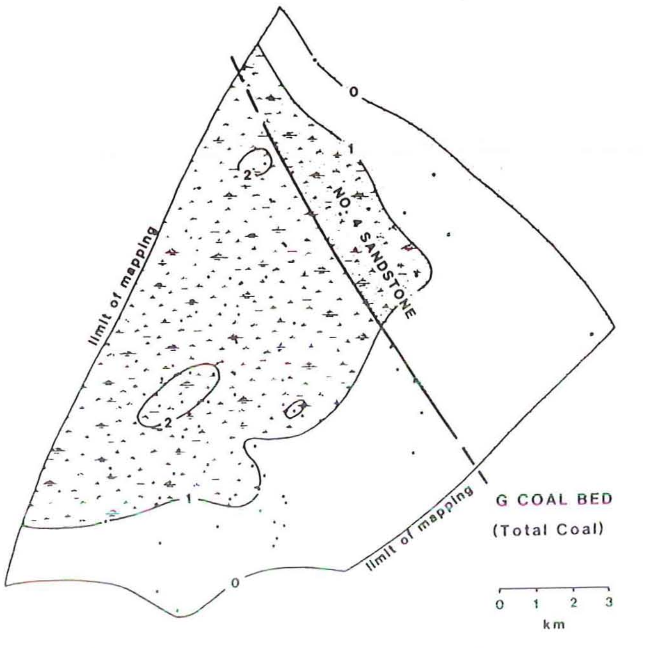

FIG. 17—Isopach map of G coal bed of Emery coalfield.

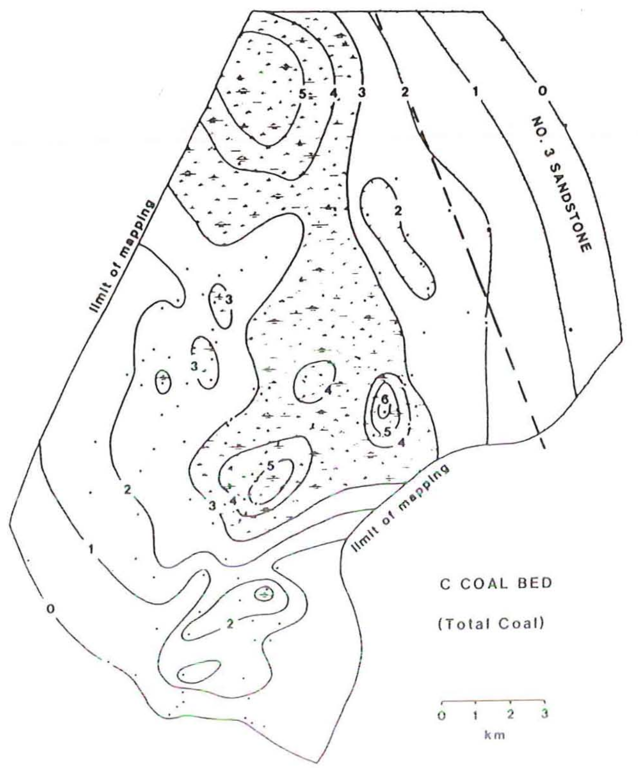

FIG. 18—Isopach map of C coal bed of Emery coalfield.

ing about 10 km in width and extending landward from its associated pinch-out.

Why does this relation between coal thickness and location of pinch-outs exist? The reasons are not entirely clear, though two contributing factors may be (1) the fact that the delta-front sandstones show evidence of stratigraphic rise during progradation, and (2) the effects of early compaction of fine-grained and organic-rich sediments.

### Stratigraphic Rise

Units consisting of the combined prodelta and delta-front facies of the Ferron Sandstone Member thicken seaward from their landward pinch-outs by progressive addition of strata at the bottom of each unit (Fig. 12). On outcrops, this is most easily discerned as seaward thickening of the prodelta facies. The rate of thickening exceeds that which would be expected had the deltas simply prograded, at constant relative sea level, across the gently seaward-dipping to horizontal surfaces developed during the preceding transgressions. The uppermost parts of the delta-front sandstones commonly interfinger, on a small scale, with strata of the delta plain facies (Fig. 6). The seaward thickening of the combined prodelta and delta-front units and their interfingering with delta-plain deposits indicate that relative sea level, or "base level," rose during the period of time represented by the progradational phase of each of the deltaic cycles. This rise of relative sea level, expressed as seaward stratigraphic rise of facies contacts within the progradational sequences, reflects continuous subsidence within the basin of deposition, local subsidence produced by loading and compaction of underlying sediments, or both.

Deposits of the delta plain accumulate at or near sea level. Unlike the delta-front strata, which record lateral accretion of sediment on the seaward-dipping delta front (Weimer, 1970), delta-plain deposits record principally vertical accumulation of sediment (splays and active channel fills being exceptions).

Because of these facts, the upper delta-plain facies thins seaward within a depositional cycle (Fig. 21a). The thickest delta-plain deposits tend to be associated with the landward pinch-outs of the delta-front sandstones. These were the areas where delta-plain sediments were initially deposited during the first stages of progradation and also the areas where vertical accumulation of these sediments could occur for the longest periods of time. The thicker coal bodies of the major coal beds of the Ferron occur primarily within the delta-plain facies. The same argument may be applied to them—the greatest thicknesses of peat (and therefore coal) would be expected in the areas just landward of the pinch-outs. However, delta-plain deposits in these areas are prone to erosion by meandering channels of the seaward advancing alluvial plain facies. Conversely, erosion of delta-plain deposits from the more distal parts of a delta system during the succeeding delta-destructive phase accentuates the seaward thinning of the delta-plain facies.

### Compaction of Sediments

All sediments undergo compaction during their trans-

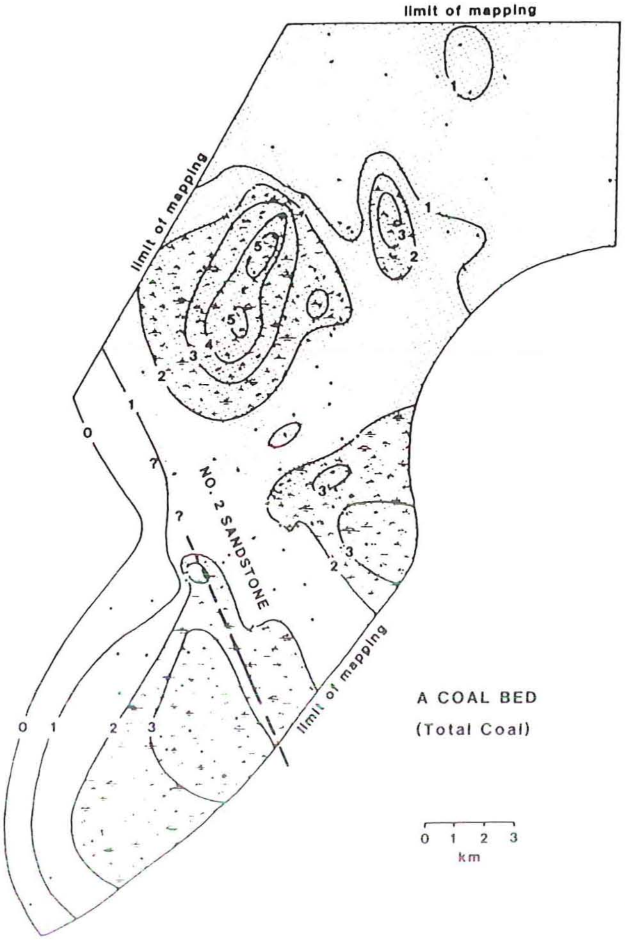

FIG. 19—Isopach map of A coal bed, the most widespread coal bed of Emery coalfield.

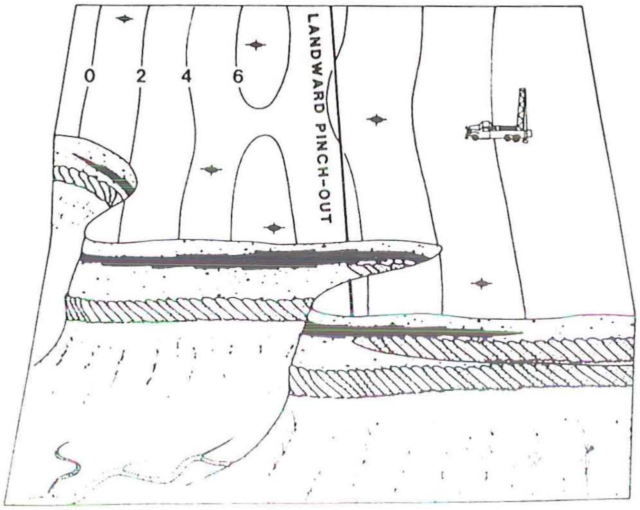

FIG. 20—Simple predictive model showing relation between coal thickness and location of pinch-out of delta-front sandstone.

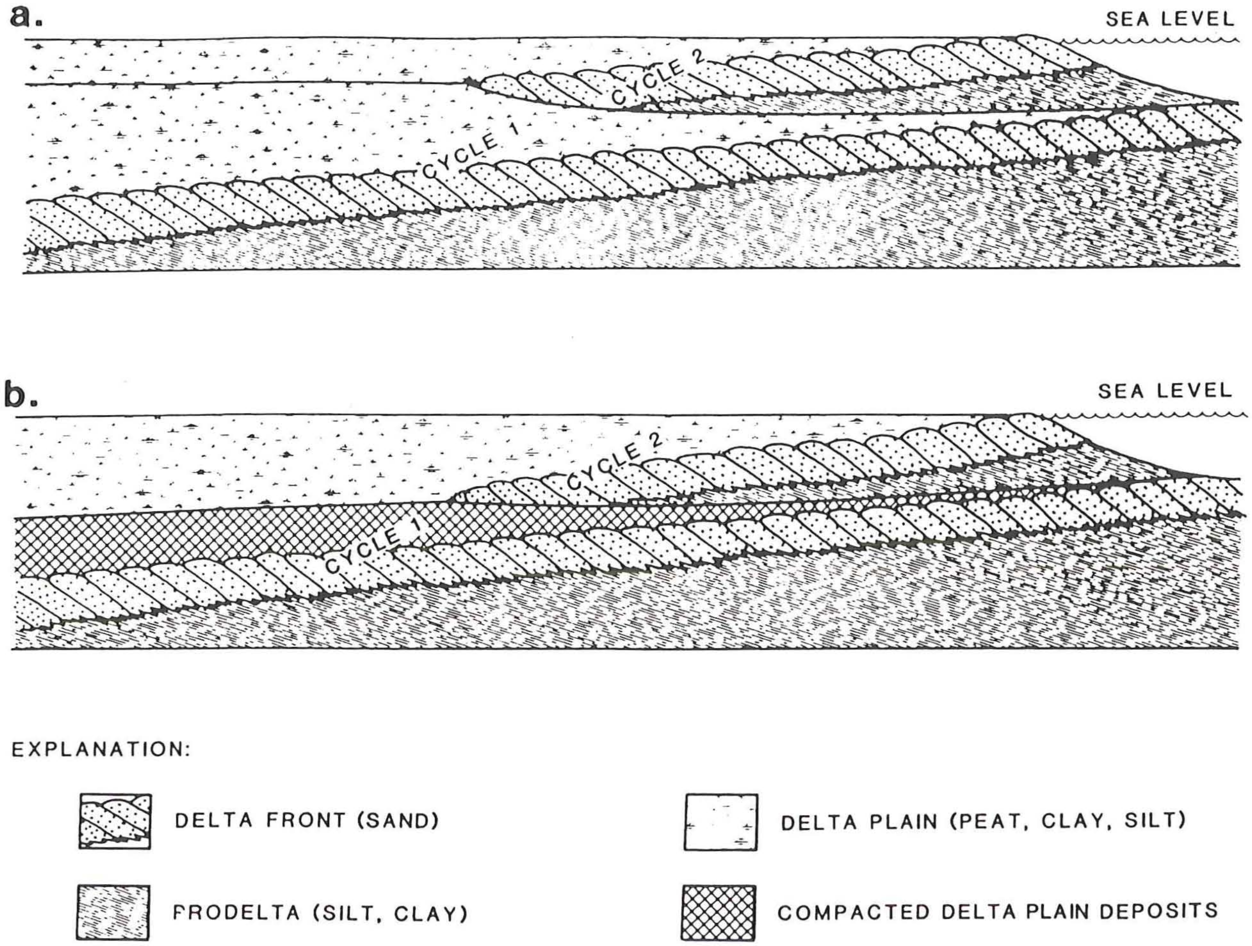

**FIG. 21—Diagram showing effects of (a) stratigraphic rise during progradation, and (b) early compaction of fine-grained and organic-rich sediments.**

formation to sedimentary rocks (Weller, 1959). The compaction begins early in the history of burial (Conybeare, 1967). Of the sediments present in a deltaic system like that represented by the Ferron, well-sorted sands and peat represent the minimum and maximum extremes in terms of compactibility. The sand-to-sandstone transformation involves little or no compaction; the peat-to-coal transformation involves a compaction ratio of about 10:1 (Ryer and Langer, 1980). Delta-plain deposits contain large amounts of peat, plus organic-rich clays and silts that are also susceptible to compaction.

The landward pinch-outs of the delta-front sandstones most commonly overlie, with erosional contacts, delta-plain strata of the preceding delta cycle. This provides another mechanism that can accentuate the thickening of delta-plain deposits in the vicinities of the pinch-outs (Fig. 21b). Deposits of two cycles are shown. The landward pinch-out of the second cycle occurs within delta-plain deposits of the first cycle. If, during the period of time represented by the second cycle, the fine-grained and organic-rich deposits of the first cycle undergo compaction, a greater-than-expected thickness of delta-plain sediments can accumulate in the vicinity of the landward pinch-out of the delta-front sandstone. Compaction of the delta-front sandstone seaward of the pinch-out is negligible.

These two mechanisms, stratigraphic rise during progradation and early compaction of sediments, both favor the accumulation of thick bodies of peat in the vicinities of and just landward of the landward pinch-outs of the delta-front sandstones. The former is probably the more important of the two mechanisms.

## EFFECTS OF CHANNELS AND A MORE REFINED MODEL

The predictive model shown in Figure 20 is too simple; it does not provide for the elongation of the thicker coal bodies, as observed in Figures 15, 16, 18, and 19, parallel with depositional dip.

The C coal bed, because it is very well exposed on the outcrops and because it contains distinctive beds of altered volcanic ash that can be correlated over the lateral extent of the bed, is probably the best understood of the coal beds in the Emery coalfield. The depositional history of the C coal bed is described elsewhere (Ryer et al, 1980) and will only be summarized here.

The C coal bed (Fig. 18) illustrates the shortcomings of the simple model. As predicted by the model, an area of thicker coal is associated with, and generally parallels, the landward pinch-out of the No. 4 delta-front sandstone, but that area can be divided into two bodies of thicker coal. The shape of the southeasternmost body is controlled by channel systems that were partly contemporaneous with accumulation of the peat.

The depositional history of the C coal bed is shown in Figure 22. Two fluvial channel systems are shown feeding sediment to the delta front of the No. 3 delta (Fig. 22a-c). The southeasternmost (closer) channel system can be examined on the outcrops; the other is known only from subsurface data. Outcrops of the southeasternmost channel system display one or, more commonly, a series of stacked point bar sequences, indicating that these strata accumulated within the alluvial-plain facies, where the channels were highly sinuous and meandering. Because the two channel systems are separated by a distance of only a few kilometers, it is highly unlikely that they represent two different, contemporaneous rivers. It is believed, instead, that a single river repeatedly occupied these two systems, switching from one to the other, and probably to additional systems spaced along the depositional strike, by avulsion. Peat that would eventually produce the southeasternmost thicker coal body of the C coal bed accumulated in the area between the two channel systems. Peat, unlike sands and silts deposited by a meandering channel, is a fibrous, cohesive material that resists erosion. Once a bed of peat has accumulated, it is unlikely that a new channel system can be developed across it by river avulsion. Thus the placement of the channels controls the location of initial peat accumulation, and the peat then keeps the courses of the channel systems fixed. Channel systems that postdate peat accumulation can and do erode peat beds; they produce the sand rolls or cutouts that cause localized erosional thinning of coal beds, and which often create problems in mine planning and development. It is the channels that exist contemporaneously with peat accumulation, however, that exert the greatest influence upon the configurations of coal beds. Because the positions of channel systems along the depositional strike in an area like the Emery coalfield must, with few exceptions, be determined by drilling, only their general effects can be considered in the predictive model.

The predictive model, then, must be made to incorporate two elements: a predictable element—the location of areas of thicker coal relative to the landward pinch-outs of the delta-front sandstones; and, superimposed, a basically unpredictable element—the effects of channel systems, which isolate thicker bodies of coal. These two elements are shown in Figure 23. Figure 23b represents a more refined predictive model for deltaic coals of the Ferron Sandstone Member.

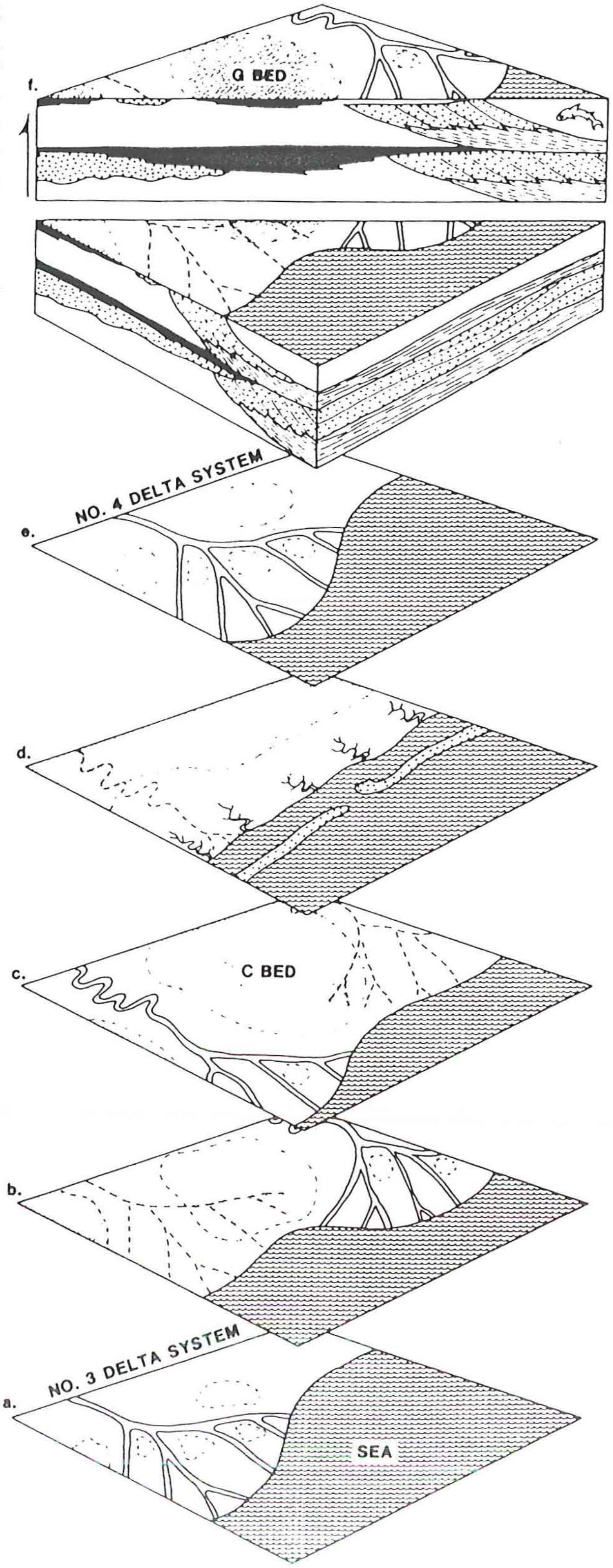

FIG. 22—Depositional history of C coal bed. View is toward west. Areas of most rapid peat accumulation are indicated by "scrub" pattern. Progradation of No. 3 deltaic system and accumulation of peat (a-c) in area between channel systems; (d) abandonment of No. 3 deltaic system and beginning of delta-destructive phase; (e-f) progradation of No. 4 deltaic system.

## APPLICATION OF MODEL TO OTHER AREAS

The predictive model presented here and modifications of it should prove to be generally applicable to coal-bearing strata deposited along the western margin of the Interior Cretaceous seaway in North America and perhaps to similar rocks of other ages and in other areas.

The Ferron Sandstone Member in the vicinity of the Emery coalfield records stacking of the deposits of a lobate, river-dominated deltaic system under conditions of near balance between the rate of change of sea level and the rates of regional subsidence and sediment input (Ryer, 1981c). Speculations on modifications that might make the predictive model applicable to areas characterized by other sets of conditions follow.

### Wave-Dominated Deposits

Most Cretaceous coal-bearing strata in the Western Interior represent wave-dominated paleoenvironments—wave-dominated deltas and strand-plain systems. The deposits of these paleoenvironments generally contain fewer channel systems than do the deposits of river-dominated deltas. This is particularly true of strand-plain deposits. In these deposits, segmentation of the areas of thicker coal associated with landward pinch-outs into distinct coal bodies should be less pronounced or absent, and the simple model shown in Figures 20 and 23a should apply. An area that appears to conform to the simple model is the Kaiparowits coalfield of south-central Utah (Peterson, 1969; Vaninetti, 1979). Another possible example may be seen in the distribution of coals in the Rock Springs Formation in the Rock Springs coalfield of southwestern Wyoming (Roehler, 1978a, b).

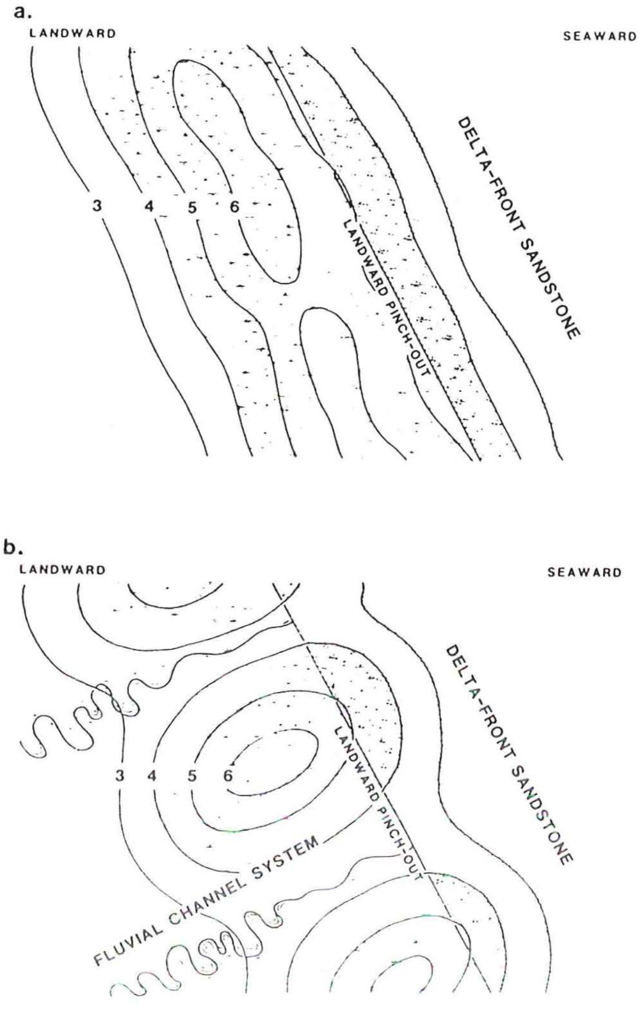

FIG. 23—Predictive model for Ferron Sandstone Member: (a) simple model as in Figure 20; (b) effects of fluvial channels; represents more refined model for Ferron.

### Regressive Phase Deposits

Shoreline deposits of the regressive phases of the major Cretaceous transgressive-regressive cycles of the Western Interior (Kauffman, 1977), as exemplified by the Mesaverde Group in Utah (Fig. 4), locally display stacking of delta-front or shoreface units (Fassett and Hinds, 1971, p. 11) but are generally characterized by seaward shingling of units. As a result, individual progradational units generally have a much greater extent parallel with the depositional dip than do the delta-front sandstones of the Ferron. Coal beds are associated with the landward pinch-outs but also overlie the platforms provided by the prograded delta-front or shoreface sandstones. This pattern is exhibited by deposits of the No. 2 delta of the Ferron Sandstone Member. It has also been documented in the Wasatch Plateau and Book Cliffs coalfields, both in central Utah, by Marley et al (1979) and by Balsley (1980), respectively, and in the Rock Springs coalfield by Levey (1981). The model described here, though applicable to deposits of this type, cannot be used to predict the occurrences or locations of additional coal bodies that may overlie these shoreline sandstones. The occurrence of coal bodies in this stratigraphic position are expected in association with shoreline deposits that have prograded seaward a distance of 20 km or more.

### Transgressive Phase Deposits

Strata deposited on the transgressive phases of the major transgressive-regressive cycles, as exemplified by the Dakota Sandstone in central and eastern Utah and western Colorado (Fig. 4), generally do not contain thick beds of coal, though there are exceptions: Almond Formation, Rock Springs coalfield, southwestern Wyoming (Roehler, 1976); Dry Hollow Member (Hale, 1960) of the Frontier Formation, Hams Fork coalfield, southwestern Wyoming (Veatch, 1907; Myers, 1977); Coalville Member (Hale, 1960) of the Frontier Formation, Coalville coalfield, north-central Utah (Doelling and Graham, 1972; Ryer, 1976); and the upper part of the Frontier Formation, Tabby Mountain coalfield, northeastern Utah (Doelling and Graham, 1972). When coal does occur, it is usually associated with minor episodes of progradation, like that represented by the J coal bed of the Emery coalfield and its associated marine sandstone. Such occurrences of coal bodies should conform to the predictions of the model. Coal beds in this stratigraphic position, though, were subject to erosion by landward advancing shorefaces during succeeding periods of transgression and, because they are commonly overlain by marine roof rocks, tend to be high in sulfur (Horne et al, 1978).

## CONCLUSIONS

Depositional models have proven valuable in coal mine planning and development; they can also be valuable in coal exploration. In the Emery coalfield of central Utah, the thicker parts of the major coal beds are associated with the landward pinch-outs of the delta-front sandstones of the Ferron Sandstone Member, extending about 10 km landward from the vicinities of the pinch-outs (Figs. 15-19). This relation forms the basis of a predictive model (Figs. 20, 23) that may, with some modifications, be used in designing drilling programs to evaluate Cretaceous coal-bearing strata of the Western Interior. A coal exploration program utilizing the model should include the following: (1) analysis of outcrops and available subsurface data to reconstruct the basic stratigraphic framework of the coal-bearing unit; (2) delineation of the landward pinch-outs of the major delta-front or shoreface sandstone units and establishment of the trends of the pinch-outs; (3) delineation of 10-km-wide belts located just landward of and paralleling the trends of the pinch-outs, these belts being the areas most likely to contain thicker bodies of coal; (4) designing of drilling and coring programs to evaluate the belts. In river-dominated deltaic systems, the trends of thicker coal bodies within the belts may parallel the direction of depositional dip; in wave-dominated deltaic and strand-plain systems, the bodies are more likely to parallel depositional strike. In shoreline deposits that have prograded seaward a distance of 20 km or more, the possibility that additional bodies of coal will occur overlying the platforms formed by the shoreline deposits must be considered.

A coal exploration program employing these guidelines should be more cost-effective than one employing a hit-or-miss approach.

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