BRIGHAM

YOUNG

UNIVERSITY

GEOLOGY STUDIES

Volume 22, Part 3—July 1976

CONTENTS

Brigham Young University Geology Studies

Volume 22, Part 3—July 1976

Aspects of Coal Geology, Northwest Colorado Plateau
Some Geologic Aspects of Coal Accumulation, Alteration, and Mining
In Western North America: A Symposium

Papers prepared for presentation at a symposium at the annual meeting of the Coal Geology Division of the Geological Society of America, Salt Lake City, Utah, October 20, 1975, and adjunct papers pertinent to the annual field trip, October 17-19, 1975, in the Western Book Cliffs, Castle Valley, and parts of the Wasatch Plateau, Utah. *The Field Guide and Road Log* appears as Volume 22, Part 2—October 1975, *Brigham Young University Geology Studies.*

Editors

Aureal T. Cross
Michigan State University
East Lansing, Michigan

E. Blair Maxfield
Southern Utah State College
Cedar City, Utah

A publication of the
Department of Geology
Brigham Young University
Provo, Utah 84602

Editor

W. Kenneth Hamblin

Brigham Young University Geology Studies is published semiannually by the department. *Geology Studies* consists of graduate-student and staff research in the department and occasional papers from other contributors. *Studies for Students* supplements the regular issues and is intended as a series of short papers of general interest which may serve as guides to the geology of Utah for beginning students and laymen.

ISSN 0068-1016

Distributed July 30, 1976

Price $5.00

(Subject to change without notice)

7-76 600 15639

The Role of Deltas in the Evolution of the Ferron Sandstone and Its Coals, Castle Valley, Utah

EDWARD COTTER

Department of Geology and Geography
Bucknell University, Lewisburg, Pennsylvania 17837

ABSTRACT.—The Ferron Sandstone Member of the Mancos Shale (Upper Cretaceous) in the Castle Valley of east-central Utah evolved through the development of two separate deltaic depositional systems. The Last Chance Delta prograded northeastward into what is now southern Castle Valley as a clastic wedge of coal-bearing deltaic and fluvial sediments. In the northern part of the valley the Ferron comprises thin, sheetlike, nearshore and offshore sandstone units which were derived from the Vernal Delta that is centered in northeastern Utah.

The Last Chance Delta contains recoverable reserves of over 400 million tons (363 million metric tons) of high volatile C bituminous coal that has low sulfur and medium ash content (Doelling, 1972). Two coal beds in the lower part of the formation are the most extensive laterally and contain the most significant recoverable reserves; they were deposited in delta plain marshes and/or swamps. Higher in the sequence are generally thinner and more areally restricted alluvial plain coals; locally thick zones of such coals contain the only two mines currently active in the Ferron Sandstone.

There are no coals in the thin sandstone units exposed in northern Castle Valley, but there are significant quantities of coal of probable delta plain and alluvial plain origin in subsurface Vernal Delta deposits less than ten miles (16 km) west and north of the northern Castle Valley outcrops.

INTRODUCTION

In Late Cretaceous time in what is now eastern Utah, the western margin of a broad epeiric sea migrated back and forth as a series of pulses of clastic debris was shed eastward from the spasmodically uplifted Sevier orogenic belt. Commonly these migrations are referred to and illustrated in terms of littoral zone or barrier beach translation to the east, followed as it goes by the coastal lagoon environment in which the organic matter, that becomes coal, accumulates. In many cases the return westward migration is presented in barrier beach translation terms resulting in a symmetrical depositional cycle.

This conceptual scenario undoubtedly fits the basic pattern of developmen of many Cretaceous clastic wedges of the United States Western Interior, but it does not fit the Ferron Sandstone.

The Ferron Sandstone Member of Mancos Shale was formed in Middle Carlile (Turonian) time, as the earliest of the Late Cretaceous regressions moved through east-central Utah (Figure 1). Exposures of the Ferron Sandstone in Castle Valley (Figures 2, 3, 4) and information from the subsurface Ferron west of the outcrop belt show that this unit evolved through the development and progradation of two deltaic depositional systems, the Last Chance Delta to the south and the Vernal Delta to the north. On the subsequent marine transgressive part of the cycle there were essentially no coastal zone deposits, and thus the cycle is asymmetrical.

This paper is a general review of the salient features of these two deltas as they are demonstrated in the Ferron Sandstone; it also attempts to show the nature of the coal in the Ferron and the fundamental role of the deltas in the accumulation of that coal.

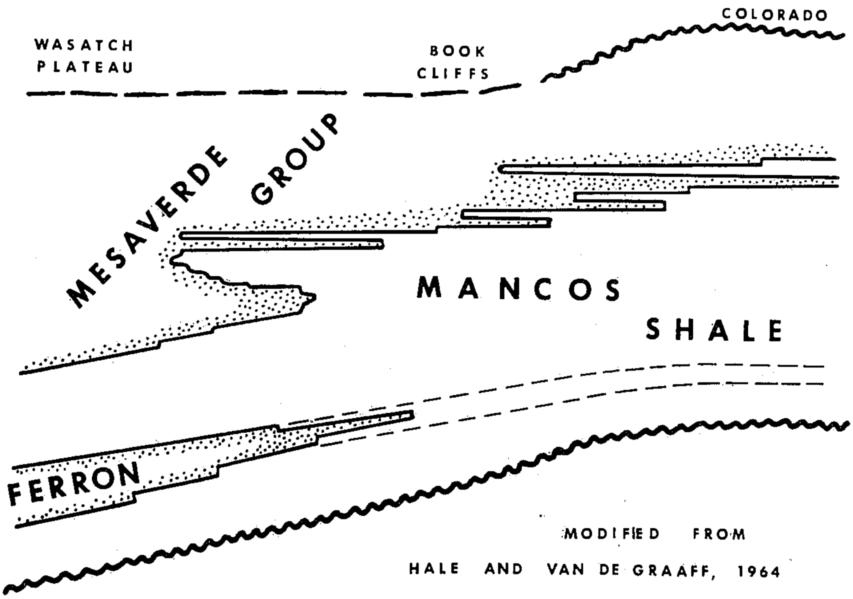

FIGURE 1.—Restored diagrammatic cross section of Upper Cretaceous rocks of eastern Utah.

GENERAL PATTERN OF EVOLUTION

It has been known for some time that the Ferron Sandstone exposed in Castle Valley comprises two separate depositional systems (Katich, 1954; Davis, 1954). In the northern part of the valley the Ferron consists of several thin sheetlike sandstone units that were derived from a source to the west and north, a source that has become identified as the Vernal Delta (Hale and Van De Graaff, 1964; Cotter, 1975b). Although deposits of the Vernal Delta itself do not crop out in Castle Valley, its coal-bearing sandstones do occur in the subsurface less than ten miles west and north of the outcrop (Gray, Patalski, Schapiro, 1966; Doelling, 1972; Hale, 1972).

To the south in Castle Valley the Ferron Sandstone is a southward-thickening wedge of deltaic and fluvial sediments known as the Last Chance Delta (Hale, 1972). Katich (1953) was the first to demonstrate that this southern depositional system was derived from a source area to the southwest, a situation that was discussed and diagrammed paleogeographically by Hale and Van De Graaff (1964) and Hale (1972).

Detailed correlation of the exposed Ferron Sandstone demonstrates that in Castle Valley the two depositional systems are not contemporaneous. The thinner northern sandstone units, derived from the Vernal Delta, are stratigraphically beneath, and therefore, older than deposits of the Last Chance Delta (Davis, 1954; Katich, 1954; Cotter, 1975b) (Figure 5).

Thus, the evolution of the Castle Valley Ferron Sandstone involves the development of two deltaic depositional systems. The northerly Vernal Delta did not prograde quite as far as the Ferron outcrop, but it did provide the sediment for the thin northern units. And slightly later, the Last Chance Delta built a wedge of clastic debris up into Castle Valley from the south (Figure 6).

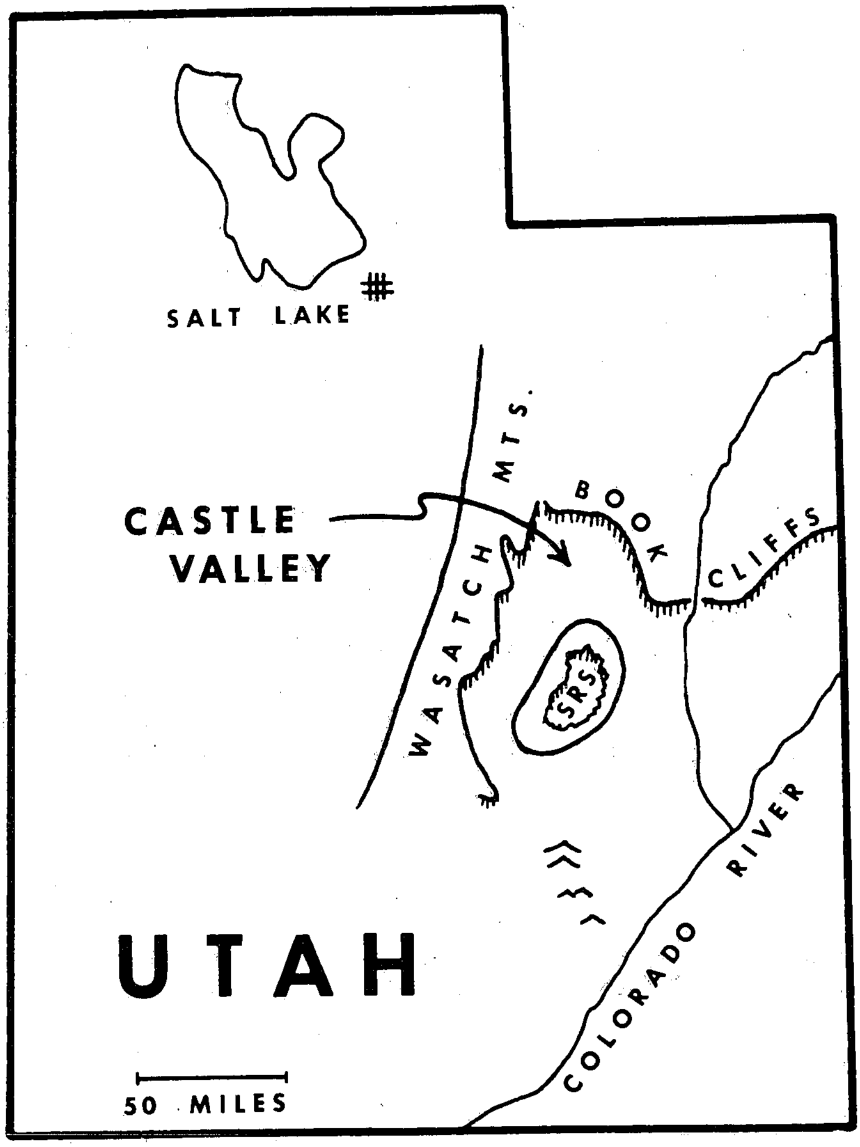

FIGURE 2.— The state of Utah, showing the location of Castle Valley between the San Rafael Swell (SRS) and the Wasatch Mountains on the west and the Book Cliffs on the north and northeast.

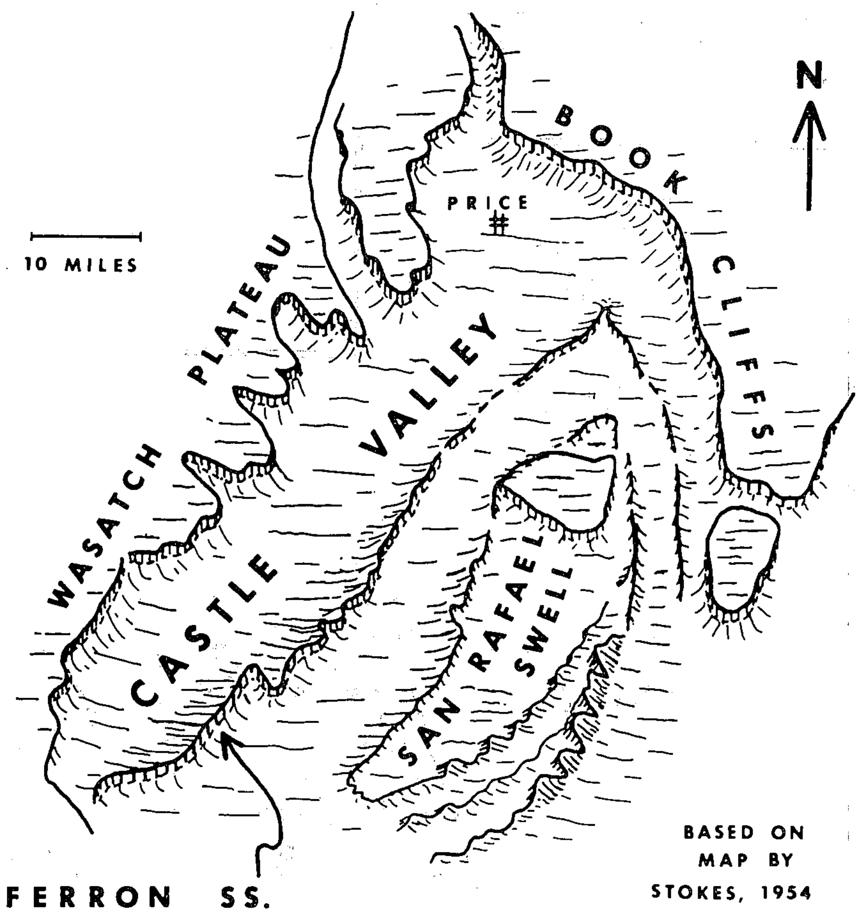

FIGURE 3.—Generalized sketch map of the area of Castle Valley, depicting the gentle cuesta formed by the Ferron Sandstone as it dips away from the San Rafael Swell.

DEPOSITIONAL ENVIRONMENTS

Units in Northern Castle Valley

The thin sheetlike sandstone units in the northern part of Castle Valley are readily interpretable in the context of sedimentation along a relatively low-energy coastal zone, such as the modern Sapelo Island coast of Georgia. Physical conditions in such an environment are normally of relatively low intensity, and the dominant process is biogenic reworking of the sediment by burrowing organisms (Howard and Reineck, 1972). Sediment distribution takes place primarily during periods of storm activity, when nearshore sediment is thrown into suspension and moved farther offshore, and traction current processes are accelerated in tidal inlets and on offshore bars. Thus, the deposits of such an environment record an interplay between fair-weather and storm conditions (Cotter, 1974).

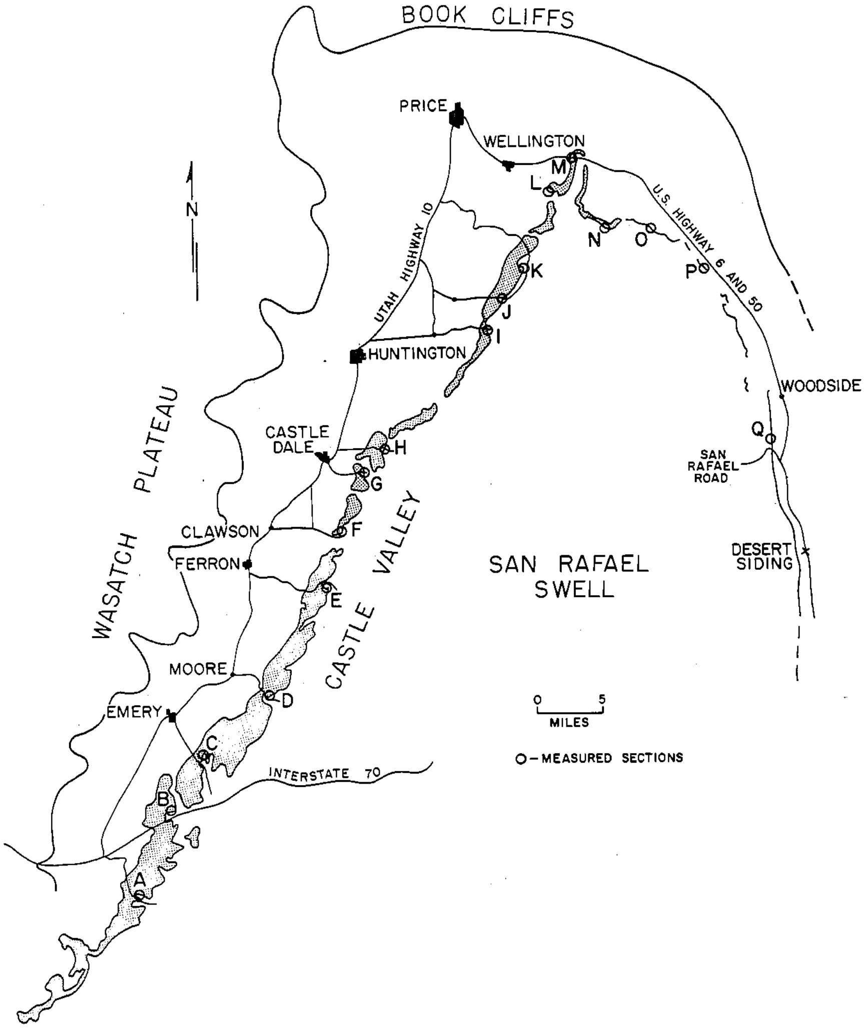

FIGURE 4.—Map of the Ferron Sandstone outcrop in Castle Valley.

Details of the characteristics and interpretations of the northern Ferron units are presented elsewhere (Cotter, 1975b); a brief summary is included as Table 1.

The lobate tongue of clastic sediments making up the Vernal Delta sticks out almost due eastward in the northeastern corner of Utah (Hale and Van De Graaff, 1964, fig. 5). A moderately complex pattern of development of this delta in the vicinity of Vernal, Utah has been worked out by Maione (1971). Through the evolution of various deltaic and marine transgressive phases the coastline in the Vernal area, about 90 miles (145 km) northeast of northern Castle Valley, was oriented generally northeast-southwest (cf. Maione,

TABLE 1
UNITS OF THE FERRON SANDSTONE EXPOSED IN NORTHERN CASTLE VALLEY

UNIT	ENVIRONMENT OF DEPOSITION	CHIEF DIAGNOSTIC CHARACTERISTICS
WOODSIDE	Offshore marine sand bars	Furthest eastward unit: seaward of and separated from shoreface deposits. Enveloped in offshore bioturbated dark siltstone. Coarse, mature sandstone for the most part thoroughly bioturbated by filter feeders. Intercalated less burrowed, trough and planar cross-laminated sandstone beds indicating bipolar, coast-parallel transport. Numerous mollusk shells in various stages of fragmentation.
WASHBOARD	Lower shoreface	Mostly silty, very fine-grained sandstone that is thoroughly bioturbated by deposit feeders, *viz.* retrusive *Teichichnus*, and contains large concretions. Intercalated thin beds of cleaner sandstone that typically are even parallel laminated and have burrowed tops; some burrowing by filter feeders (*Ophiomorpha*, *Thalassinoides*). Unit thins, becomes finer grained, and has fewer laminated beds when traced from northernmost exposures.
FARNHAM	Tidal inlet	Enclosed within Washboard unit in limited region. Above a sharp base, commonly a shell lag. Fine to very fine sandstone that has bipolar, coast-normal, trough cross lamination, with set bases and infilling laminae lined with shell fragments. Diminished number and variety of biogenic structures. Lateral migration to the southwest, parallel with coast.
CLAWSON	Offshore (shelf)	Completely bioturbated silty sandstone; numerous large concretions.

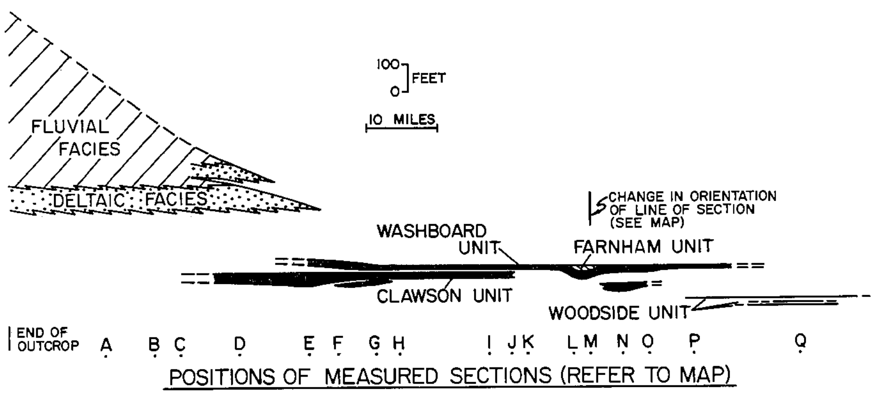

FIGURE 5.—Cross section of the Ferron Sandstone along the outcrop belt from the southwest (left) to the north and then back to the southeast (right). *See* fig. 4 for locations of measured sections. Illustrates the two depositional systems: Last Chance Delta as the clastic wedge on the left (SW) and the thin units derived from the Vernal Delta in the center and on the right (N and SE).

1971, pl. V). If the barrier island facies interpreted by Maione is indeed contemporaneous with active deltation, it implies that a fair amount of wave modification accompanied progradation. Thus, it is possible that the Vernal Delta would be classed a high-destructive, wave-dominated delta system by Fisher and others (1969), but in view of the extensive eastward projection of the prograded delta, it might be more likely that it is a high-constructive, lobate delta system. In either case, downcoast interdeltaic strandplain or barrier island systems are likely to be derived from such a delta system under the influence of wave-generated longshore or strike transport (Fisher and others, 1969; LeBlanc, 1972).

Grain size of Vernal Delta sediment ranges up to very coarse (Maione, 1971, p. 44), and the dominant direction of longshore transport has been interpreted, somewhat tenuously, to have been to the southwest (Maione, 1971, p. 51), thus setting the stage for explaining the source of all the thin, northern Castle Valley Ferron units. However, there still remains the question: Where is the Vernal Delta closer to the Castle Valley?

There have been numerous reports of thick, coal-bearing sediment in the Ferron Sandstone a short distance west and north of the Castle Valley outcrops from Huntington to Price (Katich, 1954; Kuehnert, 1954; Gray and others, 1966; Hale, 1972; Doelling, 1972). And yet the exposed Ferron less than 10 miles (16 km) to the east has no coal in the thin nearshore and offshore sandstone units. There is also a problem in that exact correlation of the exposed units with the subsurface units has not been established.

The cross sections of Hale (1972, fig. 5, 6, 7) are very instructive with respect to the origin of this subsurface Ferron Sandstone, especially in light of the deltaic interpretation of equivalent rocks to the northeast by Maione (1971). At the base of the progradational sequence is an essentially continuous sheet of delta front sandstone. This is overlain by a coal-bearing delta plain facies that also has some distributary channel sandstones. Higher in the

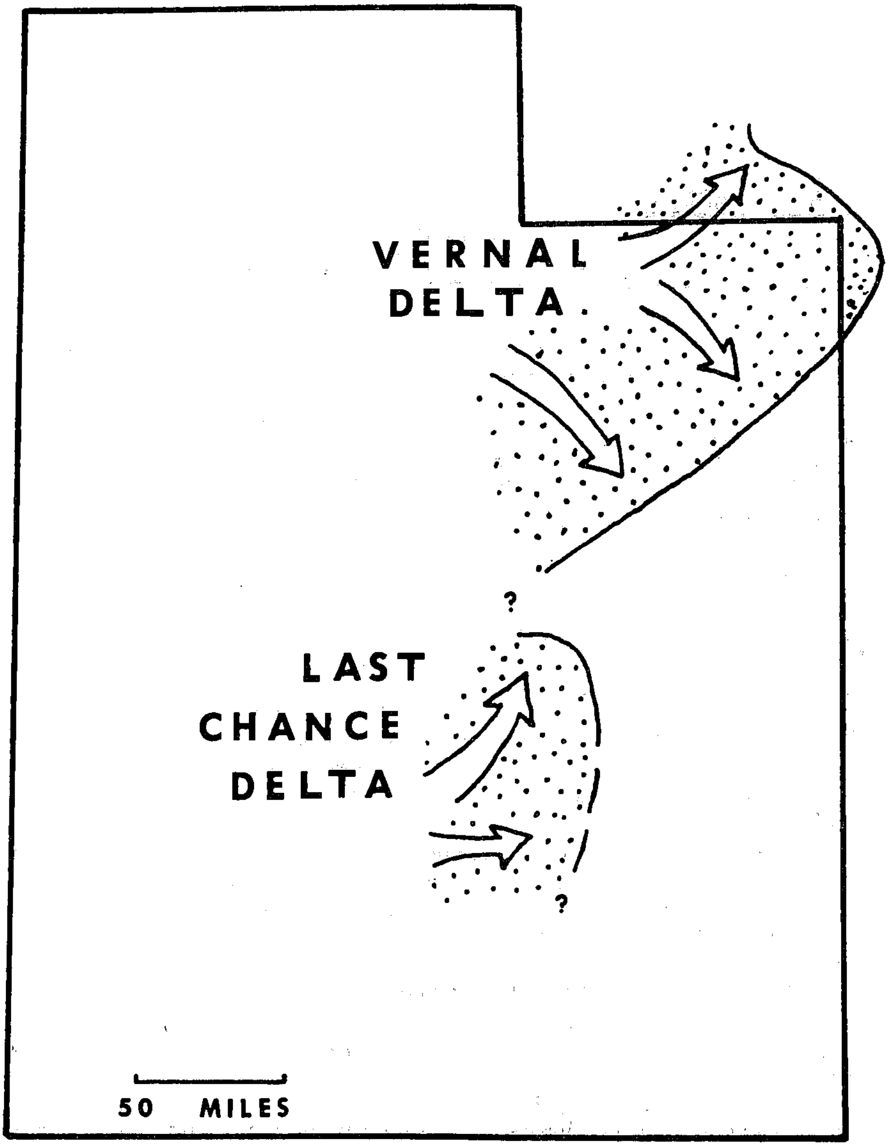

FIGURE 6.—Generalized areas of development of the Vernal Delta and the Last Chance Delta; based in part on the map of Hale and Van De Graaff (1964).

sequence is the fluvial facies with laterally discontinuous fluvial channel sandstones in a finer alluvial plain mudstone.

As the exact relationship between the thin, northern valley sandstone units and the proximate subsurface Vernal Delta is only ambiguously established, in both physical and interpretative senses, there is a possible argument that the thin units might better be placed in a setting more clearly emphasizing the genetic relationship with the delta system, such as the prodelta or delta platform setting of units interpreted elsewhere by Hubert and others (1972). However, the depositional processes demonstrated by rocks of the thin northern units do not reflect significant deltaic influence but more closely indicate coastal, interdeltaic agencies. For example, the exposed, relatively well-sorted laminated sandstones do not contain noticeable plant matter, and the only channel-like feature exposed is clearly a tidal inlet rather than a distributary channel. Thus, it appears more likely that the thin units were derived from the northeast, from another part of the Vernal Delta, rather than from that proximate part of the delta to the west. It is possible that there is a distinct age difference between the exposed and the proximate subsurface units, unlike the situation diagrammed by Hale (1972, fig. 5, 6).

A hypothetical paleogeographic view of the relationship between the Vernal Delta and the thin northern Castle Valley sandstone units is sketched in Figure 7.

Southern Castle Valley—the Last Chance Delta

A second deltaic system was responsible for deposition of the Ferron Sandstone in another part of Castle Valley (Figures 5 and 6). From a southwesterly source, the Last Chance Delta prograded into the region of the southern Castle Valley to form a northeastwardly thinning wedge of clastic debris. From a thickness of nearly 800 feet (244 m) at its southernmost exposure, this wedge thins to essentially nothing near the village of Clawson, a distance along the outcrop of some 45 miles (72 km). In this distance the average grain size of the sandstone drops from coarse to fine.

At the distal part of the clastic wedge the deposits of the Last Chance Delta overlie the thin northern sandstone units, with more than one hundred feet (30 m) of mudstone between (Figure 5). Because of this the Last Chance Delta is considered not to be contemporaneous with the deposition of the northern units and thus probably not contemporaneous with the Vernal Delta.

Details of the characteristics of the Last Chance Delta and its composite facies are also presented in another publication (Cotter, 1975a) and only a summary of the more significant diagnostic features is set forth in Table 2.

The Last Chance Delta was a high-constructive lobate deltaic depositional system (Fisher and others, 1969) that was made up of numerous coalescing and overlapping subdelta lobes, each of which had an essentially continuous fringe of sand in the delta front environment. As it prograded into about 40 feet (12 m) of water in the Late Cretaceous Mancos Sea it developed a broad distribution of sequentially seaward-displaced facies (Figure 8). The delta prograded in a generally northward or northeastward direction into the region of the Castle Valley, but it very likely also had an easterly component of growth, causing the deposition of some deltaic sediment in the Henry Mountains region to the southeast of Castle Valley.

The Last Chance Delta as an entire complex was, then, a broad fan in overall outline, smaller parts of which were the subdelta lobes mentioned above. As individual lobes were no longer provided with sediment because of upstream avulsion they subsided beneath the sea, recording the sea's encroachment in the form of thin transgressive sandstones capping delta plain deposits

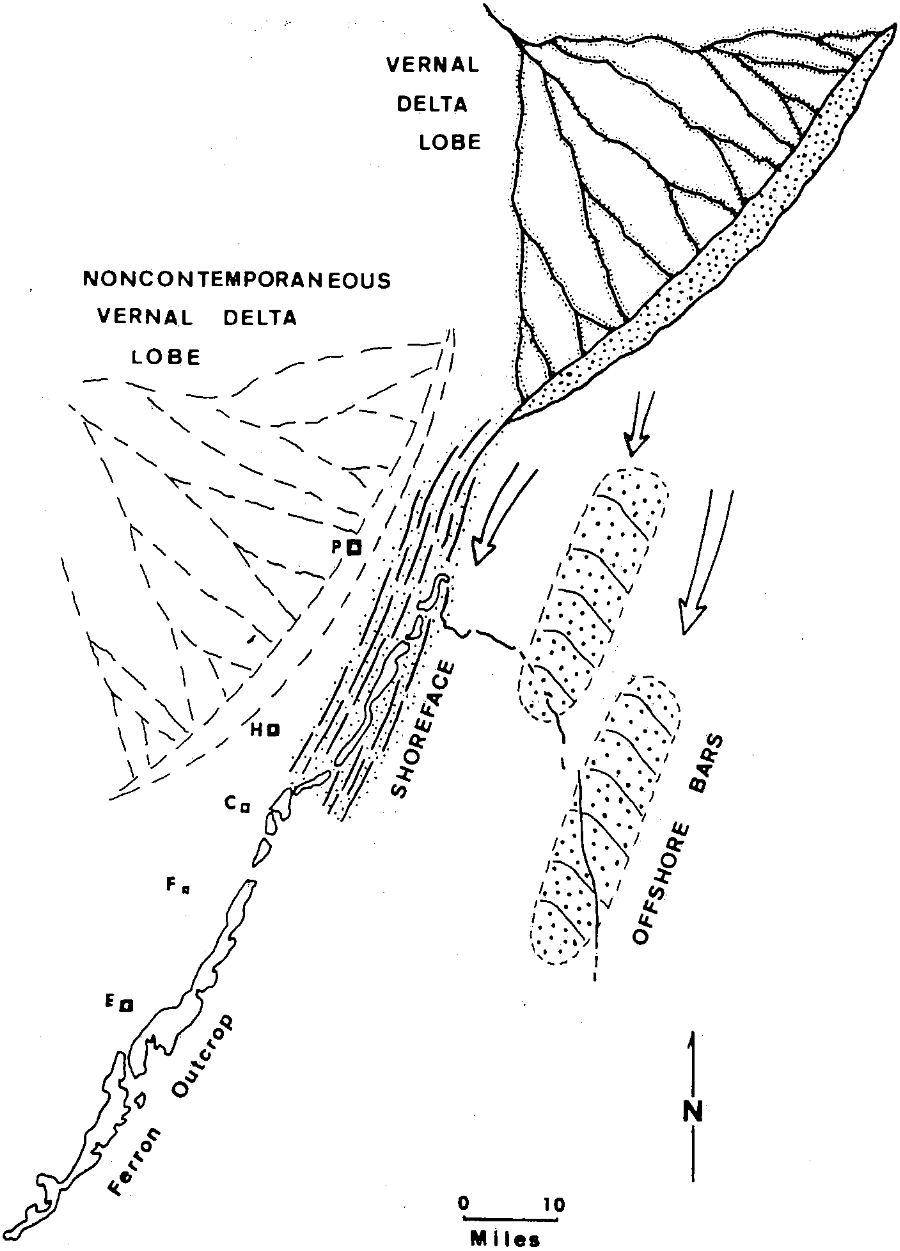

FIGURE 7.—Diagrammatic portrayal of possible manner of development of the thin northern Castle Valley units that were derived from part of the Vernal Delta. Also depicted is another lobe of the Vernal Delta as it might occur in the subsurface west of the Ferron outcrop. Towns indicated are Emery (E), Ferron (F), Castle Dale (C), Huntington (H), and Price (P).

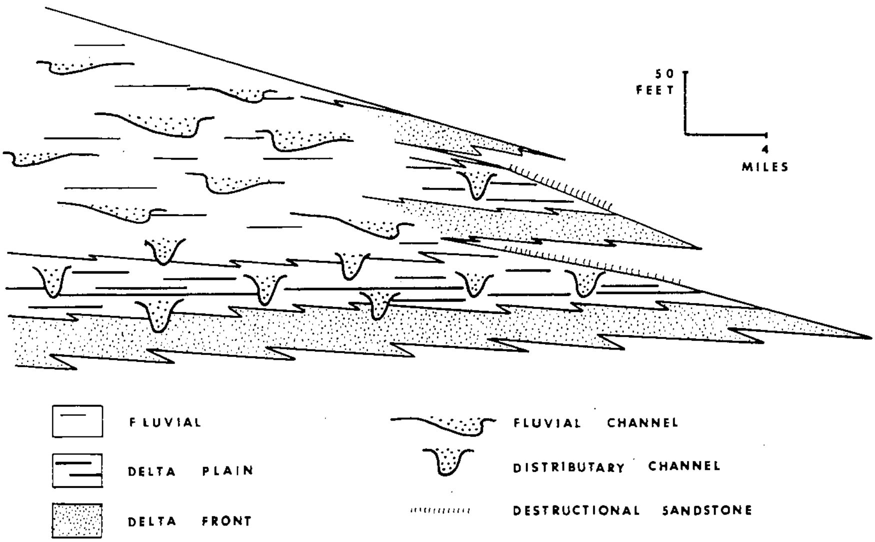

FIGURE 8.—Facies profile of the Last Chance Delta in southern Castle Valley approximately along the outcrop belt from the southwest (left) to the northeast (right).

(Figure 9). In many places subsequent lobes built over earlier foundered ones, producing multicyclic delta sequences.

Some subdelta lobes had a character somewhat different from the typical lobes with very gentle delta front inclinations. Certain lobes that prograded to the west or northwest developed steep delta front inclinations, in the manner of a Gilbert-type delta. One can only speculate that such steep delta front foreset beds were caused by an approximate equality of density between the inflowing river water and the water of the receiving basin (homopycnal flow). The westerly component of such steeply inclined sequences suggests that there might have been a westerly embayment of reduced salinity involved in this situation.

As the Last Chance Delta evolved, successively later deltaic advances did not prograde as far as earlier, until the delta complex was covered by the Mancos Sea (Figure 8).

The river system that fed the delta left its record in the fluvial facies that forms the upper part of the Ferron Sandstone in this southerly clastic wedge. The characteristics of this river system can be estimated by detailed analysis of the fluvial deposits. In an earlier report (Cotter, 1971), estimates were presented of the paleoflow characteristics of the ancestral Ferron River, which should probably now be called the Last Chance River. These estimates are summarized in Table 3.

COAL IN THE FERRON SANDSTONE

Discovery and Evaluation

The first documented record of coal in the Ferron Sandstone came surprisingly early in the last century. It was October, 1853, when Capt. J. W. Gunnison of the Corps of Topographic Engineers and his party discovered

TABLE 2
FACIES OF THE FERRON SANDSTONE — LAST CHANCE DELTA IN SOUTHERN CASTLE VALLEY

FACIES	CHIEF DIAGNOSTIC CHARACTERISTICS
PRODELTA	Transitional from underlying Tununk Shale; gradual increase in number and thickness of thin sandstone beds. Sandstones mostly even parallel laminated; some ripple laminated. Some beds graded; comminuted plant debris abundant; biogenic structures rare in typical occurrence.
DELTA FRONT	From 20 to 40 feet (6 to 12 m) of essentially laterally continuous, coarsening-upward, progradational sequence. Changes upward include: 1. increase in grain size from very fine to fine and medium. 2. increase in thickness of individual sandstone beds. 3. interbedded siltstone layers became thinner and less numerous. 4. dominant sedimentary structure changes from even parallel lamination (or stacked symmetrical ripples in some places) to trough cross lamination. Beds typically very gently inclined generally to the north; some sequences have steep, Gilbert-type dips to the northwest or west. In most sequences biogenic structures are uncommon, but fine plant trash is abundant, particularly in intercalated siltstones.
DELTA PLAIN	Basically horizontal layers of sandstone, mudstone, and coal interrupted in places by channelform sandstone; thickness up to 40 feet (12 m).
1) Lakes, marshes, swamps	Dark and light gray or brown mudstone that is extensively mottled from animal burrowing and plant root penetration. Numerous coal beds and carbonaceous mudstone. Lenticular zones of sandy, plant-rich coquina.

TABLE 2 (continued)

2) Distributary channels	Trough cross-laminated fine or medium-grained sandstone in zones with concave-upward bases and relatively flat tops. Elongation of zones and orientation of troughs indicate sediment transport generally south to north. Inclusions of coal and shale near channel base.
3) Destructive delta margin sands	Relatively thin, widespread zones of sandstone at top of delta plain facies. Well-sorted, thin- to medium-bedded, typically fine-grained, with even parallel lamination and some broad trough cross lamination. Common filter feeder biogenic structures (*Ophiomorpha, Thalassinoides*).
FLUVIAL FACIES	Mudstone, with interbedded coal and carbonaceous shale; some very thin beds of siltstone alternating with claystone. Fining-upward, dominantly trough cross-laminated, point bar sandstone; typically in laterally-migrated sheets about 30 feet (9 m) thick, rarely in channel form.

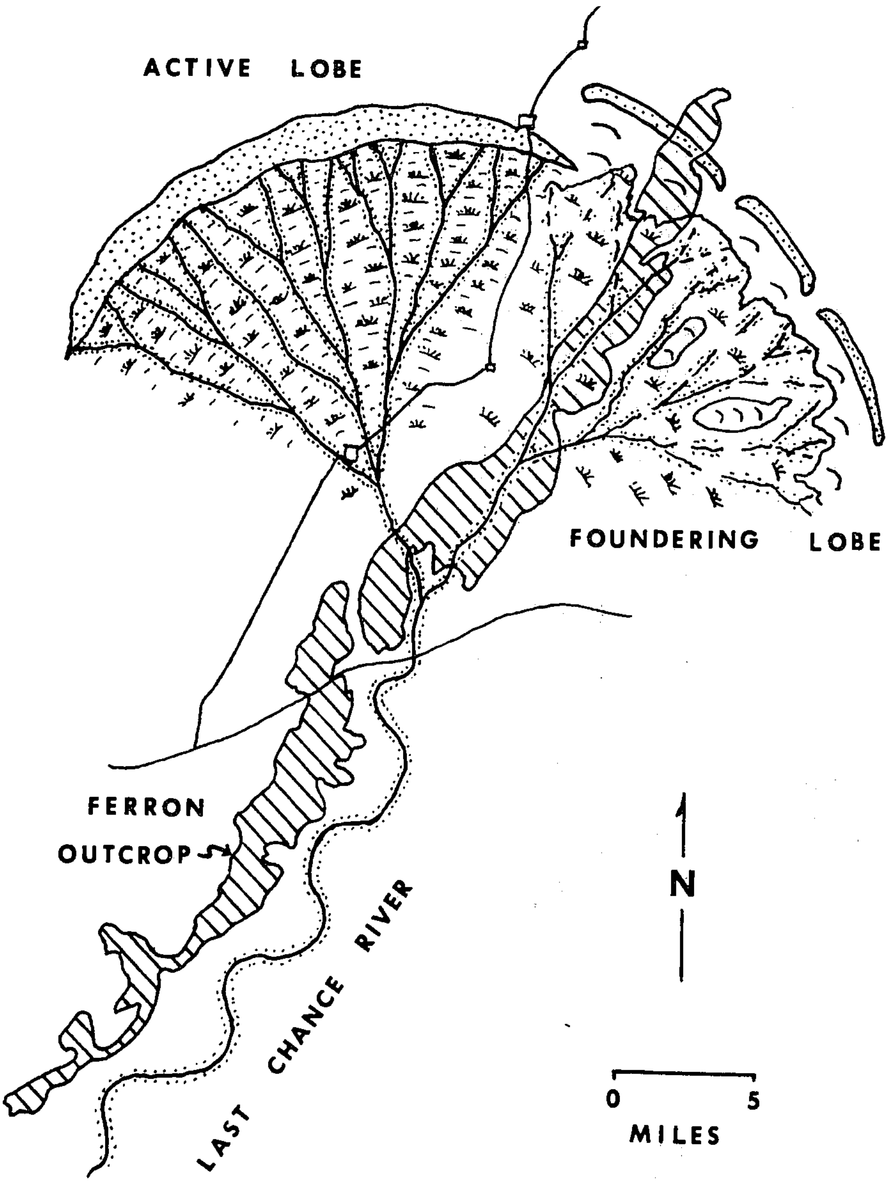

FIGURE 9.—Diagrammatic portrayal of two of the many lobes involved in the evolution of the Last Chance Delta; these two are at approximately the most northeasterly advance of the deltaic facies.

TABLE 3

ESTIMATED PALEOFLOW CHARACTERISTICS OF THE LAST CHANCE RIVER

PARAMETER	ESTIMATED VALUE
Stream Type	Suspended load stream; bedload about 2% of total load
Flow Regime	Upper part of lower regime
Bed Form	Dunes
Flow Velocity	2.0–4.6 feet/second (0.6–1.4 m/sec)
Stream Depth	25 feet (7.6 m)
Stream Width	300 feet (91 m)
Sinuosity	1.8–2.1
Meander Length	2,500–4,100 feet (762–1,250 m)
Mean Annual Discharge	6,000–7,000 cubic feet/second (170–198 cubic meters/sec)
Mean Annual Flood	22,000 cubic feet/second (623 cubic meters/sec)
Channel Slope	1.0–1.5 feet/mile (0.19–0.28 meters/km)
Stream Length	200 miles (322 km)
Drainage Area	6,000–8,000 square miles (15,540–20,720 square km)

Ferron coal in outcrops east of Emery (Lupton, 1916, p. 9). This discovery doubtless had nothing to do with the fact that Gunnison and several others were killed by Indians in the Sevier Valley a few days later.

Two other surveys, those of Hoxie in 1873 and Taff in 1905, also examined Ferron coal in southern Castle Valley (Lupton, 1916, p. 9, 10) before Charles T. Lupton was assigned to conduct a detailed study of the geology and coal reserves of Castle Valley, in order "to determine the quality and quantity of the coal" (Lupton, 1916, p. 8). Lupton did this in 1911 and 1912, and in 1916 he produced a report of impressive quality, despite having worked under difficult circumstances, such as the need to map in topography by triangulation.

Very recently, the Utah Geological and Mineralogical Survey built upon the solid foundation of Lupton's work when it reevaluated the coal resources of the Emery Coal Field, which comprises the coal-bearing part of the Ferron Sandstone (Doelling, 1972).

Coal in the Ferron in northern Castle Valley was encountered in the subsurface west and north of the outcrop belt (Katich, 1954; Gray and others, 1966; Kuehnert, 1954; Hale, 1972), but there has not yet been any published evaluation of its quantity and quality. It is in the southern Castle Valley, in deposits of the Last Chance Delta, that coal production has occurred and where significant reserves promise increased production in the future.

Production

Beginning with the opening of the Browning mine in 1881 (Lupton, 1916, p. 84) coal production from the Ferron Sandstone was irregular until 1930 and modest from then until relatively recently. Total production through 1970 has been about 1,640,000 tons (1,489,000 metric tons) (Doelling, 1972, p. 433).

Presently, only the two most important mines are active:

	BROWNING MINE	SUN VALLEY (DOG VALLEY) MINE
1969 PRODUCTION	36,978 tons (33,569 metric tons)	20,685 tons (18,778 metric tons)
1970 PRODUCTION	115,239 tons (104,614 metric tons)	23,334 tons (21,183 metric tons)

Reserves

A recent reevaluation of coal reserves in the Ferron Sandstone of southern Castle Valley was made by Doelling (1972). He worked on the basis of assumptions that only beds thicker than 4 feet (1.2 m) are minable, and that an acre-foot of coal weighs 1,742 tons (1,581 metric tons). Reserves were calculated in the standard categories:

Class I	*Measured reserves* based on adequate exploration and development data; properly correlated; control no more than ½ mile (0.8 km) apart.
Class II	*Indicated reserves* based on geologic measurement supplemented by limited drill-hole information

	and limited to 1½ miles (2.4 km) from a control point.
Class III	*Inferred reserves* based on geologic inference and projection of the habit of the coal beyond 1½ miles (2.4 km) from control points.
Class IV	*Potential reserves* based on geographic and geologic position with little supporting data; includes coal under as much as 3,000 feet (914 m) of cover.

Reserve estimates in these categories are reported by Doelling (1972, p. 437):

Classes I and II	757,600,000 tons	(687,749,000 metric tons)
Class III	672,800,000 tons	(610,770,000 metric tons)
Class IV	634,500,000 tons	(576,000,000 metric tons)
TOTAL RESERVES	2,064,900,000 tons	(1,874,500,000 metric tons)

The first three categories more closely reflect the potential of an area or field. For the Ferron Sandstone coal in the Emery Field, these three, the principal reserve, total 1,430,400,000 tons (1,298,500,000 metric tons). With the estimate that only about 30 percent of this is recoverable and that another small amount is eliminated by mining, this leaves a recoverable reserve for the Emery Field of 427,500,000 tons (388,080,000 metric tons) (Doelling, 1972, table 8, p. 554), or about 5.5 percent of the remaining recoverable reserves in Utah (Doelling, 1972, fig. 14, p. 553).

Recall that total production through 1970 was about 1,640,000 tons (1,488,000 metric tons) or about 0.4 of one percent of the remaining recoverable reserves.

Quality

Ferron Sandstone coal in the Emery Field ranks as high volatile C bituminus, with medium ash and low sulphur content (Doelling, 1972, table 9, p. 555). Table 4 summarizes the quality characteristics of 47 samples of coal from the Ferron; it also includes an abstraction of about 30 of these 47 sample analyses that come from the Acord Lakes SE (Walker Flat) quadrangle, for these latter analyses are nearly all from the two active mines and might minimize the problems associated with surface samples. Doelling (1972, p. 433) states that the analyses from these two mines, the Browning and Sun Valley (Dog Valley), are probably characteristic of the field. However, such a conclusion might be premature, for both mines are in the upper zone of the Ferron, in the bed labeled I by Lupton (Doelling, 1972) and, in view of the fact that certain aspects of coal quality are apparently controlled by depositional environment, (Cheek and Donaldson, 1969; Guber, 1972) other beds from other depositional environments should be used for corroboration.

The coal in the subsurface in the northern Castle Valley, near Price, is reported by Gray, Patalski, and Schapiro (1966) to be of high volatile A or B in rank and generally "of slightly better or equivalent coking quality than the Sunnyside seam high-volatile coal." This is interesting in view of the fact that in the exposed part of this Vernal Delta system, in the Frontier Formation of the Vernal Field, the coal is high volatile C bituminous and has me-

TABLE 4

QUALITY OF THE COAL IN THE LAST CHANCE DELTA OF THE FERRON SANDSTONE

PARAMETER	NUMBER OF ANALYSES	VALUE (As Received) AVERAGE	RANGE	SOURCE OF DATA IN DOELLING, 1972
Moisture	47	7.4%	2.3–23.6%	Table 2, page 433
Volatile Matter	46	37.7%	32.3–43.9%	" "
Fixed Carbon	46	44.8%	32.9–52.2%	" "
Ash	47	8.5%	4.0–23.6%	" "
Sulfur	46	0.95%	0.31–4.66%	" "
Btu/lb	44	11,450	7,823–12,970	" "
(Analyses from the Acord Lakes SE (Walker Flat) Quadrangle, 2 of which are surface samples, 20 from the Browning Mine, and 8 from the Sun Valley Mine)				
Moisture	30	5.6%	3.7–16.7%	Table 7, page 456
Volatile Matter	29	38.9%	34.3–41.1%	" "
Fixed Carbon	29	46.1%	37.3–51.9%	" "
Ash	30	7.5%	5.8–17.2%	" "
Sulfur	29	0.82%	0.36–2.31%	" "
Btu/lb	29	12,322	9,500–12,970	" "

dium sulfur (1.0-2.0%) and very high ash (greater than 12%) content (Doelling, 1972, table 9, p. 555).

Distribution

Stratigraphic.—Lupton (1916) reported that the Ferron Sandstone contains 14 coal beds, which he designated by the letters A through L, Ma, and M, in order from the lower to the upper part of the formation. Usually not all beds are present in vertical sequence at a given locality, and in some places there is an extra coal bed for which there is no letter designation.

In his recent updating of Lupton's work, Doelling (1972) organized the letter-designated beds into three zones: lower, middle, and upper. The lower coal zone, which is about 75 feet (23 m) thick, lies above a thick barren sandstone at the base of the Ferron and contains coal beds A through E. The coals of this zone are among the thickest and most widespread in the Emery Field. Above this, the middle coal zone is from 75 to 150 feet (23 to 46 m) thick. Doelling reports (1972, p. 424) that it is usually barren, but it contains coal beds F and G when they are present. The upper coal zone is from 75 to 125 feet (23 to 38 m) thick and contains coal beds H through L. In many places these beds are thin and noncommercial, but in certain places local thickening has developed important reserves. For example, bed I is the producing bed at both the Sun Valley (Dog Valley) and the Browning mines. At the latter location it is 20 feet (6 m) thick (Doelling, 1972, p. 450).

A diagram from Doelling (1972, fig. 25, p. 472) shows the relationships among the coal beds and the coal zones in the vicinity of Willow Springs Wash (Figure 10).

Geographic.—On a broad scale the coals of the Last Chance Delta of the Ferron Sandstone in southern Castle Valley are generally correlative with Straight Cliffs Formation coals of the Kaiparowits Plateau to the south and with the Ferron coals in the Henry Mountains region to the east (Doelling, 1972, p. 430). And the subsurface Ferron coal in northern Castle Valley is correlative with the exposed Vernal Delta coal in the Frontier Formation near Vernal, Utah (Figure 11).

As a result of the detailed work of Lupton (1916) and Doelling (1972), in which individual coal beds of the Last Chance Delta were labeled, measured, and correlated, maps have been prepared by Doelling (1972, fig. 13, 14, 15) showing the approximate areal distribution of a number of these coal beds. These maps indicate areas where the identified coals are greater than 4 feet (1.2 m) thick. Although this is not the same as the total areal distribution of the coal beds, it does serve as a valuable measure of the breadth of distribution.

In Doelling's (1972) lower coal zone, coal beds A and C are very widespread, the most widespread of all the Ferron coals (Figure 12). Bed A has been correlated over a distance of some 20 miles (32 km). There is a suggestion of north-south elongation of the area of distribution, but this is complicated by lack of control on the west and, to some extent, on the east. The younger bed C is "shingled" up on and north of (seaward of) bed A, in keeping with the progradational evolution of the Last Chance Delta to the north. As will be considered in the next section, these two widespread beds originated as delta plain coals.

Less widespread are the coal beds above bed C, in the middle and upper zones of Doelling (1972, figure 12). There are only 5 coal beds of the 8

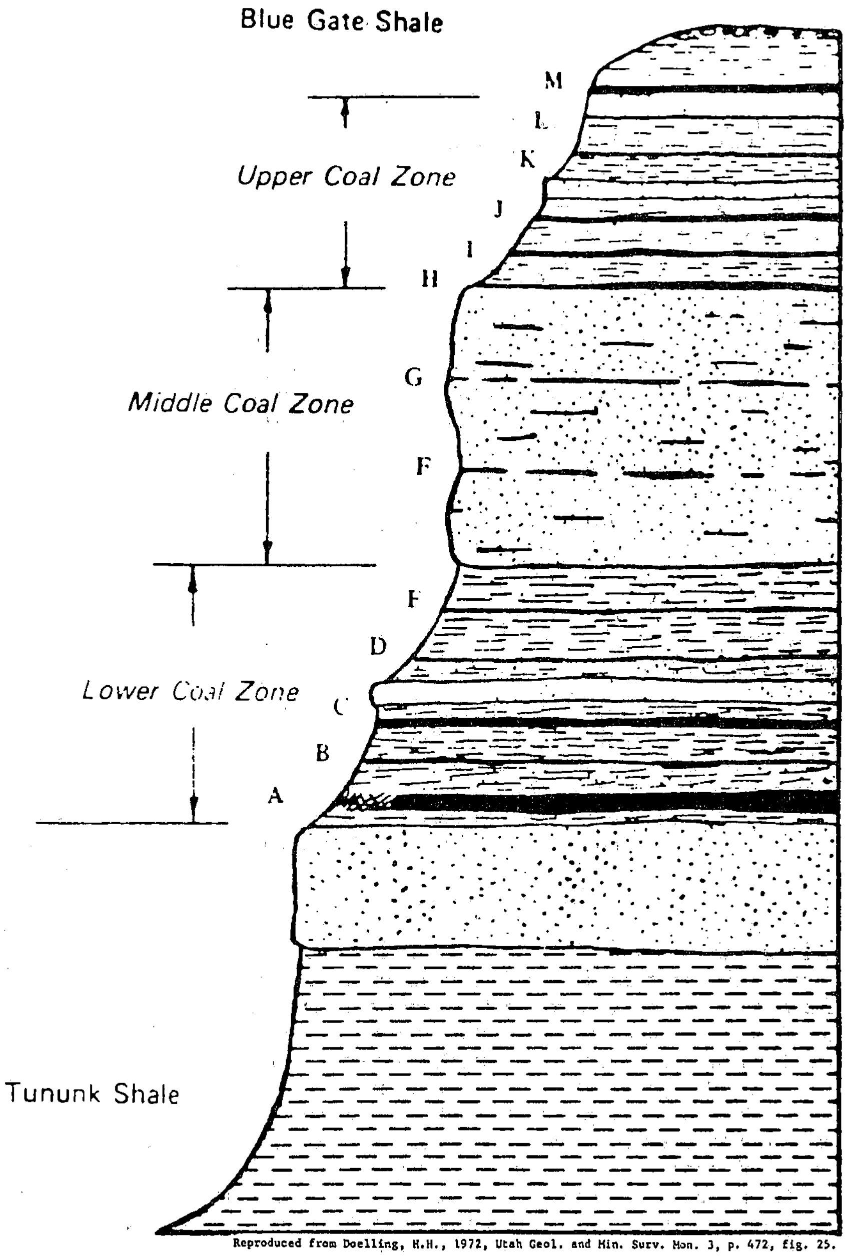

FIGURE 10.—The Last Chance Delta coal beds of Lupton (1916), organized into three zones by Doelling (1972, fig. 25); in the vicinity of Willow Springs Wash (near measured section A on Figures 4 and 5).

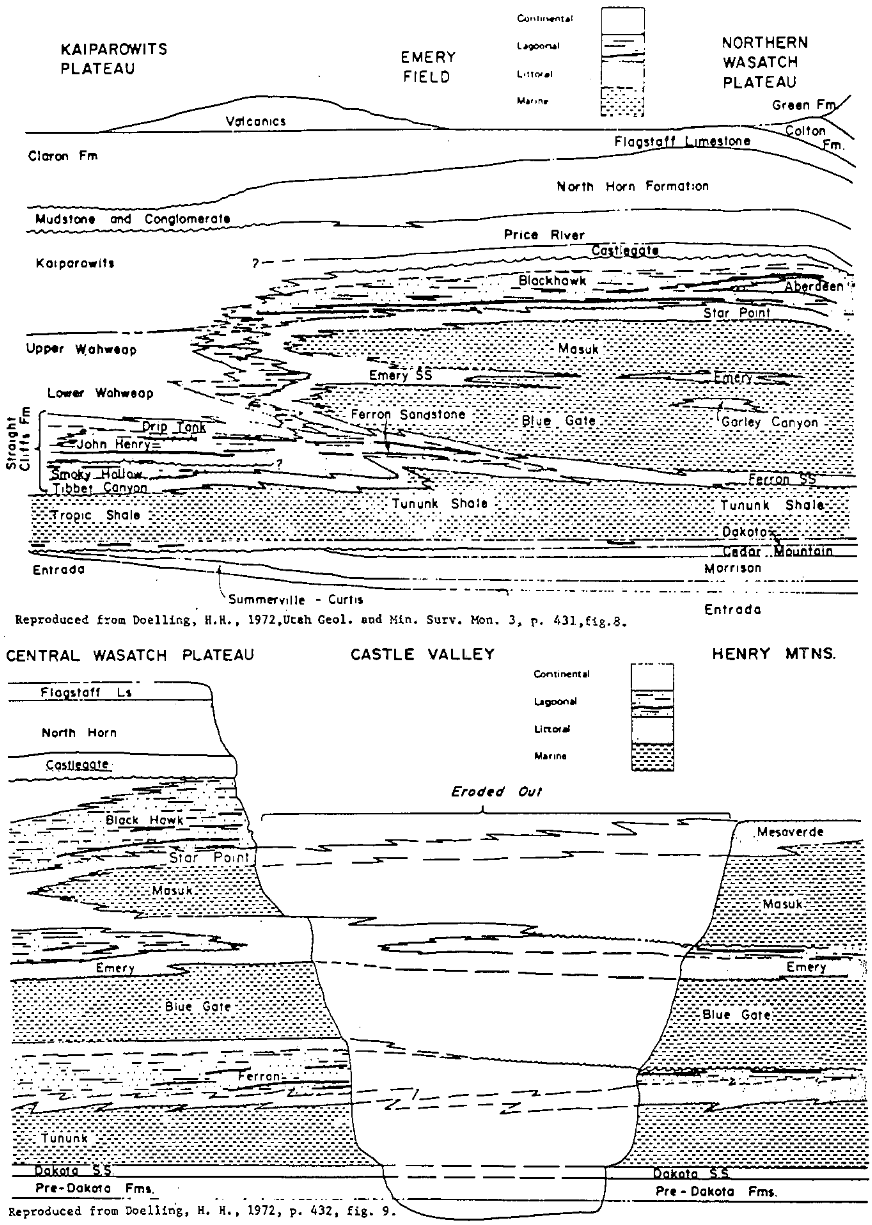

FIGURE 11.—Stratigraphic correlation diagrams showing the relationships of the Ferron Sandstone to other Upper Cretaceous units. A. Section about south to north from the Kaiparowits Plateau through Castle Valley to the northern Wasatch Plateau. B. Section about west to east from the central Wasatch Plateau to the Henry Mountains. Taken from Doelling (1972, figs. 8 and 9).

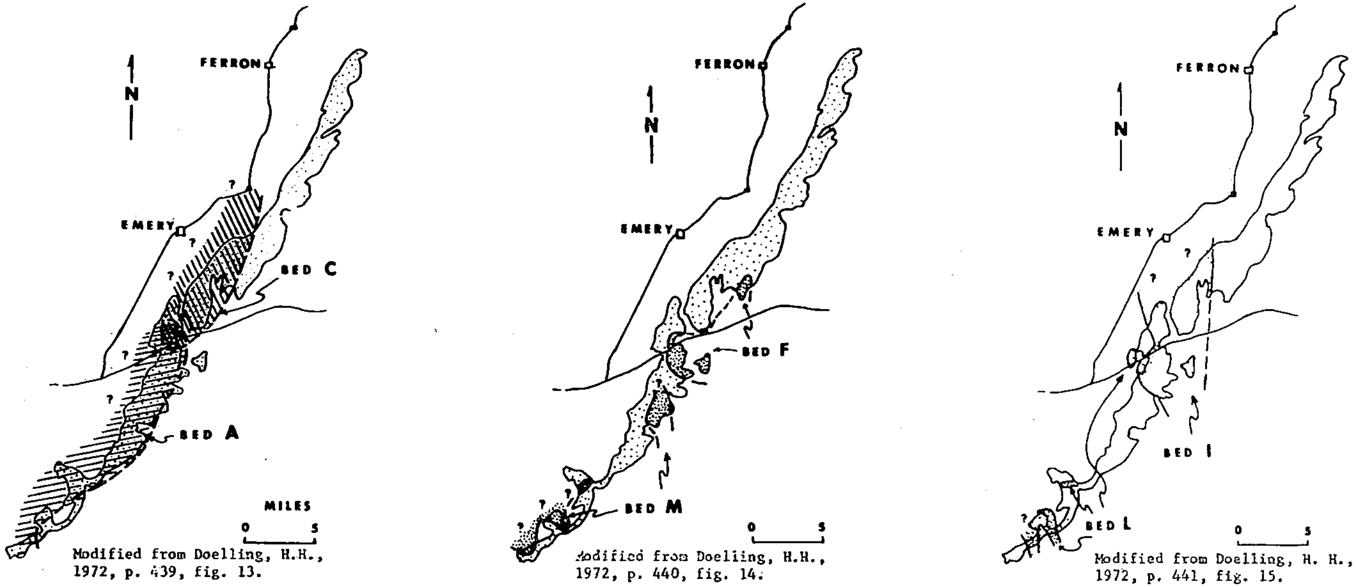

FIGURE 12.—Map showing the distribution of Ferron coal beds labelled by Lupton (1916) where they are greater than 4 feet (1.2 meters) thick; from Doelling (1972, figs. 13, 14, 15). See fig. 10 for approximate stratigraphic position of each lettered coal bed within the Ferron Sandstone.

in the middle and upper zones that have enough coal thicker than 4 feet (1.2 m) to warrant such mapping. And of these 5, only coal bed I has a distribution that approaches that of the lower zone beds A and C. Bed I is the one that contains the two currently active mines. Doelling's maps clearly show a preferred north-south orientation of the zones of thicker coal, a fact that is certain to guide future production. The origin of these upper coals in alluvial plains, as discussed in the next section, with a generally northward paleoslope can explain the depositional control of this north-south orientation as a matter of erosion of the alluvial plain organic matter by meandering fluvial channels. A situation similar to this was presented by Howard (1969).

The coal in the Ferron Sandstone in the subsurface west and north of the northern Castle Valley outcrop belt is also widespread, but it is not possible to present sufficient information about detailed correlation and zonation. Coal has been reported from the areas near Price (Katich, 1954; Gray and others, 1966; Doelling, 1972), near Huntington (Kuehnert, 1954), and under the Wasatch Plateau to the west (Edson and others, 1954). Some idea of the widespread occurrence of coal in this depositional system can be gained from cross sections compiled by Hale (1972).

Gray, Patalski, and Schapiro (1966) found numerous coal beds in the Vernal Delta system in cores taken probably just southwest of Price (Doelling, 1972, p. 442). They felt they could distinguish three zones of coal beds, and stated that "the thickness of the zones and the distance between zones were extremely variable from one hole to another." Hale (1972, fig. 5, 6, 7) also shows a number of coal zones in many wells, a lateral correlation of some of these zones from wells, and a tendency toward the overstepping or shingling of younger coal zones seaward over older zones.

Origin

There has long been a general understanding that the coal in the Ferron Sandstone formed in association with a prograding shoreline, but there is a certain lack of unanimity of opinion about the nature of that shoreline. A deltaic origin of the clastic wedge in southern Castle Valley has been clearly proposed since at least 1964 (Hale and Van De Graaff), and in 1972, Hale rather formally proposed that it be called the Last Chance Delta. Another view of the nature of the shoreline is reflected in this quotation from Doelling (1972, p. 430):

> To the west orogenic pulsations had begun to elevate the land. One of these pulses shed a significant amount of clastics eastward, pushing the shoreline back across the present-day San Rafael Swell to Green River. Lagoons formed behind the shorelines gave rise to the coal deposits of the Ferron Sandstone.

This emphasis on coastal lagoons is made even more specific by Cleavinger (1974), who discussed the origin of certain Ferron coals in one local area as being of a lagoonal origin behind barrier beaches.

Admittedly, beaches are significant components of a variety of delta styles (Fisher and others, 1969; Coleman and Wright, 1975) and of destructive stages in the development of many deltas, and it might be argued that such differences in interpretation of the depositional environment might merely be a difference of emphasis. However, such differences of environmental interpretation are probably more important than a matter of scale or emphasis, for an exploration and production strategy (Howard, 1969) and the quality characteristics of the coals (Donaldson, 1969; Cheek and Donaldson, 1969; Guber, 1972) are significantly related to the depositional environment.

It is not appropriate at this point to review all the details and reasoning that led to an environmental interpretation for each subenvironment (subfacies; unit) of the Ferron Sandstone in Castle Valley. A summary of significant diagnostic characteristics of the Last Chance Delta and the units in northern Castle Valley is presented earlier in this paper, and details are available elsewhere (Cotter, 1971, 1975a, 1975b). However, it is appropriate to consider here the environments in which the coal beds formed in the context of the Last Chance and Vernal Deltas.

The Last Chance Delta depositional system in southern Castle Valley is the record of the complex progradation of delta lobes to the north and northeast, followed by the gradual encroachment of the Mancos Sea back over the accumulated wedge of sediments (Figure 8). The asymmetrical regression-transgression couplet has the deltaic facies at the base, overlain by the fluvial facies (Figure 8). Transgression did not leave a sedimentary record of shoreline deposits. Complexities of lobe switching and readvancement made the sequence contain multiple progradational cycles in many places, particularly in the distal, northern part of the depositional system.

Coal beds in the Last Chance Delta occur in the delta plain facies in the lower part of the formation and in the fluvial facies above. In many cases the environmental interpretation seems unequivocal. An example of such a situation is the common occurrence of coal beds overlying the delta front facies (steeply or gently inclined) and below thin, widespread destructive delta margin sandstones; the coals are interbedded with bioturbated siltstones containing brackish water mollusks and abundant large and small wood fragments. Higher in the formation are coals intimately associated with unfossiliferous mudstones and laterally-migrated, point bar-deposited, fluvial sandstones. In between, however, there are coals for which an environmental interpretation is indefinite because of the inconclusive nature of the associated finer-grained deposits, because of the absence of diagnostic companion facies, such as destructive delta margin sandstones, and because it is not possible to conclude whether the sandstones were deposited in fluvial or distributary channels.

These origins, as delta plain and as alluvial plain deposits, are made manifest in the stratigraphic and geographic distribution of the coals. In the preceding section on coal distribution, Doelling's (1972) organization of the Ferron coal beds into three zones was discussed. The widespread and generally thicker coals of the lower coal zone are delta plain coals; the thick, barren sandstone below them is the delta front facies. The middle zone, with thin, laterally limited coals, was deposited in fluvial environments. It is possible that at this time the streams were more powerful and carried more sediment from the source area, producing a generally sandier and less coaly alluvial plain environment. The upper zone has some thin and laterally limited coals, but it also has certain beds that are relatively thick and widespread, such as coal bed I. As the supply of sediment from the source and the strength of the rivers waned, alluvial plains could once more support the extensive swamp environments that eventually produced the coal. The preferred north-south orientation of many coal beds is a result of the erosional cut-out of the coal by meandering channels that flowed northward down the paleoslope.

The subsurface coal in the Vernal Delta system in northern Castle Valley is understandably more difficult to interpret because of its inaccessibility. In outcrop and subsurface in the Vernal area, Maione (1971, p. 46, 47) found coals that he interpreted to have been deposited in poorly drained regions on a delta plain. My conclusions with respect to the origin of the Ferron Sandstone in the subsurface just west and north of the Castle Valley outcrop have been presented in an earlier section. In such a system of deltaic deposits it is likely that in the lower part of the sequence are delta plain coals, in the upper part of the sequence are alluvial plain coals, and at some intermediate levels there are coals of indeterminate alluvial or deltaic plain origin. The regression-transgression couplet suggests that somewhere in the central part of the sequence there would be coals that were deposited at the greatest distance from the distal delta margin.

The difference between this deltaic depositional system interpretation of the subsurface coals and the barrier bar-lagoon interpretation of Hale (1972) might be significant if there is to be any significant exploration and production. Orientation of sandstone trends and resulting coal "wants" might be 90 degrees apart, depending on which interpretation is closer to the truth. It will be interesting to follow development of this coal with the different interpretations in mind.

CONCLUSIONS

Two deltaic depositional systems were fundamental to the evolution of the Castle Valley Ferron Sandstone and its coals. Exposed in the southern part of the valley, the Last Chance Delta is a clastic wedge of deltaic sediments overlain by fluvial. Because it built from a southwesterly source, the clastic wedge thins to the northeast, up the valley, the same direction in which the grain size becomes finer and the beds thinner, where the currents flowed and the facies are sequentially displaced. Coal beds in this high-constructive lobate delta complex were deposited in the delta plain, where the thickest and most widespread coals formed, and upstream from the delta in the alluvial plain, where the accumulating plant matter was in places cut out by northward-flowing meandering streams. These latter coals are not as widespread and are generally thinner than the delta plain coals, although they are locally thicker, such as at the two currently active mines. There is estimated to be more than 400 million tons (363 million metric tons) of recoverable high volatile C bituminous coal, with low sulfur and medium ash content, in the Last Chance Delta in southern Castle Valley.

The Vernal Delta is not itself present in Castle Valley, but it is represented by thin, sheetlike sandstone units that were derived from the Vernal Delta and transported southwestward, parallel to the coast, to their nearshore and offshore depositional sites. The delta itself is found in the subsurface west and north of Castle Valley, its distal end prograded to a location less than ten miles from the outcrop belt. Numerous coal beds occur in the Vernal Delta in the subsurface; it appears probable that they were deposited in delta and alluvial plain environments analogous to those of the Last Chance Delta to the south.

ACKNOWLEDGMENTS

I would like to thank Bucknell University for their generosity in supporting much of my field work and Aureal T. Cross for his kind invitation to participate in this symposium. I must also acknowledge the significant contribution the publication of Doelling (1972) made to this paper. Mrs. Jody Maddox worked in an extraordinary way to do her usual superb job of typing.

REFERENCES CITED

Cheek, Robert, and Donaldson, Alan, 1969, Sulfur facies of the Upper Freeport coal of northwestern Preston County, West Virginia: *in* A.C. Donaldson, (ed.), Some Appalachian Coals and Carbonates: Models of Ancient Shallow-Water Deposition: West Virginia Geol. and Econ. Surv., Morgantown, West Virginia, p. 279-305.

Cleavinger, H. B., II, 1974, Paleoenvironments of deposition of the Upper Cretaceous Ferron Sandstone near Emery, Emery County, Utah: Brigham Young Univ. Geol. Studies, v. 21, p. 247-74.

Coleman, J. M., and Wright, L. D., 1975, Modern river deltas: variability of processes and sand bodies: *in* M.L. Broussard, (ed.), Deltas, Models for Exploration: Houston Geological Society, Houston, Texas, p. 99-149.

Cotter, Edward, 1971, Paleoflow characteristics of a Late Cretaceous river in Utah from analysis of sedimentary structures in the Ferron Sandstone: Jour. Sedimentary Petrology, v. 4, p. 129-38.

———, Edward, 1974, Interplay between fair-weather and storm processes along a Late Cretaceous epeiric sea margin: Geol. Soc. America, Abstracts with Programs, v. 6, no. 7, p. 696.

———, 1975a, Deltaic deposits in the Upper Cretaceous Ferron Sandstone of Utah: *in* M.L. Broussard, (ed.), Deltas, Models for Exploration: Houston Geological Society, Houston, Texas, p. 471-84.

———, 1975b, Late Cretaceous sedimentation in a low-energy coastal zone: the Ferron Sandstone of Utah: Jour. Sedimentary Petrology, v. 45.

Davis, L. J., 1954, Stratigraphy of the Ferron Sandstone: Intermountain Assoc. Petrol. Geologists, 5th Annual Field Conference Guidebook, p. 55-58.

Doelling, H. H., 1972, Central Utah coal fields, Sevier-Sanpete, Wasatch Plateau, Book Cliffs, and Emery: Utah Geol. and Min. Survey, Monograph Series No. 3, 571 p.

Donaldson, Alan, 1969, Ancient deltaic sedimentation (Pennsylvanian) and its control on the distribution, thickness and quality of coals: *in* A.C. Donaldson, (ed.), Some Appalachian Coals and Carbonates: Models of Ancient Shallow-water Deposition: West Virginia Geological and Economic Survey, Morgantown, West Virginia, p. 93-121.

Edson, D. J., Jr., Scholl, M. R., Jr., and Zabriskie, W. E., 1954, Clear Creek gas field, central Utah: Intermountain Assoc. Petrol. Geologists, 5th Annual Field Conference Guidebook, p. 89-93.

Fisher, W. L., Brown, L. F., Jr., Scott, A. J., and McGowen, J. H., 1969, Delta systems in the exploration for oil and gas: A research colloquium: Univ. Texas, Bureau Econ. Geology.

Gray, R. J., Patalski, R. M., and Schapiro, N., 1966, Correlation of coal deposits from central Utah: *in* Central Utah Coals, Utah Geol. and Min. Survey Bull. 80, p. 81-86.

Guber, A. L., 1972, Pyritic sulfur as a paleoecologic indicator in Carboniferous cycles: 24th Internat. Geol. Congress, Montreal, Canada, section 6, p. 389-96.

Hale, L. A., 1972, Depositional history of the Ferron Formation, central Utah: Utah Geological Assoc., Publ. No. 2, Plateau—Basin and Range Transition Zone, central Utah, p. 29-40.

———, and Van De Graaff, F. R., 1964, Cretaceous stratigraphy and facies patterns—northeastern Utah and adjacent areas: Intermountain Assoc. Petrol. Geologists, 13th Annual Field Conference Guidebook, p. 115-38.

Howard, J. D., 1969, Depositional control of Upper Cretaceous coal units: Mountain Geologist, v. 6, p. 143-46.

———, and Reineck, H. E., 1972, Georgia coastal region, Sapelo Island, U.S.A.: Sedimentology and biology. IV. Physical and biogenic sedimentary structures of the nearshore shelf: Senckenbergiana Maritima, v. 4, p. 81-123.
Hubert, J. F., Butera, J. G., and Rice, R. F., 1972, Sedimentology of Upper Cretaceous Cody-Parkman Delta, southwestern Powder River Basin, Wyoming: Geol. Soc. Amer. Bull., v. 83, p. 1649-70.
Katich, P. J., Jr., 1953, Source direction of Ferron Sandstone in Utah: Am. Assoc. Petroleum Geologists Bull., v. 37, p. 858-62.
———, 1954, Cretaceous and Early Tertiary stratigraphy of central and south-central Utah with emphasis on the Wasatch Plateau area: Intermountain Assoc. Petrol. Geologists, 5th Annual Field Conference Guidebook, p. 42-54.
Kuehnert, H. A., 1954, Huntington anticline, Emery County, Utah: Intermountain Assoc. Petrol. Geologists, 5th Annual Field Conference Guidebook, p. 94-95.
LeBlanc, R. J., 1972, Geometry of sandstone reservoir bodies: *in* Underground Waste Management and Environmental Implications, Am. Assoc. Petroleum Geologists Memoir No. 18, p. 133-90.
Lupton, C. T., 1916, Geology and coal resources of Castle Valley in Carbon, Emery, and Sevier Counties, Utah: U.S. Geological Survey Bull. 628, 84 p.
Maione, S. J., 1971, Stratigraphy of the Frontier Sandstone Member of the Mancos Shale (Upper Cretaceous) on the south flank of the eastern Uinta Mountains, Utah and Colorado: Earth Science Bull., Wyoming Geol. Association, v. 4, p. 27-58.
Stokes, W. L., 1954, Geomorphology of south-central Utah: Intermountain Assoc. Petroleum Geologists, 5th Annual Field Conference Guidebook, p. 2-14.