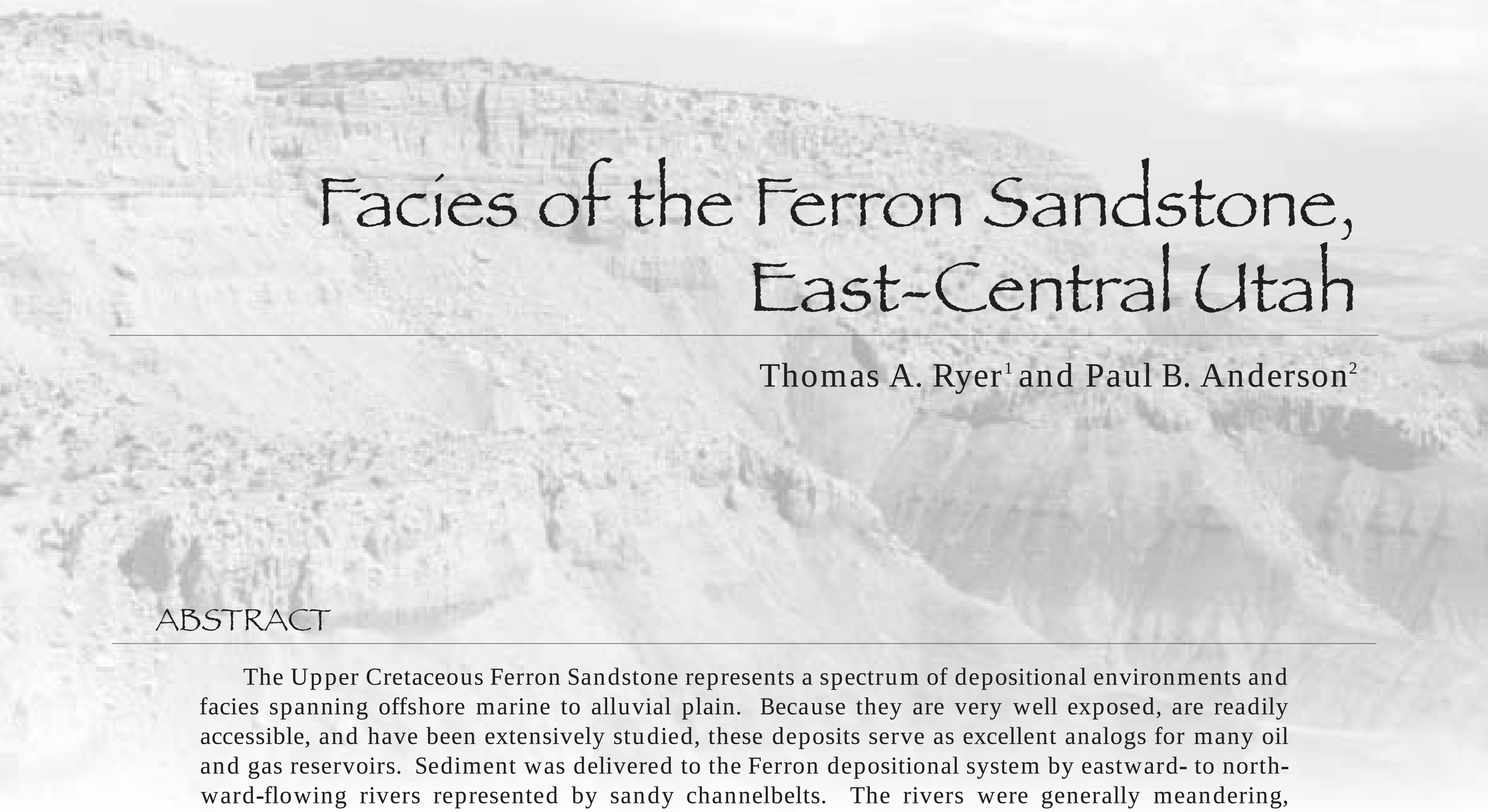
Analog for Fluvial-Deltiac Reservoir Modeling: Ferron Sandstone of Utah
AAPG Memoir ??
T.C. Chidsey, Jr., R.D. Adams, and T.H. Morris, editors



Facies of the Ferron Sandstone, East-Central Utah

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ABSTRACT

The Upper Cretaceous Ferron Sandstone represents a spectrum of depositional environments and facies spanning offshore marine to alluvial plain. Because they are very well exposed, are readily accessible, and have been extensively studied, these deposits serve as excellent analogs for many oil and gas reservoirs. Sediment was delivered to the Ferron depositional system by eastward- to northward-flowing rivers represented by sandy channelbelts. The rivers were generally meandering, although some were lower-sinuosity streams. Flood basins adjacent to the channelbelts accumulated predominantly muddy sediment, sandy crevasse-splay deposits, and, locally, peat. Peat accumulated in belts that roughly correspond to the lower part of the coastal plain and generally paralleled the shoreline. The geometries of individual, thick bodies of coal vary greatly. The dynamics of peat accumulation was controlled primarily by the rate of relative sea level rise.

The balance between sediment supply and wave energy was such that most Ferron shorelines were characterized by wave-dominated, cuspate deltas that graded laterally into strandplains. During the early part of Ferron deposition, however, the supply of sediment was great enough that fluvial processes predominated locally. Lobate deltas with numerous distributaries and interdistributary bays were well represented. Shoreface and delta-front deposits graded seaward into offshore marine mud. Sandy Ferron shoreline strata interfinger extensively with marine shale. Elongated sand bodies or sand plumes accumulated on a shallow-shelf area that lay east and northeast of the Ferron shoreline during early Ferron deposition.

Barrier islands developed during transgressions and are preserved, along with the lagoons that lay landward of them, at the “turnaround” points where episodes of transgression ended and shoreface progradation began. Landward pinchouts of the shoreface sandstone bodies are a key element for deciphering the transgressive-regressive history of the Ferron Sandstone. Tidal inlets and associated flood-tidal deltas are present locally in the vicinities of the landward pinchouts.

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INTRODUCTION

The Upper Cretaceous Ferron Sandstone consists predominantly of fluvial-deltaic deposits. The majority of Ferron sand bodies that could reservoir substantial volumes of oil and gas and, therefore, may constitute useful analogs, were deposited on prograding shorelines and by the fluvial channels that supplied the sediment to the shorelines. As a whole, the Ferron Sandstone exposures in the southern part of Castle Valley (Figure 1) have roughly equal amounts of these two principal sand-body types. There is great variation, however, in the abundance of facies from place to place along the Ferron outcrop belt: fluvial strata and their associated overbank deposits predominate in the southwest, grading seaward to predominantly shoreline strata in the northeast.

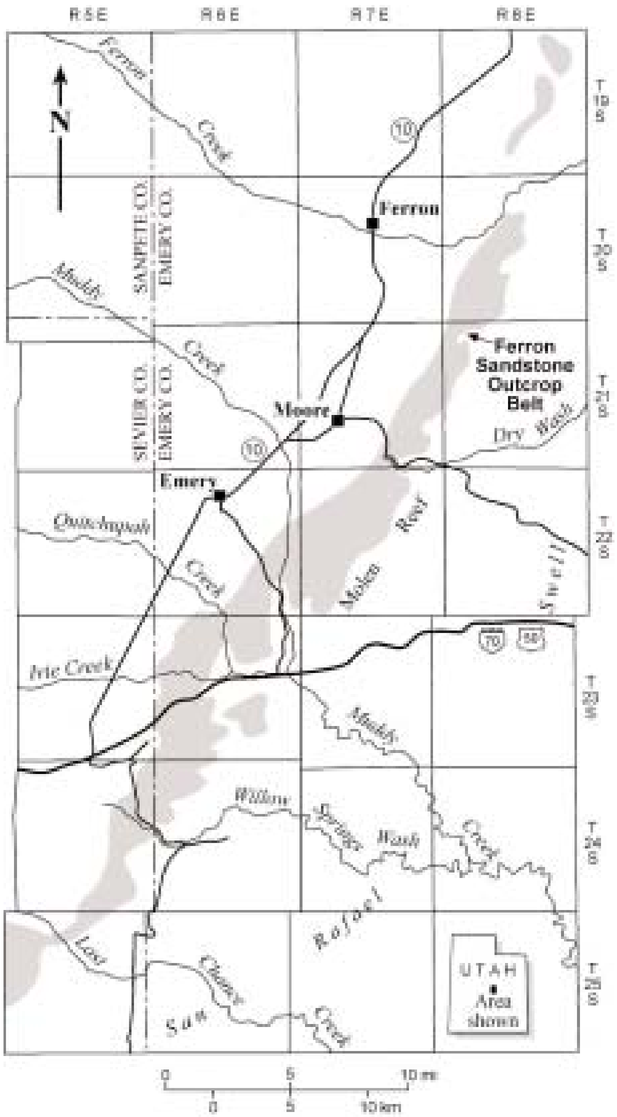

Figure 1. Location of the Ferron Sandstone study area in southern part of Castle Valley, between Ferron Creek and Last Chance Creek, east-central Utah. The Ferron outcrop belt is shown by shading.

Gardner (1993) included very detailed discussions of facies, their rock types, sedimentology, and ichnology: his dissertation stands as the most thorough treatment of Ferron facies. Here, a very generalized discussion of Ferron facies is offered with the goal of "setting the stage" for the papers that follow. Facies are discussed generally from seaward to landward, as they would occur in a stratigraphic succession recording progradation of the shoreline.

SYNOPSIS OF FERRON STRATIGRAPHY AND DEPOSITIONAL HISTORY

Stratigraphy

The Ferron Sandstone Member of the Mancos Shale is an eastward-thinning clastic wedge deposited during Turonian-Coniacian (Upper Cretaceous) time. Lower and upper parts of the Ferron are distinguished. The Lower Ferron consists, on outcrop, of shelf sandstone deposits that were transported generally from north to south; the Upper Ferron consists of fluvio-deltaic deposits that prograded generally from southwest to northeast. Nine correlatable and mappable units, designated Kf-Last Chance through Kf-8 (Figure 2), are recognized in the Upper Ferron. Each unit records a transgressive-regressive cycle of sedimentation and is defined on the basis of marine-flooding surfaces, most of which are widespread. The shoreline sandstone units that define the cycles are characterized by an initial forward-stepping arrangement, followed by vertical-stacking, and then back-stepping arrangements. This architecture indicates an initial strong supply of sediment relative to the accommodation space within which sediment could accumulate, followed by near-balance, and then a relative decrease in sediment supply. The older shoreline units, specifically Kf-1 and Kf-2, have much greater lengths along the Ferron outcrop belt, which roughly parallels deposition dip, than do the younger units.

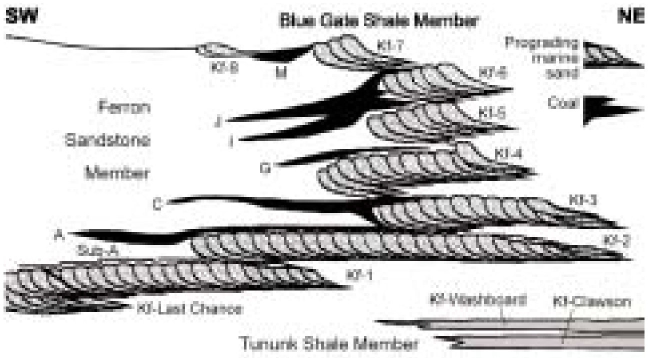

Figure 2. Diagrammatic cross section of the Ferron in the southern part of Castle Valley showing relative positions of Ferron depositional units and distinguishing their associated coal zones (black). The diagram has no scale.

Paleogeography

The Ferron Sandstone Member of the Mancos Shale and equivalent parts of the Frontier Formation in northern Utah and Wyoming record a widespread regression of the Western Interior Cretaceous seaway (Figure 3) during middle and late Turonian time. Rapid subsidence of a foredeep immediately east of the Sevier orogenic belt began in late Early Cretaceous time and continued through early Late Cretaceous time. Subsidence, however, was not uniform: during the Cenomanian (Figure 4A), the foredeep was strongly elongate and extended throughout Utah; during Turonian (Figure 4B) and Coniacian through Santonian time (Figure 4C), subsidence became concentrated in northern Utah and southwestern Wyoming.

The relatively straight, north-northeast-trending western shoreline of the seaway had transgressed to parts of western Utah during early Turonian time (Figure 5A). The shoreline encroached to within tens of miles of the Sevier orogenic belt in some areas, the closest that it was to come during the Cretaceous. The Tununk Shale accumulated at sub-wave-base depths in central Utah at this time. As the shoreline prograded eastward during middle Turonian time (Figure 5B), the shoreline configuration changed. A pronounced curve of the shoreline developed, reflecting interaction between sediment supply and subsidence. This regression is represented by the Ferron Sandstone in central

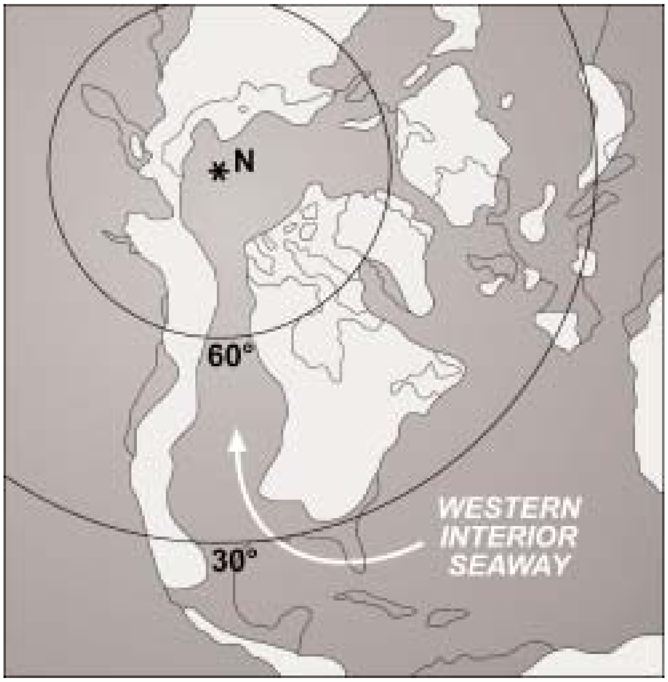

Figure 3. Paleogeography of North America at the peak of Cretaceous transgression during early Turonian time (modified from Hay et al., 1993). Light areas represent landmasses; dark areas represent water bodies.

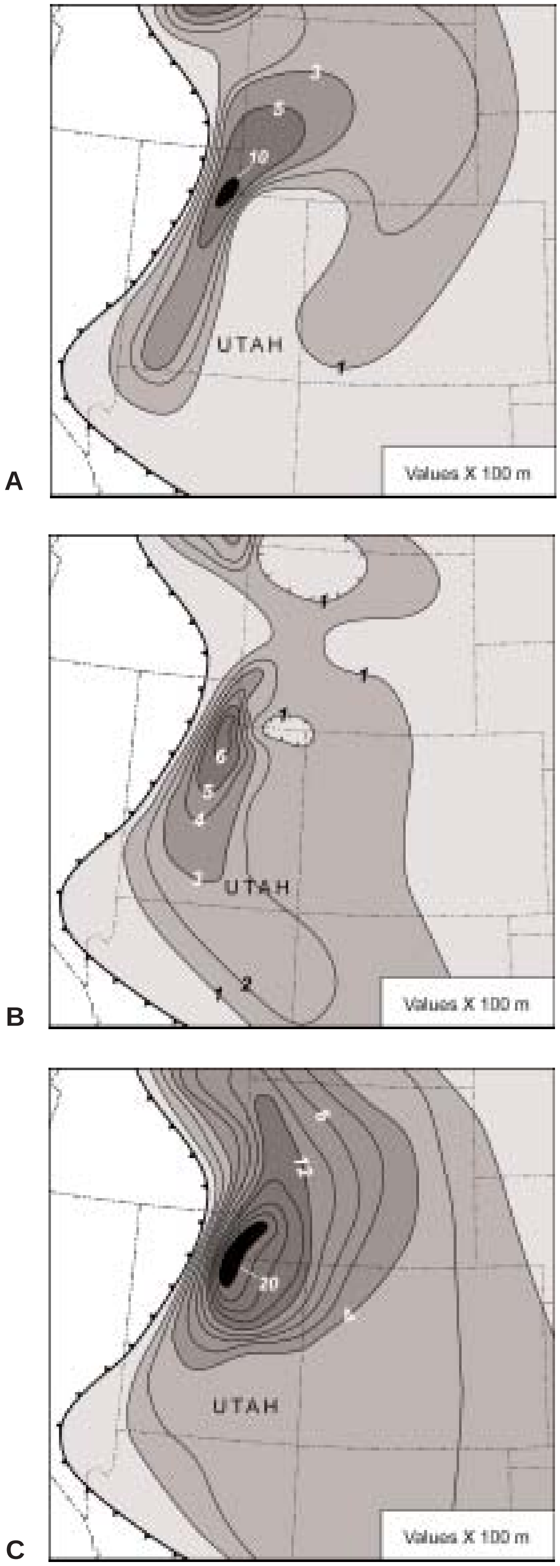

Figure 4. (A) Isopach map of Cenomanian strata. A pronounced foredeep lay east of and parallel to the Sevier orogenic belt, whose eastern edge is approximated by the thrust fault symbol. (B) Isopach map of Turonian strata. The foredeep remained, but subsidence became concentrated in northeastern Utah and southwestern most Wyoming. (C) Isopach map of Coniacian and Santonian strata. Subsidence became strongly focused in northeastern Utah and southwestern Wyoming. Modified from Roberts and Kirschbaum, 1995.

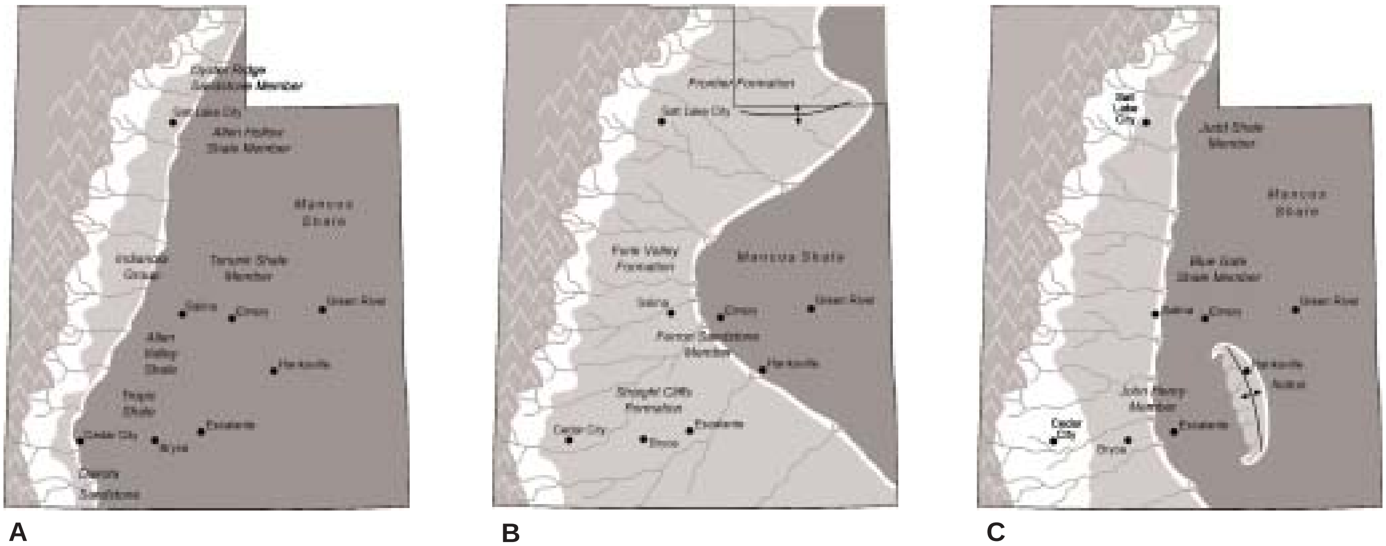

Figure 5. (A) Paleogeography of Utah during early Turonian time. Labels identify principal stratigraphic units deposited at this time. (B) Paleogeography during middle Turonian time. (C) Paleogeography during Coniacian time. Coniacian strata are missing in the Henry Mountains basin of southeastern Utah (Peterson et al., 1980). This is interpreted as evidence of erosion on an island or shoal located along the crest of a peripheral bulge.

Utah and by the Frontier Formation in northeastern Utah. In northern Utah and southwestern Wyoming, subsidence was rapid, but sediment supply was more than enough to fill the depositional space created by subsidence. In central and southern Utah, subsidence and sediment supply were more nearly balanced. The embayment that developed in central Utah during Turonian time probably reflects the northward shift of subsidence during the Turonian.

Hale (1972) and Cotter (1975a, 1975b) interpreted the bulges of the shoreline that developed in Utah during middle Turonian time to represent deltas, the Vernal delta to the north and the Last Chance delta to the south. Ryer and Lovekin (1986) argued that the embayment in central Utah was the result of a supply of sediment in central Utah that was inadequate to fill the space created by subsidence and owes its origin more to tectonics than to the distribution of rivers. The question of just what constitutes an ancient delta aside, all previous investigators have agreed that the Ferron in Castle Valley accumulated on deltaic to wave-dominated coastal environments in a rapidly subsiding portion of the Cretaceous foreland basin.

Transgression occurred during Coniacian time (Figure 5C). The sea transgressed very rapidly across the Ferron coastal plain to a position near the western edge of the Wasatch Plateau. Coniacian strata are not known in the Henry Mountains basin, to the southeast, indicating that an unconformity exists there between continental strata of the Ferron and overlying marine shales of the Blue Gate Shale. This unconformity may represent uplift of and erosion on a peripheral bulge. The erosion may have occurred subaerially, as pictured in Figure 5C, or entirely in marine environments.

Ferron Architecture

Ferron stratigraphy and architecture is shown diagrammatically in Figure 2. The Clawson and Washboard units, which constitute the Lower Ferron, are shelf sandstone deposits that drifted southward along a shoal that likely corresponded to the hinge of the foreland basin, sourced from the shoreline in the vicinity of the present-day Book Cliffs. The Upper Ferron consists of fluvio-deltaics that were generally transported from southwest to northeast.

Ryer (1981) recognized that the Upper Ferron consists of a series of stacked, deltaic units that can be defined in outcrop on the basis of cliff-forming shoreline sandstone bodies. These record transgressive-regressive cycles of sedimentation. Five major, correlatable, sandy delta-front units, Kf-1 through 5 in ascending order, plus three less widespread delta-front sandstones, later designated Kf-6, Kf-7, and Kf-8, were mapped. Each delta-front unit, with the exception of Kf-8, was found to have an associated coal bed. The coals carry letter designations originally assigned to them by Lupton (1916). Gardner (1993, 1995a, 1995b), Barton (1994), Garrison et al. (1997) and Anderson et al. (this volume) have completed recent studies of the stratigraphy of the Ferron. All of these authors place the Ferron in sequence stratigraphic frameworks, although their interpretations, particularly with respect to the number and placement of sequence boundaries, differ significantly.

OFFSHORE-MARINE DEPOSITS

The Tununk and Blue Gate Shale Members of the Mancos Shale, which under- and overlie, respectively,

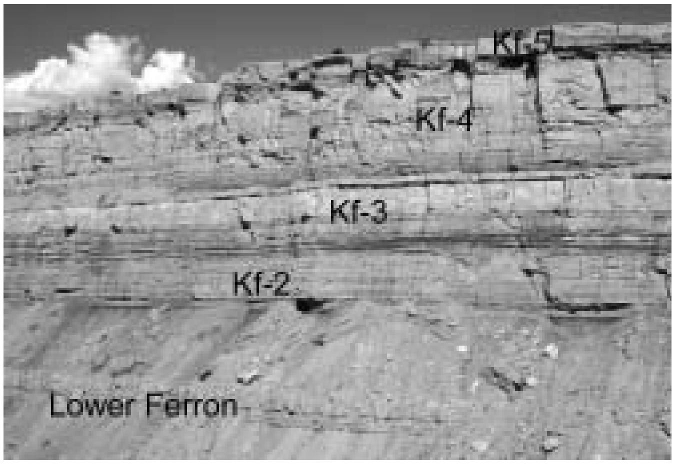

Figure 6. Section exposed on the cliffs of Molen Reef, south of Dry Wash. Dark gray units are marine shales. The Lower Ferron consists of the Clawson and Washboard shelf-sand units: only the upper, Washboard Unit is visible is this photo. A unit of marine shale separates the Lower and Upper Ferron. Units Kf-2 through Kf-5 of the Upper Ferron are labeled.

the Ferron Sandstone Member, were deposited in offshore-marine paleoenvironments at depths below storm-wave base. Offshore-marine shale is a relatively minor component of the Ferron in the study area, found in increasing amounts toward the northeast. Units of marine shale that separate the shoreline sandstone units of the Ferron in the northeastern part of the study area (Figure 2) may be considered as representing southwestward-thinning tongues of the main body of the Mancos Shale.

SHELF SAND DEPOSITS

The Clawson and Washboard units of the Ferron Sandstone (Kf-Clawson and Kf-Washboard, respectively, of our terminology; Figures 2 and 6) are commonly referred to together as the Lower Ferron. They were deposited on the shelf ranging from about storm-wave base to somewhat shallower than fair-weather wave base. They represent an elongate deposit (or “plume”) of sand that was transported south-southwestward on the shelf (Thompson et al., 1986) from the bulge of the shoreline commonly referred to as the "Vernal delta."

The Clawson and Washboard units consist predominantly of very fine and fine-grained sandstone. Most of the sandstone has been bioturbated. Planar lamination and oscillation ripple lamination are the most common sedimentary structures in these sandstones where physical structures have not been obliterated by burrowing. Both units generally coarsen upward from a gradational base on marine shale; both the Clawson and Washboard have abrupt tops that correspond to marine-flooding surfaces.

In the southern part of Castle Valley, the Clawson and Washboard units form minor ledges beneath the larger cliffs formed by the shoreline sandstone units of the Upper Ferron (Figure 6). As the shoreline sandstones of the Upper Ferron grade northeastward into marine shale, the ledges formed by the Clawson and Washboard units become relatively more significant until, in the northernmost part of the study area, the Clawson becomes the most conspicuous feature of the Ferron outcrop belt. The sandstone content of the units varies: in the north, the Clawson unit generally forms a more prominent ledge than does the Washboard unit, while in the south the situation is reversed.

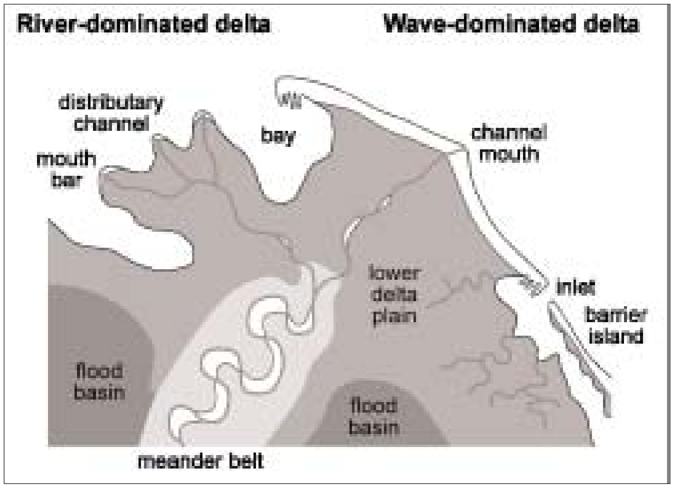

Figure 7. Diagram showing range of shoreline types present in the Ferron Sandstone.

SHORELINE DEPOSITS

Shoreline types preserved in the Ferron Sandstone range from wave-dominated to strongly fluvial-dominated. Figure 7 shows the range in shoreline types interpreted to have existed in the Ferron. Although highly diagrammatic, this figure shows that the shoreline orientation had a large influence on shoreline type. The western shoreline of the Interior Cretaceous Seaway generally trended northward (Figures 3 and 5A) but, because of the aforementioned embayment in central Utah (Figure 5B), the shoreline in the study area generally trended northwestward. Shoreline orientations varied locally, however, particularly on the deltas. Ferron shorelines that faced eastward or northeastward were reworked by waves; much of the sand from east-facing, wave-dominated deltas was carried along shore to accumulate in adjacent strandplains. Ferron deltas that built northward or northwestward, toward the subsiding area (Figure 4B and 4C), faced the embayment and were sheltered from waves. This explains why the most strongly fluvial-dominated deltaic deposits of the Ferron accumulated on deltas that prograded toward the north or northwest, an observation that was first made by Cotter (1975a, 1975b).

There is clear evidence of tidal deposits preserved in

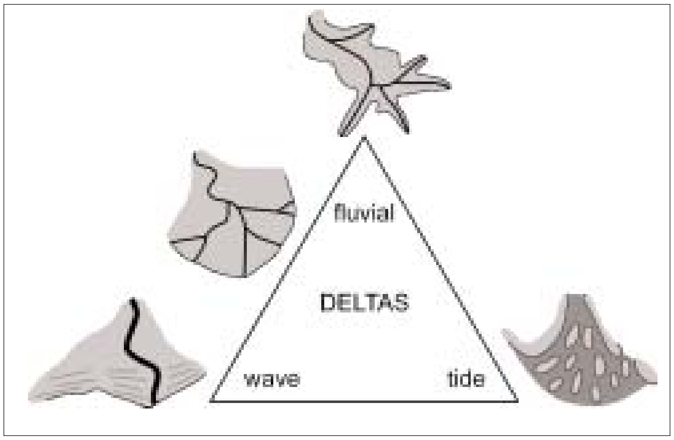

Figure 8. Ternary diagram showing the principal forces that shape delta morphology: fluvial input of sediment, wave reworking of sediment, and reworking of sediment by tidal currents (after Galloway, 1975).

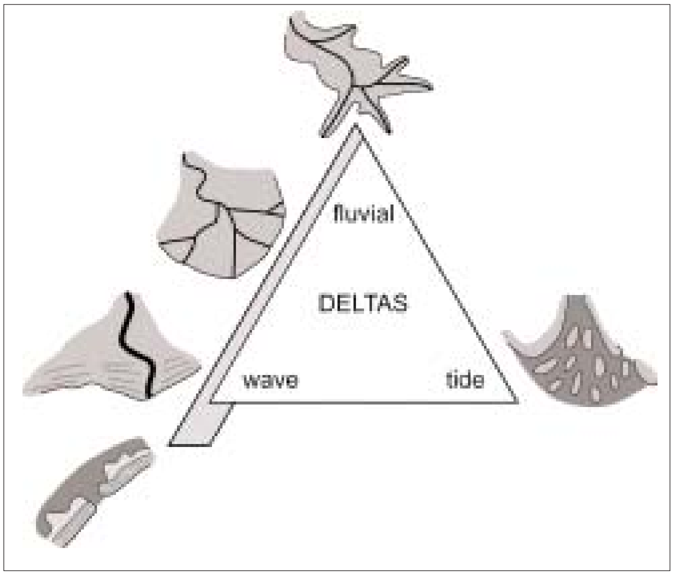

Figure 9. Shoreline types recognizable in the Ferron Sandstone include wave-dominated, non-deltaic shorelines deposited as prograding strand plains and on barrier islands (after Galloway, 1975).

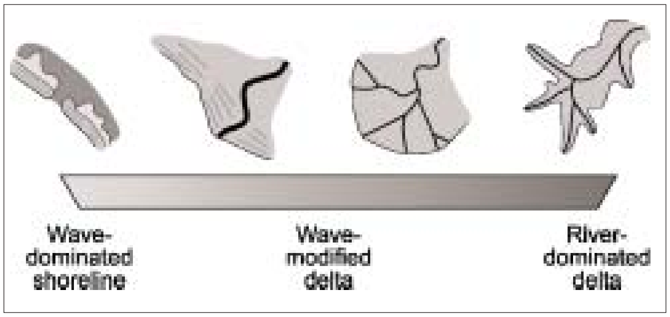

Figure 10. Diagram showing the three basic categories of shoreline types distinguished in the Ferron Sandstone. There is a gradation of types over the recognized range and the three types are arbitrarily defined.

Ferron strata (primarily in deposits of bays, lagoons, and tidal inlets, all of which are discussed later), but no evidence to indicate that the tidal range exceeded microtidal. Delta types in the Ferron Sandstone range from wave-dominated to fluvial-dominated (Figure 8). Shoreline strata of the Ferron as a whole, therefore, can be considered to lie along a linear axis extending from strongly wave-dominated deposits of the shoreface through wave-dominated deltas to strongly fluvial-dominated deltas (the later two being included as the upper apex and lower left apex in Figures 9 and 10).

Three basic shoreline types are distinguished in the Ferron Sandstone: wave-dominated (i.e. shoreface), wave-modified deltaic, and fluvial-dominated deltaic. The boundaries between these categories are arbitrary: examples representing the entire range between the end members can be recognized on the Ferron outcrops. The end members are described first, then the intermediate, wave-modified deltaic category.

WAVE-DOMINATED SHORELINES

Shoreface

Deposits of wave-dominated shorelines (Figure 11) predominate in the Ferron Sandstone. A typical outcrop of a wave-dominated, shoreface deposit is shown in Figure 12. The thickness of Ferron shoreface successions is generally from 30-60 ft (9-18 m). Stratigraphic successions of the Ferron deposited on wave-dominated shorelines (both wave-dominated deltas and shorefaces) have one or more shoreface subfacies: transition zone; lower, middle, and upper shoreface; and foreshore.

Most of the shoreline sandstone bodies that contain these subfacies accumulated on prograding shorefaces that were not directly influenced by rivers, although they were undoubtedly nourished largely with sediment transported by longshore drift from river mouths. Some

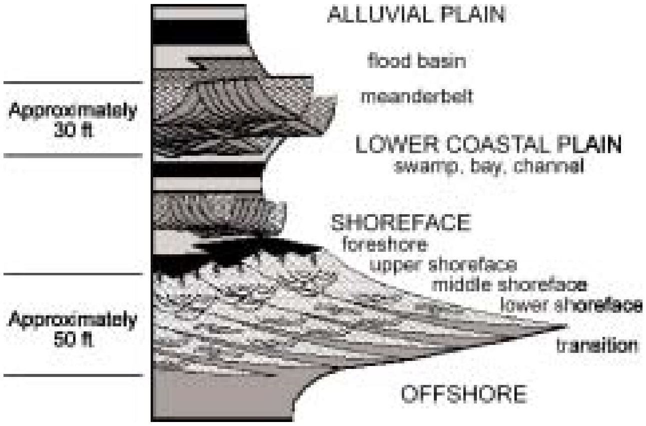

Figure 11. Diagram distinguishing facies and, in the shoreface, subfacies within a depositional sequence formed by progradation of a wave-dominated coast.

of the shoreline deposits may represent the margins of strongly wave-modified deltas, areas that morphologically would be included in the delta but which lack active distributary channels and that receive most of their sediment by longshore drift.

Transition Zone and Lower Shoreface

The transition zone and lower shoreface include interbedded sandstone and mudstone deposited between storm and fair-weather wave bases. Strata assigned to the transition zone consist of mudstone with thin beds of sandstone. Sandstone constitutes less than 50% of the rock. The sandstone typically occurs in thin beds that have abrupt bases, are predominantly planar laminated in their lower parts, and commonly grade upward to oscillation-ripple laminated tops. Thicker beds may include hummocky/swaley cross-stratification. The beds generally fine upward to mudstone. Burrows of invertebrate organisms are rare to common. Burrowing is most common in the uppermost parts of the sandstone beds, affecting the oscillation-rippled tops. The sandstone beds represent storm layers deposited below fair-weather wave base.

The term "lower shoreface," as used here, designates the section of interbedded sandstone and mudstone overlying the transition zone and underlying the middle shoreface. It is characterized by the same style of bedding as the transition zone, but the amount of sandstone exceeds 50% and the sandstone beds tend to be thicker and generally contain more hummocky/swaley cross-stratification (Figures 13 and 14). The combined transition zone and lower shoreface part of the succession is thin, commonly 10 ft (3 m) or less.

Figure 12. Thick shoreface unit (parasequence Kf-2-Miller Canyon-b as defined by Anderson and Ryer, this volume) on the east side of Muddy Creek Canyon. The sandstone has a well-developed "white cap." The abrupt, flat contact at its top is a marine-flooding surface.

Middle Shoreface

The middle shoreface (Figure 15) consists of planar laminated and hummocky/swaley cross-stratified sandstone. These beds represent storm layers deposited

Figure 13. Lower shoreface strata of Kf-5 in Muddy Creek Canyon. The abrupt-based beds of fine-grained sandstone, averaging about 6 in. (14 cm) in thickness, were deposited during storms. The thinner layers of mudstone that separate them represent fair-weather sedimentation. A transgressive surface of erosion (tse) separates the basal storm layer from an underlying interval of floodbasin mudstone assigned to Kf-4.

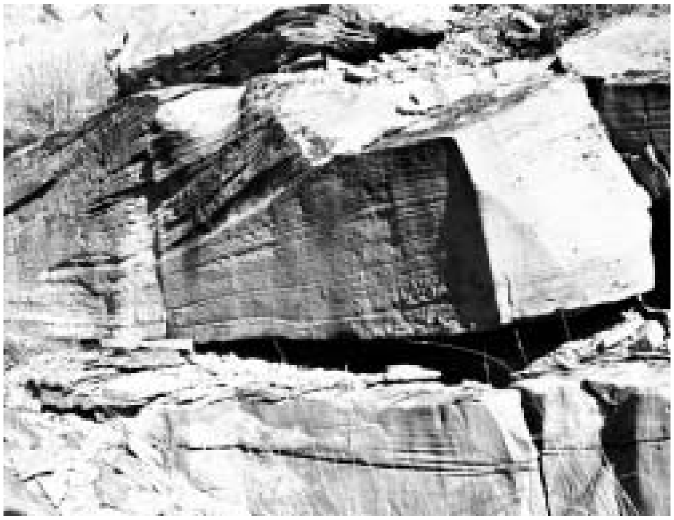

Figure 14. Hummocky and swaley cross-stratification are common in lower and middle shoreface strata (parasequence Kf-2-Muddy Canyon-b as defined by Anderson and Ryer, this volume). In this example, the strata are only sparsely burrowed.

Figure 15. Middle shoreface strata (parasequence Kf-1-Indian Canyon-a) in Indian Canyon. These strata are intensely burrowed. Remnant flat bedding is apparent. The top of the sandstone unit is a transgressive surface of erosion overlain by transition zone strata of the next parasequence.

Figure 16. Oscillation ripples in the middle shoreface of Kf-2-Miller Canyon-b in Muddy Creek Canyon. Gastropod grazing traces are visible in some of the ripple troughs. U.S. quarter for scale.

above fair-weather wave base. Mudstone layers are generally absent in the middle shoreface. In the Ferron, middle-shoreface sandstone typically is very fine to fine-grained. Oscillation ripples are commonly preserved in the upper parts of individual storm beds (Figure 16). Most of the sandstone occurs in sharp-based beds whose tops are burrowed to bioturbated (Figure 17).

The middle shoreface is commonly thick, 15-30 ft (5-9 m), representing 50% or more of the total thickness of the shoreface succession. Middle-shoreface deposits may include abundant burrows. In any given vertical shoreface section, the degree of burrowing in the middle shoreface is usually greater than in the underlying, storm-layered sandstones of the lower shoreface. The diversity of burrow types is great, with *Ophiomorpha* and *Thalassinoides* (Figure 18) being the most conspicuous forms.

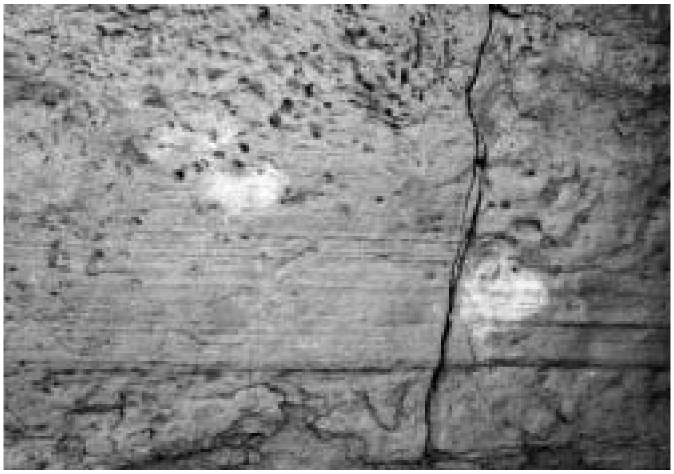

Figure 17. Planar lamination in a remnant storm layer in the middle shoreface (parasequence Kf-2-Muddy Canyon-b) in Muddy Creek Canyon. Burrowing has extended downward from the top of the storm bed, obliterating the original physical structures in its upper part. The burrows did not extend downward to the base of the storm layer, which abruptly places laminated sandstone on burrowed sandstone of the preceding storm layer.

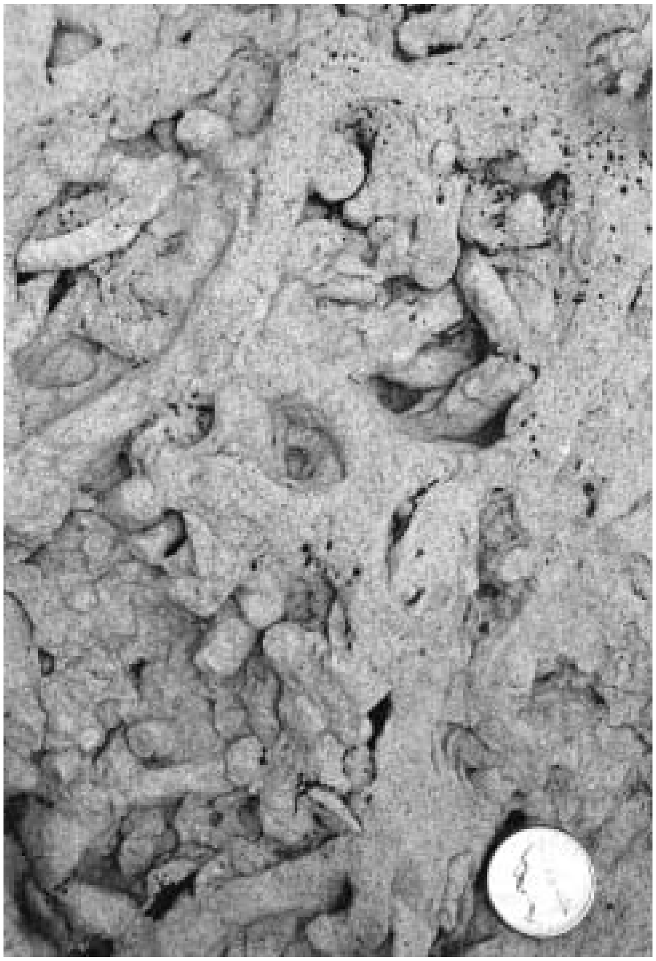

Figure 18. Thalassinoides is the most common burrow form in middle-shoreface deposits of the Ferron. This example of a bioturbated middle-shoreface deposit outcrops (parasequence Kf-2-Muddy Canyon-b) in Muddy Creek Canyon.

Figure 19. Upper-shoreface strata (parasequence Kf-2-Miller Canyon-b) in Muddy Creek Canyon. The strata are predominantly trough cross-stratified and display high variability in transport direction. Burrows at the top of the photo extend downward from a transgressive surface of erosion: these Ophiomorpha and Thalassinoides burrows are superimposed from the lower-shoreface to offshore environments that existed during and following the transgression. Strata in the lower, center part of the photo are shown in Figure 20.

Figure 20. Trough cross-stratification of the upper shoreface. The bed in the middle part of the photo includes burrows (although burrows are generally rare upper shoreface deposits of the Ferron). The burrows are truncated at the top of the bed, indicating that they existed in the upper-shoreface environment and were not superimposed, as were the burrows at the top of parasequence Kf-2-Miller Canyon-b, as shown in Figure 19.

Upper Shoreface

The upper shoreface is characterized by a distinctly different set of sedimentary structures than the underlying middle shoreface and the overlying foreshore. It consists of trough cross-stratified sandstone with only minor amounts of planar lamination (Figures 19 and 20). The upper shoreface is usually coarser than the middle shoreface. In the Ferron Sandstone, upper-shoreface strata are typically composed of medium-grained sandstone. The transport directions recorded by the trough cross-stratification are generally highly variable, but oblique onshore directions tend to predominate. The upper/middle shoreface contact is generally abrupt and slightly erosional, possibly as a result of scouring by rip-current channels.

Where the upper shoreface is well developed, it commonly has a thickness of 5-10 ft (1.5-3 m). The thickness may reach 20 ft (6 m) or more near landward pinchouts of parasequence-level shoreline units, particularly where the underlying transgressive surface of erosion overlies carbonaceous shale or coal and syndepositional compaction of the underlying, organic-rich material occurred.

Foreshore

A foreshore can commonly be recognized at the top of shoreline successions that include upper-shoreface strata. The foreshore consists of planar-laminated sandstone (Figure 21) in sets that dip seaward at angles of a few degrees to as much as about 10-15 degrees. Foreshore deposits in the Ferron Sandstone generally consist of fine-grained sandstone. The lamination is formed under upper-flow-regime conditions in the swash zone. Foreshore deposits in the Ferron rarely exceed about 5 ft (1.5 m) in thickness. A “white cap” is commonly present, affecting foreshore and upper-

Figure 21. Upper-shoreface (sf-u) and foreshore (sf-fs) deposits of Kf-6 in Muddy Creek Canyon. The boundary between planar, gently seaward inclined foreshore strata and trough cross-stratified upper-shoreface strata is usually abrupt, as is the case here.

shoreface strata. The top of the succession, except where affected by channels, is abrupt. It represents the berm of the beach and generally forms a flat bench that is easily traced on outcrops. Such a surface is shown in Figure 22. Foreshore deposits are also commonly root-penetrated and burrowed at their tops. Interestingly, coastal dune fields, so common along modern coasts, have not been recognized in the Ferron. The berms of the prograding Ferron beaches apparently were quickly vegetated and thus stabilized.

Figure 22. Cliff formed by a shoreface unit (parasequence Kf-1-Indian Canyon-c) in Indian Canyon. It overlies marine shale of the Tununk Shale Member. The sandstone is extensively rooted at its top and is overlain directly by carbonaceous shale of the Sub-A coal zone. The very flat top is typical of wave-dominated shoreline units. The uppermost part of the sandstone cliff weathers to a very light color and constitutes a "white-cap."

Tidal Inlet

Tidal-inlet deposits have been recognized in several units of the Ferron. They replace the wave-dominated shoreline deposits locally, removing mostly middle shoreface strata (Figure 23). Normal upper-shoreface and foreshore strata occur at the tops of most of the tidal-inlet deposits. Tidal-inlet deposits are characterized by conspicuous, sloping bedding surfaces that record migration of the inlets along the coast (Figures 23, 24, and 25). They include fine- to medium-grained, predominantly laminated sandstone. Trough cross-stratification is also present (Figures 25 and 26). Burrows are rare.

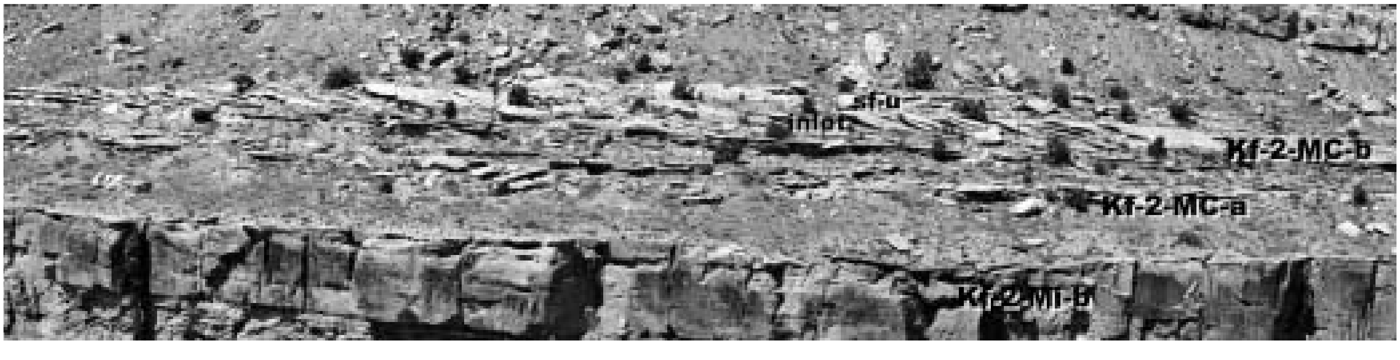

Figure 23. Tidal-inlet deposits exposed in the west wall of Muddy Creek Canyon (parasequence Kf-2-Muddy Canyon-b). Note the left to right inclination of large planar tabular beds. These beds record northward migration of the tidal inlet. Although not continuously exposed here, the upper, light-colored sandstone bed represents upper-shoreface (sf-u) and foreshore environments, which migrated across the inlet as it filled. Shoreface sandstone of parasequence Kf-2-Miller Canyon-b forms the vertical cliff at the bottom of the photo.

Figure 24. Steeply dipping, planar-tabular beds of fine- to medium-grained sandstone characterize Ferron tidal inlets. In this photo, which shows the same inlet deposit shown in Figure 23, the strata dip away from the viewer, toward the north.

Distribution of Wave-Dominated Deposits

Wave-dominated deposits are present in all nine of the Upper Ferron shoreline units. It is the predominant type of shoreline deposit in Kf-4 through Kf-8, but is also an important component in Kf-Last Chance through Kf-3. An important observation is that the oldest of the shoreline strata deposited in each of the parasequences distinguished in the Ferron Sandstone are wave-dominated. Barrier islands were common features on transgressive Ferron shorelines. Following cessation of transgression, the barrier islands prograded and the lagoons behind them filled. Even after the lagoons had filled, progradation typically continued in a wave-dominated mode. Only following a mile to several miles of progradation did conditions suitable for construction of wave-modified or river-dominated deltas come into existence. Tidal inlets existed concurrently with lagoons and so are limited to the landward-most parts of the parasequence-level shoreface sandstone bodies.

FLUVIAL-DOMINATED DELTA

General Characteristics

In the Ferron, fluvial-dominated deltaic deposits are generally distinguished by the following characteristics (Figure 27).

1. Thickness of the delta-front succession is relatively small, typically about 20-30 ft (6-9 m), indicating a shallow "mud line" and implying low wave energy (Figure 28).
2. Mudstone interbeds are common in all but the

Figure 25. Closer view of planar-tabular beds shown in Figures 23 and 24. Cross-stratification (X), ranging from planar-tabular to large-scale trough, is preserved locally among the large, inclined, planar-tabular beds.

Figure 26. Closer view of cross-stratification in tidal-inlet deposit. U.S. quarter in lower right for scale.

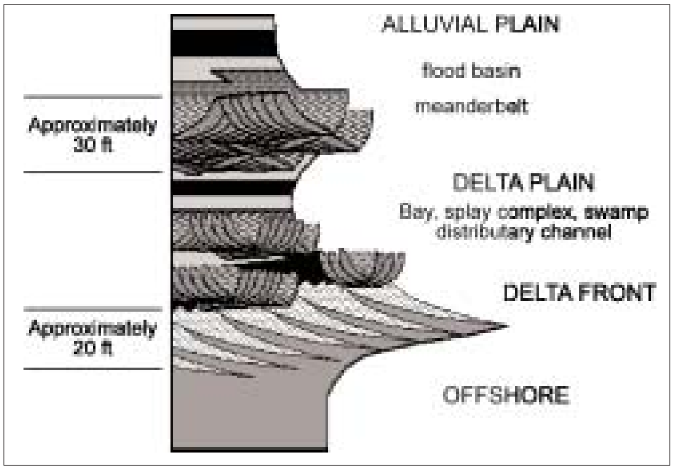

Figure 27. Diagram distinguishing facies within the depositional sequence formed by progradation of a fluvial-dominated delta.

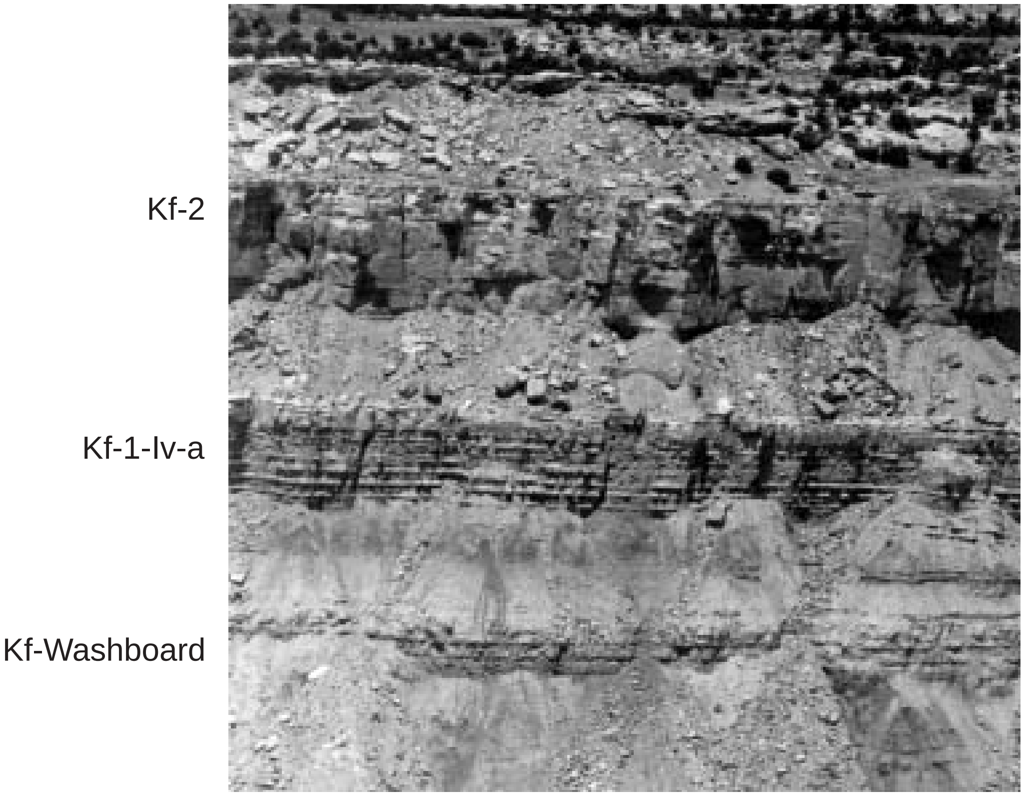

Figure 28. Typical fluvial-dominated deltaic deposits (parasequence Kf-1-Ivie Creek-a as defined by Anderson et al., this volume) are exposed along the south escarpment of Mesa Butte, south of Interstate 70. The strongly bedded appearance of the fluvial-dominated strata contrasts with the massive appearance of the wave-dominated strata of overlying Kf-2.

uppermost part of the succession (Figure 29).

3. Inclination of beds is usually very gentle, but locally may become steep enough to be quite apparent on outcrops (Figure 30). Where this happens, sandstone beds and bedsets pinch rapidly seaward as they interfinger with mudstone.
4. The succession of sedimentary structures in sandstone beds varies greatly, but the most common pattern is upward gradation from storm layers characterized by planar lamination and hummocky/swaley cross-stratification to trough cross-stratification. Where present, trough cross-stratification indicates generally unidirectional, seaward flow.
5. Contemporaneous distributary channels and small channels that may represent tidal creeks or distributary channels (see Figure 30) are common, replacing the tops of the delta-front successions in many or most outcrops. As a result, the top of a fluvial-dominated delta-front succession generally lacks the abrupt, flat top characteristic of wave-dominated shoreline deposits.
6. Burrowing is sparse. *Planolites* and *Arenicolites* are the most common burrow forms. This suggests rapid sedimentation, reduction of salinities in the vicinity of the river mouth, or both.

The morphologies of fluvial-dominated deltas in the Ferron Sandstone cannot be defined precisely. The Kf-1-Ivie Creek-a parasequence at Ivie Creek and the Kf-1-Indian Canyon-c parasequence at Willow Springs Wash, as defined and described respectively by Anderson et al. (this volume) and Dewey and Morris (this volume) include well-documented examples of fluvial-dominated deltaic facies. In both cases, the deltas built to the northwest. Kf-1-Ivie Creek-a has been mapped as having a general lobate form. The delta or deltas included in Kf-1-Indian Canyon-c are less well defined, but may have had an elongate, possibly even "bird-foot" form.

Figure 29. Typical fluvial-dominated deltaic-front facies represented by interbeds of fine-grained sandstone and mudstone (Kf-1-Ivie Creek-a in the Ivie Creek area), north side of Interstate 70, near the confluence of Quitchupah and Ivie Creeks.

Perhaps the most distinctive characteristic of fluvial-dominated deltaic deposits in the Ferron Sandstone is the presence of numerous beds of mudstone throughout much of the thicknesses of the delta-front depositional

Figure 30. Steeply inclined beds of a fluvial-dominated delta-front deposit of Kf-1-Ivie Creek-a in the Ivie Creek area. Inclination is toward the west. Note the rapid thinning of individual sandstone beds as they descend westward and interfinger with marine mudstone. A small channel of the overlying unit replaces the uppermost delta-front strata near the center of the photo.

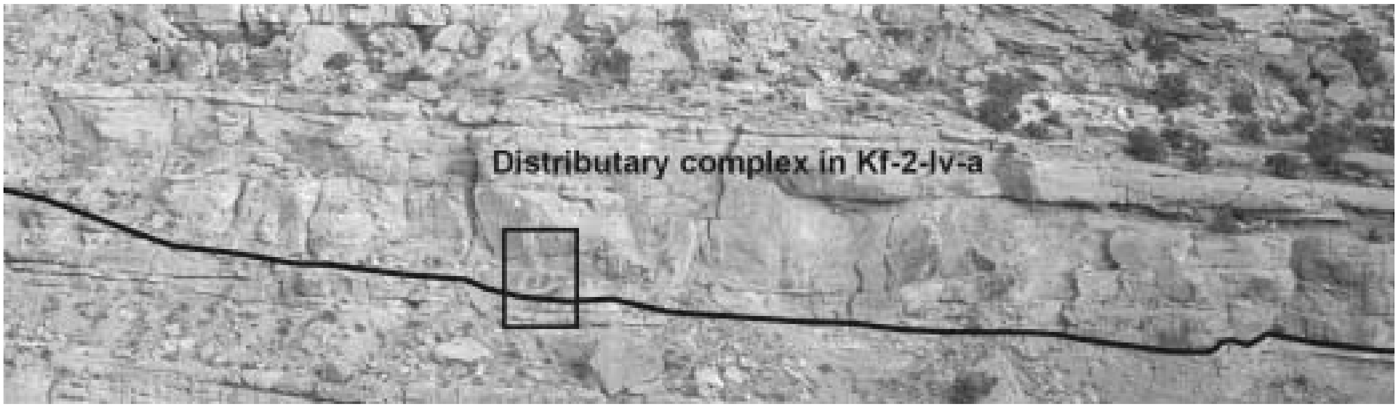

Figure 31. Facies typical of the wave-modified delta front are included in Kf-2-Ivie Creek-a in the canyon of Ivie Creek. These strata display a variety of bedforms related to distributary channels and their mouth-bars. The rectangle indicates the position of the photo shown in Figure 32.

successions. This is the characteristic that is most noticeable when viewing outcrops at a distance or when analyzing photomosaics. The presence of mudstone and the fact that beds of mudstone commonly occur within 10 ft (3 m) of the tops of the shoreline successions indicates that fair-weather periods were characterized by low wave energies on these deltas (Figure 31). By contrast, storm events, represented by the sharp-based, planar laminated to hummocky cross-stratified sandstone beds, impacted the deltas strongly, moving sand to water depths of about 30 ft (9 m).

Distribution of Fluvial-Dominated Deltaic Deposits

Fluvial-dominated deltaic deposits are an important component of Kf-1 and Kf-2. Their areal distributions have been documented by means of photomosaic mapping of the outcrop of these units within the study area (Anderson et al., 2003). They are not recognized in the other units.

WAVE-MODIFIED DELTA -- INTERMEDIATE SHORELINE TYPES

General Characteristics

Many of the shoreline sandstone units of the Ferron Sandstone correspond to neither the wave-dominated nor the fluvial-dominated categories described above. They are commonly thick, like the shoreface sandstone sequences, but include more mudstone interbeds and have, as a result, more gradational bases. In the latter respect, they resemble the fluvial-dominated deltaic deposits. They commonly include distributary channels and associated mouth-bar deposits, collectively referred to as distributary complexes (Figures 31), indicating that river mouths were present during their deposition. This

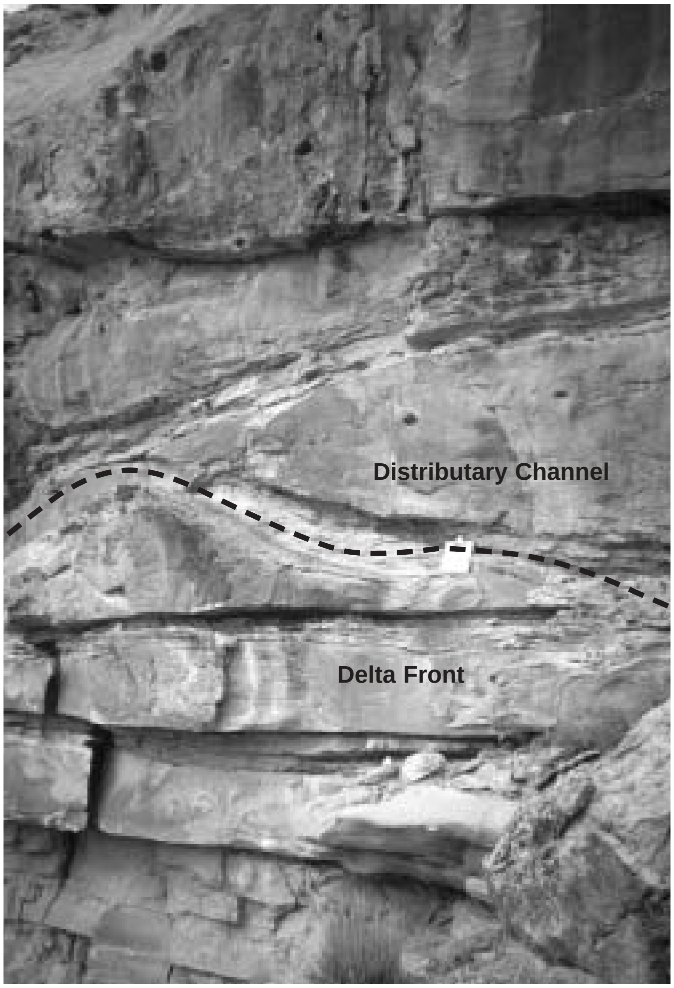

Figure 32. Cross-stratified and current-rippled sandstone of a distributary channel, part of the larger distributary complex shown in Figure 31, erosionally overlies hummocky/swaley storm deposits of the delta front in parasequence Kf-2-Ivie Creek-a.

facies is dominated by trough cross-stratification, particularly in the upper portions of the delta-front successions. Stratigraphically lower in the successions are troughs complexly mixed with parallel and current ripple lamination (Figure 32). Commonly, these facies grade laterally into more typical wave-dominated shoreface deposits. Trace fauna are less abundant than in the shoreface deposits, but constitute the typical shoreface assemblage dominated by *Thalassinoides* and *Ophiomorpha*. We classify these as intermediate deposits representing wave-modified deltas.

Wave-modified deltaic deposits accumulated on delta-fronts that experienced more wave reworking than did the fluvial-dominated delta fronts. We have no examples in the Ferron Sandstone where the form of a wave-modified delta can be reconstructed with certainty. It is likely that these deltas were broad, gently lobate forms several miles in width. Some may have been arcuate or cuspate in form. Where the orientations of inclined strata deposited on the delta fronts can be determined accurately, they indicate that these deltas prograded toward the northeast or east. Oriented in this way, they were strongly affected by waves rolling in from the Interior Cretaceous Seaway.

Figure 33. Sandstone ledge representing filling of a lagoon formed by the final stages of transgression associated with Kf-6. Location is on the western wall of Muddy Creek Canyon, about 1 mi (1.6 km) south of the landward pinchout of the shoreface sandstone of Kf-6. The ledge consists of about 6 ft (2 m) of very fine and fine-grained, intensely burrowed sandstone. It is underlain by coal of the I coal zone and overlain, with a rooted contact, by coal of the J coal zone. The basal contact is shown in Figure 34.

Distribution of Wave-Modified Deltaic Deposits

Wave-modified deltaic deposits are common in Kf-1 through Kf-4 and are documented on photomosaics of the outcrop of these units within the study area (Anderson et al., 2003). They are not recognized in Kf-Last Chance or in Kf-5 through Kf-8.

BAY AND LAGOON

Mudstone, muddy sandstone, and sandstone were deposited in bays and lagoons associated with Ferron shorelines (Figures 33 and 34). Depositional successions representing bays and lagoons are usually no more than about 10 ft (3 m) thick. Sandstones are generally sparsely burrowed to bioturbated and contain horizontal bedding, commonly with oscillation ripples. In some cases, the oscillation ripples have flat tops, indicating intertidal to very shallow subtidal settings. Shells, particularly those of oysters and corbulid bivalve, are common locally.

It is generally difficult to distinguish deposits of bays and lagoons from each other on Ferron outcrops. Invertebrate faunas are sometimes of value in distin-

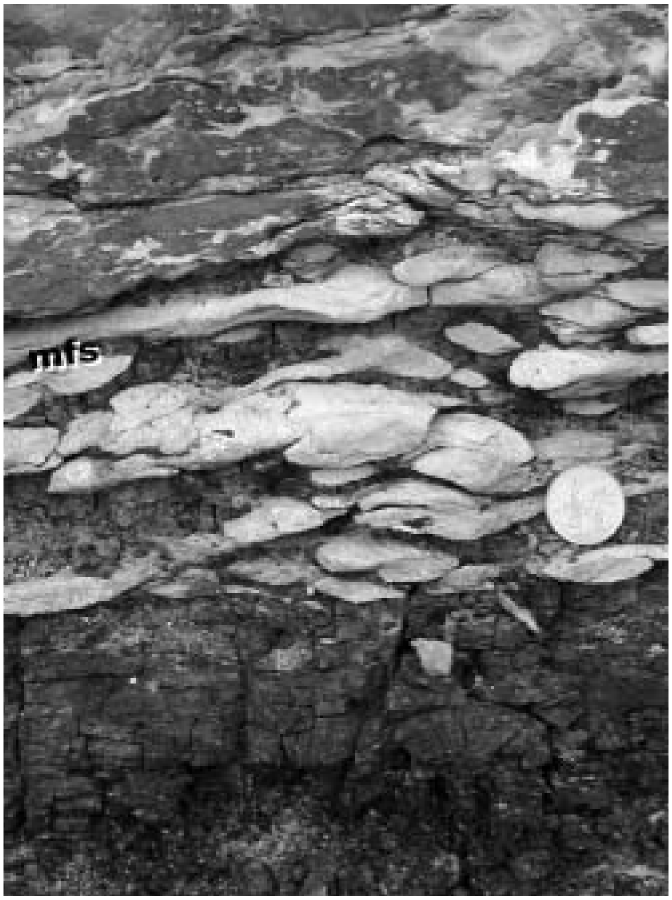

Figure 34. Sand-filled burrows extend downward into the I coal from the marine-flooding surface (mfs) at the base of the lagoonal deposit of Kf-6. Unlike the transgressive surface of erosion (a portion of the marine-flooding surface) produced by wave erosion on a transgressing shoreface, the landward extension of the mfs into the lagoon represents a low-wave-energy, passive encroachment of bay waters over peat of the I swamp. The amount of erosion was minimal.

guishing whether a particular body of water contained brackish water or water of full marine salinity, but whether a particular deposit is interpreted to represent a bay or a lagoon is most often based on interpretations of contemporaneous shoreline deposits: bodies of marine water that lay landward of wave-dominated shorelines, and specifically behind landward pinchouts of these bodies, are interpreted to be lagoons; bodies of brackish to marine water that are associated with fluvial-dominated or wave-modified deltaic deposits are interpreted to be bays.

Lagoonal deposits constitute only a very minor part of the Ferron Sandstone. The best-documented examples are located in Indian Canyon (landward of the landward pinchout of Kf-1-Indian Canyon-c), in the “Bear Gulch” and Miller Canyon exposures (Kf-2-Muddy Canyon-b), at Dry Wash (Kf-2-Dry Wash and Kf-2-Rochester), and in Muddy Creek Canyon (Kf-6; Figure 33).

Tidal channels are associated with bay and lagoon deposits and, like them, are relatively rare in the Ferron. A well-exposed example occurs in Dry Wash in strata of Kf-3 (Figure 35). The tidal-channel deposits share many of the features of tidal-inlet sandstones, the principal difference being the presence of numerous beds of mudstone. These range from a few feet to 20 ft (6 m) or more in thickness. Figure 35 shows an example of a thick, slope-forming bed lying below the label marking the transgressive surface of erosion (tse) that bounds Kf-3 and Kf-4. This body consists mostly of inclined, tabular sets of medium-grained, well-sorted sandstone. Trough cross stratification, mostly ebb directed, is common. *Ophiomorpha* burrows are locally abundant in the sandstone beds.

Small, “ribbon” sandstone bodies were deposited by minor channels (Figure 36). Many of these are probably distributary channels associated with larger channels

Figure 35. Kf-3 at Dry Wash consists of lower- to middle-shoreface sandstone erosionally overlain by a tidal inlet/tidal channel complex. The channel, which was probably closely associated with an inlet, migrated toward the north and displays prominent lateral accretion surfaces.

Figure 36. Lenticular, “ribbon” sands were deposited by minor, distributary channels that flowed into bays and lagoons on the lower coastal plain. The example shown here belongs to Kf-4 and crops out in a tributary of Quitchupah Canyon. The sandstone body, lens-shaped in cross section, occurs in a section of mudstone and carbonaceous shale.

systems. They consist predominantly of fine-grained, current-rippled sandstone and commonly display lateral accretion surfaces. They were, presumably, the principal source of the sediments that ultimately filled the lagoons and bays.

MARSH AND SWAMP

General Characteristics

Carbonaceous strata ranging from mudstone to low-ash coal are common in the Ferron Sandstone. Coalbeds have been of considerable economic importance in the past; carbonaceous mudstone is presently being mined at several locations south of the town of Emery for use as a soil conditioner. Coalbeds and associated carbonaceous strata serve as extremely useful stratigraphic markers that allow correlation of shallow-marine and continental strata.

Thick beds of coal in the Ferron Sandstone (Figure 37; Doelling, 1972; Ryer, 1981) are the products of coalification of beds of sediment-free peat that accumulated in delta-plain settings and in swamps that lay between the principal meanderbelts in the alluvial plain. Carbonaceous shale, carbonaceous mudstone, and carbonaceous sandstone formed from peats that included substantial clastic components. These impure peats were deposited in settings where clastics were repeatedly introduced to the swamp, as occurs along the margins of channels.

Dynamics of Peat Accumulation

The dynamics of peat accumulation and preservation constitute a complicated subject that is addressed here only generally. Thick bodies of clean peat accumulate in settings where suitable vegetation flourishes; the swamp environments exists, uninterrupted, for a long period of time; clastic sediments are excluded; and the resulting sediment-free peat subsides below the water table.

The fourth term is probably the most critical. Subsidence of the peat, or rising of the water table, which facilitates the preservation of the peat, must occur at about the same rate as the generation of preservable organic material by the plants: if the water table rises faster than peat can be produced, the peat swamp is flooded to form a bay or shallow pond and peat deposition ceases; if the water table rises more slowly than peat accumulates, part of the peat oxidizes prior to burial, yielding a peat that is higher in impurities. In delta plains and in alluvial plains located along the margins of the sea, relative sea level is the primary factor that controls the long-term rise or fall of water level in swamps. It can be concluded that all of the conditions required for peat formation and preservation were optimal over long spans of time during Ferron deposition.

Figure 37. Coal beds are a conspicuous component of the Ferron. Several of them, including the C coal bed, shown here, are of economic importance. In the area of this outcrop, which occurs in a tributary of Quitchupah Canyon, the C coal attains a thickness of 18 ft (5.5 m). It is overlain by bay deposits, which in turn are capped by a "ribbon" sandstone representing a small channel.

Coalbeds and Coal Zones

The Ferron Sandstone includes many beds of coal that can be correlated over considerable distances. Ferron coalbeds were originally named by Lupton (1916) and all subsequent workers have followed his terminology. The thickest and most widespread coals constitute the A, C, G, I, and J coalbeds. Coalbeds commonly split into two or more beds separated by clastic sediments. Traced laterally, coalbeds commonly thin and grade to carbonaceous mudstone. Coals, associated carbonaceous mudstones, plus non-carbonaceous strata included between the various splits of coal and beds of carbonaceous mudstone that are laterally equivalent to a principal coal bed are grouped into a "coal zone" (Doelling, 1972; Ryer, 1981; Garrison et al., 1997) that can be correlated over a wider area than the principal coalbed itself.

ALLUVIAL PLAIN

Alluvial-plain deposits laid down in river channels and in the adjacent flood plains constitute a major part of the Ferron Sandstone. They make up the bulk of the Ferron south of Interstate 70 (Figure 1). Channelbelt and overbank facies assemblages are distinguished.

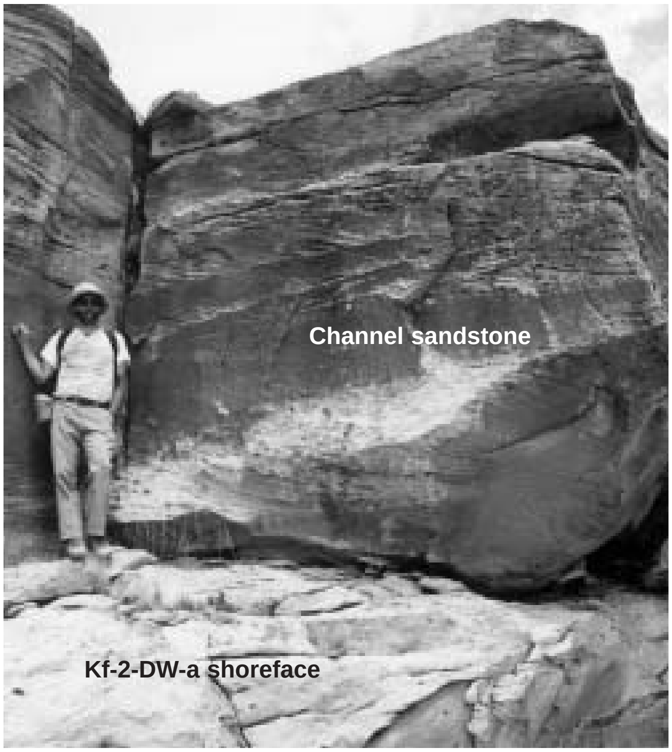

Figure 38. Unidirectional trough cross-stratified channel sandstone cutting into the shoreface of Kf-2 (parasequence Kf-2-Dry Wash at Dry Wash as defined by Anderson and Ryer, this volume). The base of the channel sandstone is at the person's feet. The height of cross-stratified lamina sets decreases upward.

Channelbelt

Predominantly sandy sediments deposited within active river channels constitute the channelbelt deposits of the Ferron Sandstone. Sand size generally ranges up to medium, but some coarse- and very coarse-grained sandstone is present, being particularly abundant in the channelbelt deposits of Kf-4. Trough cross-stratification is the most common sedimentary structure preserved in the channelbelt sandstone (Figure 38). In a typical vertical profile through a channel deposit, the preserved height of the cross-stratification sets decreases upward. Ripple-drift cross-lamination is common in the highest part, where the sand fines upward, eventually interbedding with and grading to mudstone (Figure 39).

"Channelbelt" is a general term that includes the deposits of a variety of channel forms. Many, and probably the majority, of the Ferron channelbelts were meanderbelts laid down by highly sinuous rivers. Direct evidence of this can be found in the many lateral accretion surfaces (Figure 40), representing lateral migration of point bars. Lateral accretion surfaces and, locally, abandoned channel fills provide the best evidence for determining the size of the rivers that deposited the Ferron. They indicate that the rivers were typically up to about 30 ft (9 m) in depth and up to a few hundred feet in width where they curved around their point bars. Variations in size, however, are considerable. This stems from the fact that the Ferron was not deposited by a single river and probably not by a single river system: major rivers draining northeastward from the Sevier orogenic belt as well as smaller rivers that had their headwaters within the alluvial plain east of the orogenic belt all left their marks on the deposits of the Ferron.

Ferron channelbelts range up to about 80 ft (24 m) in thickness. Thick channelbelts are the result of stacking

Figure 39. Meanderbelt deposits (parasequence Kf-2-Muddy Creek-a) in Muddy Creek Canyon. Vertical face is formed by trough cross-stratified sandstone. Person is sitting in upper part of deposit, where current rippled sandstone is interbedded with mudstone.

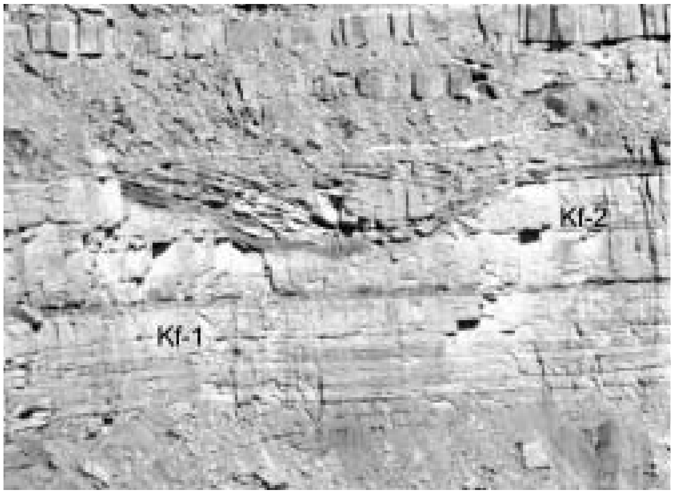

Figure 40. Lateral accretion surfaces are conspicuous is a small channel deposit of Kf-2 exposed near the mouth of Rock Canyon. It existed during deposition of the A coal zone in adjacent areas, having eroded downward through carbonaceous sediments and into the underlying shoreline sand.

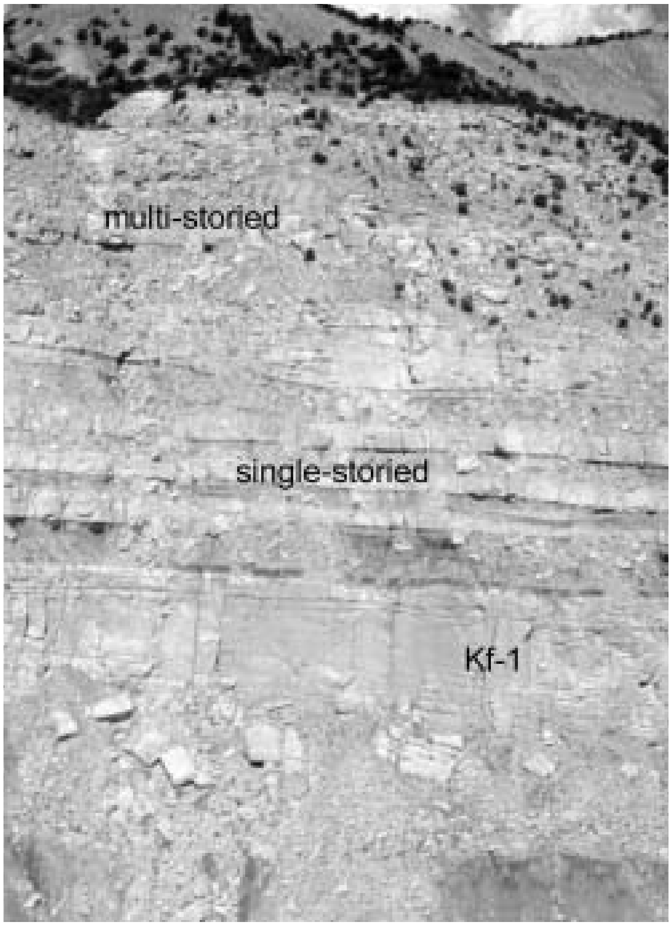

Figure 41. Single-storied and multistoried channelbelts exposed along the Limestone Cliffs. The massive cliff at the bottom of the photograph is formed by shoreline sandstone of Kf-1, beneath which the Tununk Shale is exposed. Overbank mudstone with three single-storied channelbelt sandstones of about equal thickness overlie the shoreline sandstone. Higher in the section, the style changes to thicker, multistoried channelbelt sandstones. The Blue Gate Shale forms the slopes at the top of the photo.

of individual channel depositional sequences, that is they are "multistoried" deposits. Successive channel bodies rarely stack one body directly above an immediately preceding one. Instead, they tend to be positioned one next to another, adding a "multilateral" component to the channelbelt. Continued deposition during rise of base level leads to aggradation and multiple stories of channel bodies. Channelbelts that are strongly multilateral are inferred to have been deposited during periods of more gradually rising base level; those that are more strongly multistoried are inferred to characterize periods of more rapidly rising base level (Figure 41).

The amount of mudstone included within Ferron channelbelts varies considerably. On outcrops, lateral accretion is most clearly displayed in "inclined heterolithic" channel deposits simply because of the contrast in weathering styles of the sandstone and mudstone interbeds. Lateral accretion surfaces are more difficult to recognize in point bar deposits that lack shale interbeds.

Gardner (1993) presented a detailed analysis and comparison of the arrangement of depositional "macroforms" (architectural elements representing recognizable bar forms or individual channel forms) within the seaward-stepping, "low-accommodation" units Kf-1 through Kf-3 and the landward-stepping, "high-accommodation" units Kf-4 through Kf-8. He concluded that channelbelts associated with seaward-stepping shoreline units contain thinner and more highly interconnected macroforms and include a lower diversity of fluvial facies. The channels themselves were relatively deep and narrow. By contrast, channelbelts associated with landward-stepping shoreline units contain a higher diversity of fluvial facies and thicker macroforms that tend to be separated from one another by fine-grained sediments and are, therefore, less well interconnected. They include a lower percentage of sandstone. The individual channels were shallower and wider. Channelbelts associated with back-stepping shoreline units are flanked by much larger amounts of crevasse-splay deposits than are channelbelts associated with forward-stepping shoreline units.

Garrison et al. (1997) presented an analysis of the width-to-thickness ratios of Ferron channelbelts. They utilized data they collected in Willow Springs Wash (van den Bergh, 1995; and van den Bergh and Garrison, 1996) and data gathered from other Ferron outcrops by Lowry and Jacobsen (1993) and Barton (1994). Although there is a great deal of overlap of populations, they were able to demonstrate that width-to-thickness ratios for channelbelts generally increase upward in the Ferron, passing from seaward-stepping to aggradational to landward-stepping portions.

Overbank Deposits

Overbank deposits in the Ferron Sandstone consist predominantly of mudstone and sandy mudstone deposited in flood basins as fines that settled from suspension during and in the aftermath of floods. Lenticular bodies of sandstone, generally ripple-drift cross-laminated but also including trough cross-stratification, represent channels that fed crevasse-splay complexes. The crevasse-splay channels generally were much smaller than the principal channels from which they issued. Flood-basin clastics interfinger extensively with carbonaceous shales representing swamps formed in areas of lesser clastic input. On outcrop, overbank deposits generally are slope forming, although the more resistant, sandy crevasse-splay channel deposits locally form ledges.

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