Ancient Delta Deposits in the Ivie Creek Area, Ferron Sandstone Member of the Mancos Shale, Western San Rafael Swell, East-Central Utah

Thomas C. Chidsey, Jr.[1], and Paul B. Anderson[2]

[1]Utah Geological Survey, PO Box 146100, Salt Lake City, Utah 84114-6100, tomchidsey@utah.gov

[2]Geologic Consultant, PO Box 101, Emery, Utah 84522

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Cover Image: *Clinoform medial facies in the Kf-1-Iv[a] bedset.*

INTRODUCTION

In contrast to the beautiful array of colorful layers and spectacular cliffs of the Triassic and Jurassic (251 to 148 million years ago [Ma]) sections in the San Rafael Swell of east-central Utah, most of the Upper Cretaceous (96 to 86 Ma) Mancos Shale produces a drab, barren landscape. However, lying within the Mancos, the Ferron Sandstone, is the most studied unit in the San Rafael Swell. The Ferron has world-class outcrops of rock layers deposited near the shorelines of a sinking, fluvial- (stream) dominated delta system. Along the west flank of the San Rafael Swell (figure 1), the 80-mile-long (130 km) Ferron outcrop belt of cliffs and side canyons (e.g., the Coal Cliffs, Molen Reef, and Limestone Cliffs [not actually limestone, just misnamed]) provides a three-dimensional view of vertical and lateral changes in the Ferron's rock layers (facies and sequence stratigraphy), and, as such, is an excellent model for fluvial-deltaic oil and gas reservoirs worldwide (e.g., Chidsey and others, 2004).

The Ferron Sandstone consists of a stacked series of sandstone-dominated rock layers deposited as local sea level rose and fell (depositional transgressive-regressive cycles). Collectively these sandstone layers form an eastward-thinning wedge into the Mancos Shale. The Ivie Creek area along the north side of Interstate 70 (I-70) (figure 2), displays spectacular and abrupt changes in two of these regional-scale depositional cycles ("parasequence sets" referred to as Kf-1 and Kf-2 [figure 3]). These cyclic deposits represent the those typically found in a deltaic oil and gas reservoir. The Kf-1 parasequence set displays spectacular clinoforms. The term "clinoform" is used to identify a group of beds which are inclined seaward in an *en echelon* pattern and generally separated from one another by a distinctive bounding surface. As a reservoir model, the Ferron in the Ivie Creek area displays variations that influence the reservoir (both its compartmentalization and permeability). These outcrops are often a standard stop for geology

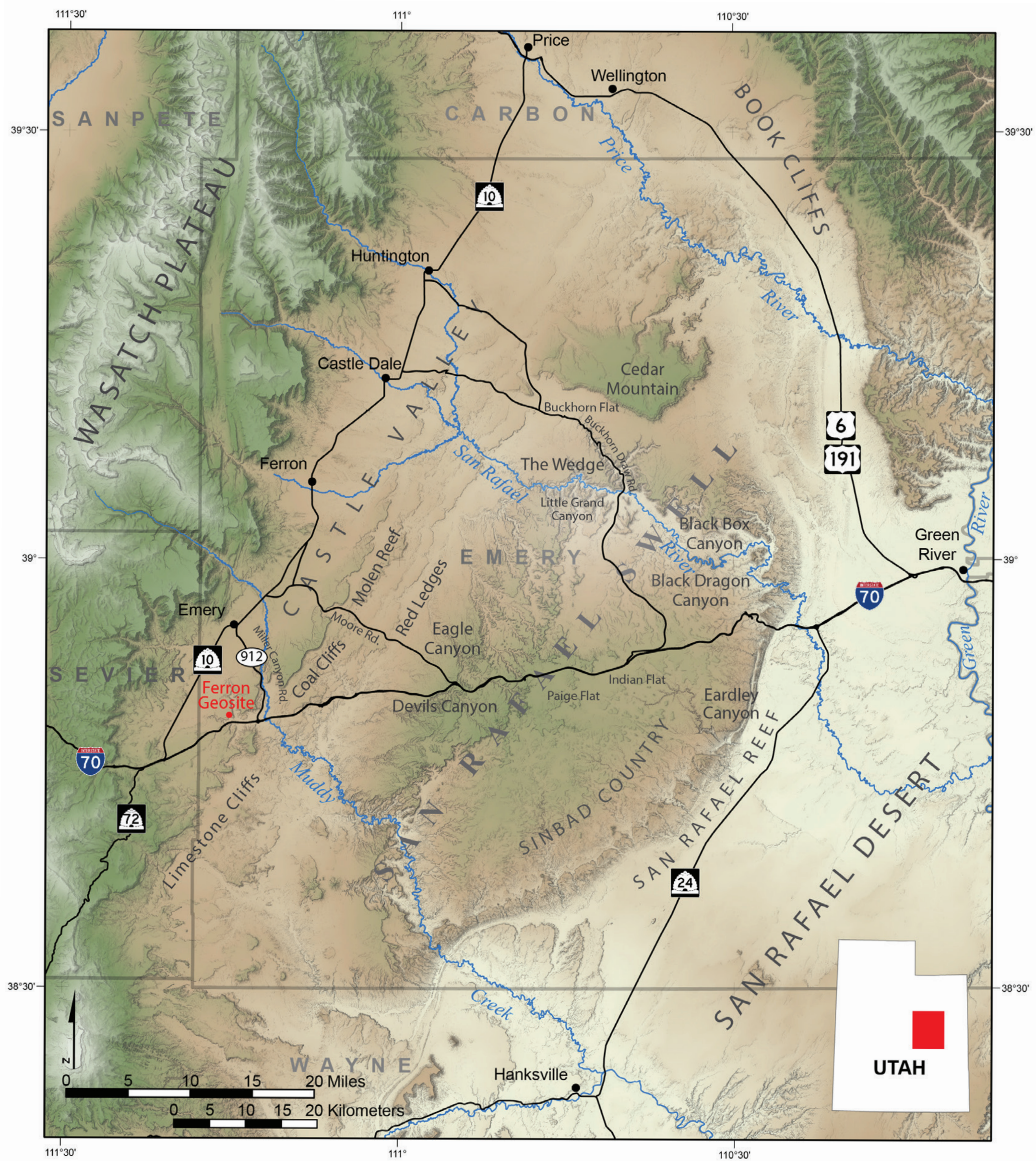

Figure 1. The San Rafael Swell and vicinity, east-central Utah, showing the location of the Ferron Sandstone geosite as well as major physiographic features, surrounding towns, and highways.

field trips. Thus, the Ferron Sandstone in the Ivie Creek area was selected as a geosite (also see Anderson's Ferron geosite in Emery County, this volume) providing a more complete picture of this classic outcrop.

HOW TO GET THERE

The Ferron Sandstone Ivie Creek area is about 170 miles (270 km) or a 2 hour and 45-minute drive from Salt Lake City, Utah, via I-15 and U.S. Highway 6 to State Highway 10 to I-70. Proceed eastbound on I-70 for 6 miles (10 km) to the junction with County Road 912 (Miller Canyon Road), cross the overpass and re-enter I-70 heading westbound for about 2.3 miles (3.7 km) to a well-used but difficult to spot dirt pull-off area for the best view (to the north) of the Ferron clinoforms, parasequence sets, and fluvial-deltaic facies in the "Ivie Creek amphitheater," an informal name applied to a broad, curving area of cliffs north of I-70 (38°48'35" N., 111°15'10" W., elevation 5813 feet [1772 m]) (figures 1 and 3). The Ferron Ivie Creek geosite is about 61 miles (98 km) west of the junction of U.S. Highway 6 and I-70 near the town of Green River, Utah (figure 1).

Upon approaching the Ivie Creek stop carefully slow down with flashers on and pull off the interstate down a slight incline to a well-used parking area along the right-of-way fence. There are no well-marked trails to examine the Ferron outcrops up close; the terrain is rugged with vertical cliffs and requires first negotiating a fence designed to keep livestock and wildlife from the interstate. Anderson and others (1997) provided a geologic field guide to several key locations within the Ferron section in the Ivie Creek amphitheater (figures 2 and 3).

GEOLOGIC OVERVIEW

San Rafael Swell

The Ferron Sandstone is exposed in an outcrop belt along the west flank of the San Rafael Swell, a broad, asymmetric, north-south- to southwest-northeast-trending anticline about 75 miles (120 km) long and 35 miles (56 km) wide. The structure formed in response to compressional forces of the Laramide orogeny between latest Cretaceous time (about 70 Ma) and the Eocene (about 40 Ma) (Hintze and Kowallis, 2009 and references therein) (figure 1). Uplift and erosion has made it a showcase of Colorado Plateau geology with a colorful array of sedimentary rocks over 7000 feet (2100 m) thick, ranging in age from Permian (276 Ma) to Cretaceous (86 Ma), exposed in spectacular cliffs along cuestas, mesas, and deep canyons. The rocks in the San Rafael Swell are folded, faulted, jointed, fractured, and uplifted, with deformation likely controlled by a large, blind, basement-involved reverse fault (up on the west side) bounding the east flank of the structure. Beds

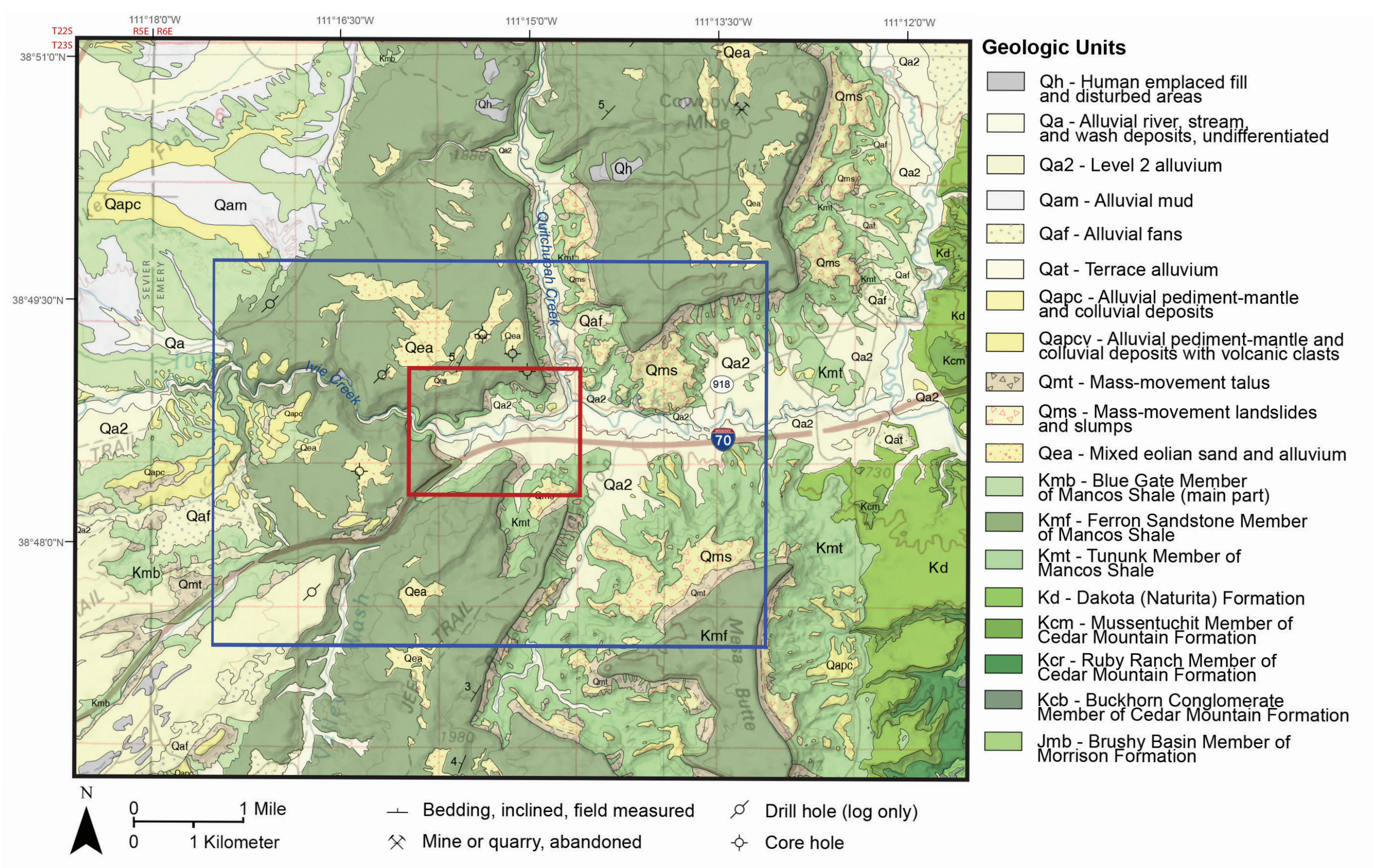

Figure 2. Geologic map of the Ferron Sandstone geosite along Ivie Creek (red box) and surrounding area, westernmost flank of the San Rafael Swell. The blue box represents the area of paleogeographic maps shown on figure 15. Modified from Doelling and Kuehne (2016).

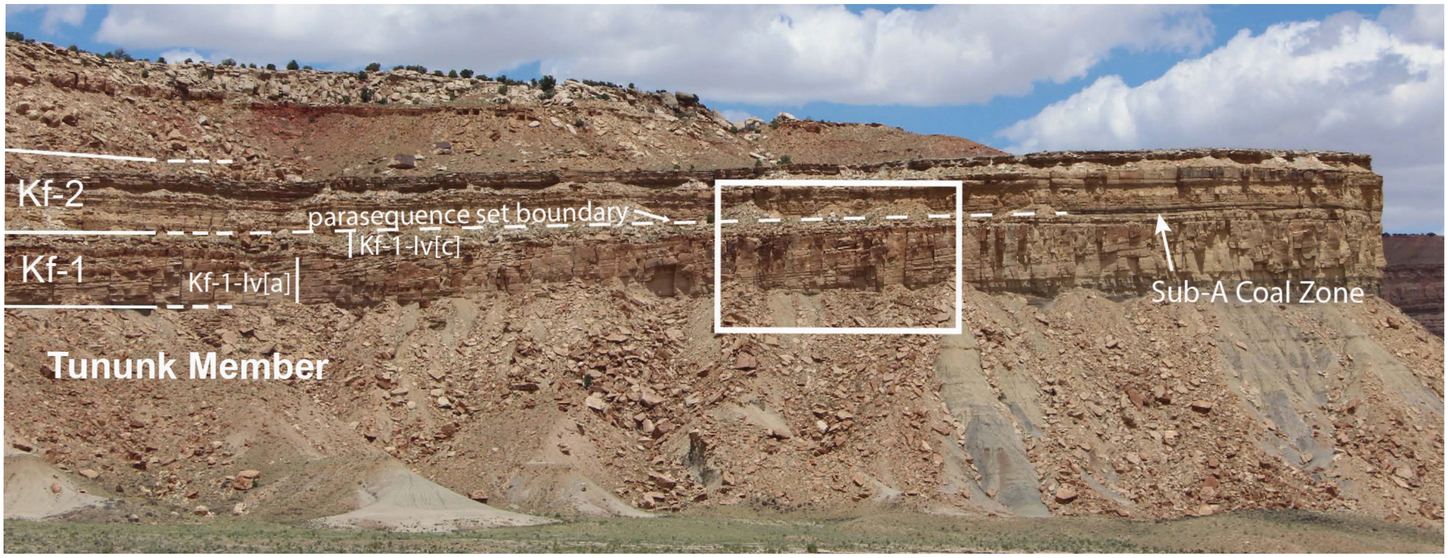

Figure 3. The Upper Cretaceous Ferron Sandstone Member of the Mancos Shale in the Ivie Creek area north of I-70 showing the area well known for the contrasting delta-front architectural styles displayed in the Kf-1 and Kf-2 Ferron parasequence sets (see figure 6); view to the northeast. The Kf-1 has distinctive steeply right- to left-dipping clinoforms representing fluvial-dominated deposition (white box represents location of close-up shown on figure 9A); note that Kf-1 bedsets are also annotated (see figure 9C). The Kf-2 represents a significant change to wave-modified deposition (subtle left-to-right dips) as seen by shoreface, distributary channel, bay, and coastal plain/swamp facies. Modified from Anderson and others (2004). Photograph by Michael Chidsey, Sqwak Productions Inc.

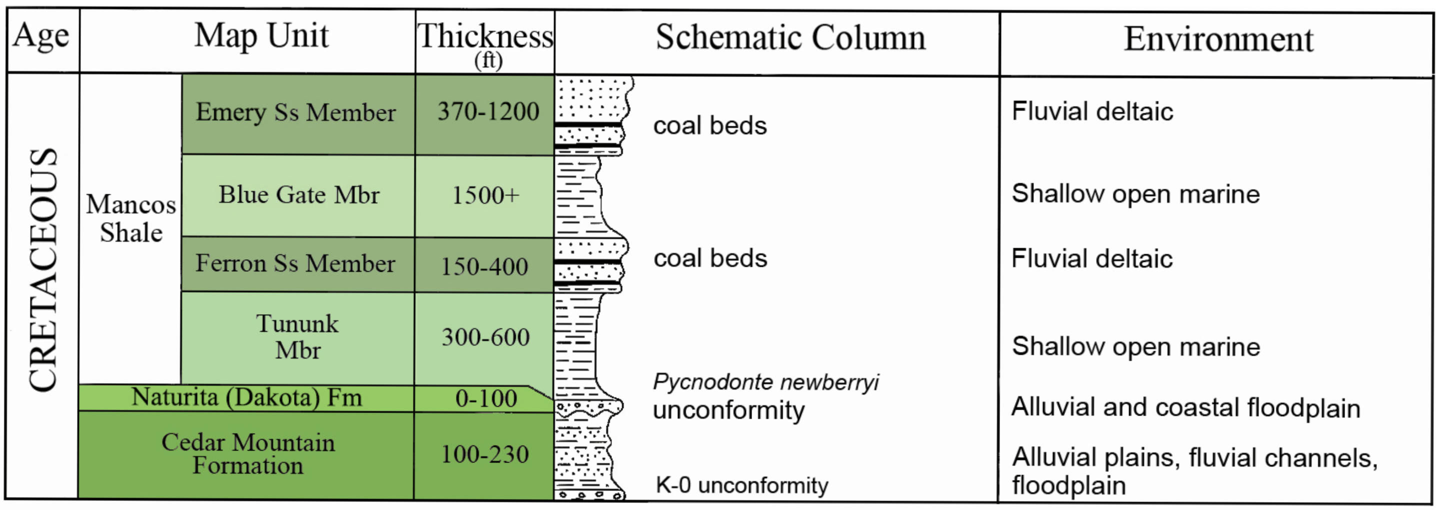

***Figure 4.** Stratigraphic column of exposed Cretaceous rocks along the west flank of the San Rafael Swell, including age, thickness, lithology, weathering profile, and depositional environment. Modified from Hintze and Kowallis (2009).*

in the Ferron outcrop belt dip west from 2° to 12° with only a few minor faults present (Gloyn and others, 2003; Quick and others, 2004). Small to large subsidiary anticlines and synclines are found north to south along the uplift. Ferron field produces natural gas from the Ferron Sandstone in one of these subsidiary structures northeast of the Ivie Creek area; farther north coalbed methane is produced from Ferron coal seams in a series of major fields (Wood and Chidsey, 2015).

Ferron Sandstone

Stratigraphy

The Mancos Shale is divided into four members along the west flank of the San Rafael Swell, which in ascending order are: Tununk, Ferron Sandstone, lower Blue Gate, and Emery Sandstone (figure 4). The Ferron Sandstone and other Upper Cretaceous units pinch out to the east; the Ferron is stratigraphically equivalent to the Juana Lopez Member of the Mancos (figure 5). The Mancos is about 2000 to 2500 feet (600–760 m) thick in the San Rafael Swell (Hintze and Kowallis, 2009 and references therein). It epitomizes deposits from the Cretaceous Interior Seaway on its western margin and the influence of the Sevier orogenic belt in western Utah.

The Ferron Sandstone ranges in thickness from 150 to 400 feet (45–230 m) on the west flank of the San Rafael Swell (Witkind, 1979, 1980, 1988; Weiss and others, 1990; Doelling and others, 2009, 2015; Hintze and Kowallis, 2009 and references therein; Doelling and Kuehne, 2012, 2016). The Ferron is informally divided into lower and upper sections. The lower Ferron consists of two thin-bedded silty intervals called, in ascending order, the Clawson

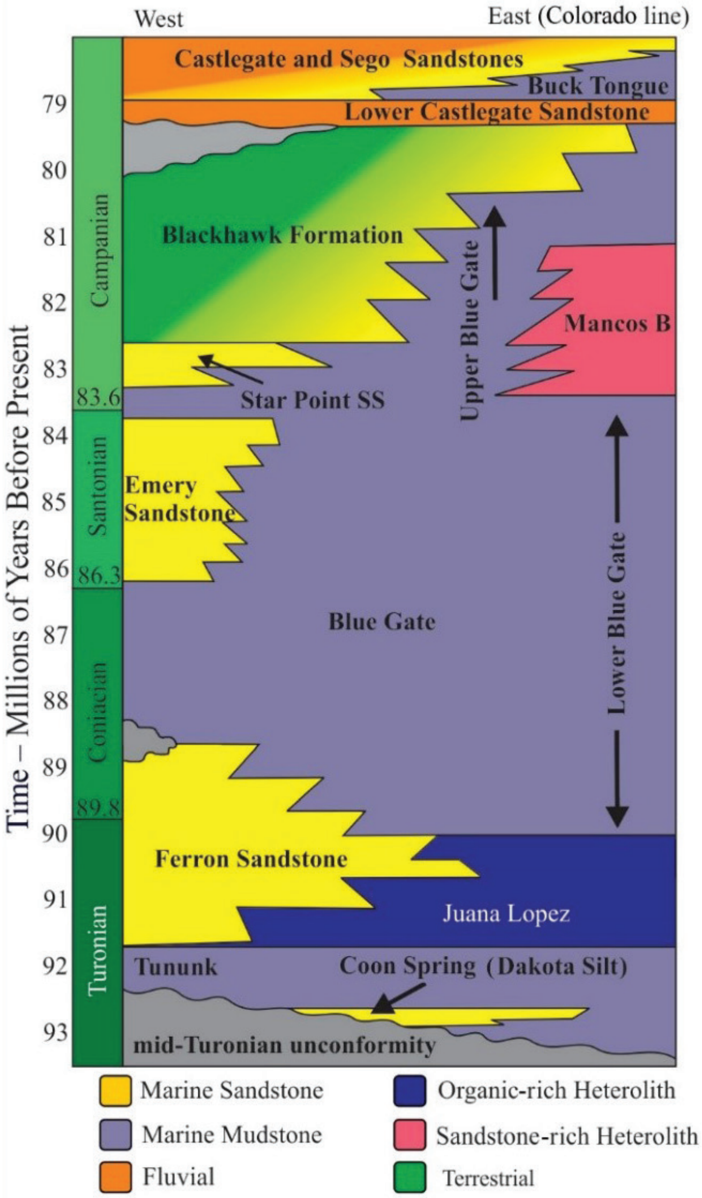

***Figure 5.** Stratigraphic relations of the Mancos Shale, its subunits, and adjacent formations in the Uinta Basin. After Birgenheier and others (2015).*

and Washboard units, that are within the Tununk Member (figure 6). The upper Ferron is a series of major cliff-forming sandstone units described by Ryer (1981, 1991, 2004), Gardner (1993), Barton (1994), Barton and others (2004), Garrison and van den Bergh (2004), Anderson and Ryer (2004), and many other workers. They have been referred to as "delta-front units" (Ryer, 1981), "genetic units" (Gardner, 1993), and "stratigraphic cycles" (Barton, 1994). Anderson and Ryer (2004) defined these units as parasequence sets based on genetically related parasequences within each set, bounded by major flooding surfaces, and they paired the parasequence sets to major coal zones (note: a parasequence is a small-scale, genetically related succession of bedsets bounded by marine flooding surfaces or their correlative surfaces on top and at the bottom [Van Wagoner and others, 1988]). The Ferron parasequence sets create stacks of seaward-stepping, vertically stacked, and landward-stepping packages of rocks, each generally composed of sandstone, siltstone, mudstone, and coal intervals (Gardner and others, 2004). There are nine parasequence sets in the Ferron, which Anderson and Ryer (2004) referred to as Kf-Last Chance through Kf-8: "Kf" for Cretaceous Ferron Sandstone, followed by the first, second, third, etc. (Kf-LC, Kf-1, Kf-2…) (figures 6 and 7); we use this nomenclature. The parasequences in each set include an abbreviation for the location followed by the letter "a" for the lowermost unit (e.g., Kf-2-Iv-a, Kf-2-Iv-b, and Kf-2-Iv-c parasequences, where Iv stands for Ivie Creek [figure 7]) (Anderson and Ryer, 2004). Bedsets are recognizable on outcrop as distinct and mappable genetic units but unrelated to flooding surfaces (Van Wagoner and others, 1990; Anderson and Ryer, 2004). The nomenclature used for the bedsets in the Ivie Creek area are the Kf-1-Iv[a] and Kf-1-Iv[c] (Anderson and Ryer, 2004).

Lithology

The Ferron Sandstone consists of yellow-gray, light-brown, to white sandstone and siltstone, gray sandy to black carbonaceous shale, and coal. Sandstone (quartz arenites to quartzo-feldspathic arenites) is very fine to coarse grained, poor to moderately sorted, subrounded to angular, and cemented with calcite, dolomite, or iron oxide (Jarrard and others, 2004). Sedimentary structures in the sandstone that determine facies include ripples, channel scours, soft-sediment deformation, cross-stratification (trough, swaley, and hummocky), and planar beds. Many beds contain rooted zones, plant fossils, and a large variety of trace fossils from burrows to dinosaur tracks. Fauna such as bivalves and gastropods are common; some are so enriched with shells that the rocks are considered coquinas. Bedding in sandstone is thin or lenticular to massive, forming vertical cliffs, whereas siltstone, shale, and coal create recesses and slopes. Coal beds are persistent but lenticular and commonly burned (due to spontaneous combustion or lightning strikes), creating "clinker" zones with red oxidation staining.

Paleogeography and Facies

The Ferron Sandstone was deposited in fluvial-dominated and wave-modified deltaic environments that prograded into the Cretaceous Interior Seaway (figure 8). Sediment was transported by east- to northeast-flowing rivers and streams that originated in the nearby Sevier orogenic belt. The alluvial to lower delta or coastal plain of the Ferron contained meandering streams (creating single- and multi-storied complexes), swamps and peat bogs, distributary channels, levees, crevasse spays/overbanks, and bays. Deltaic facies varied and were primarily controlled by sediment input and accommodation space. Wave energy at the coastline influenced the redistribution of these sediments and fluctuations in sea level had profound effects on the accumulating sediment package. Sediment supply was high during early Ferron deposition resulting in seaward-prograding fluvial-dominated conditions that

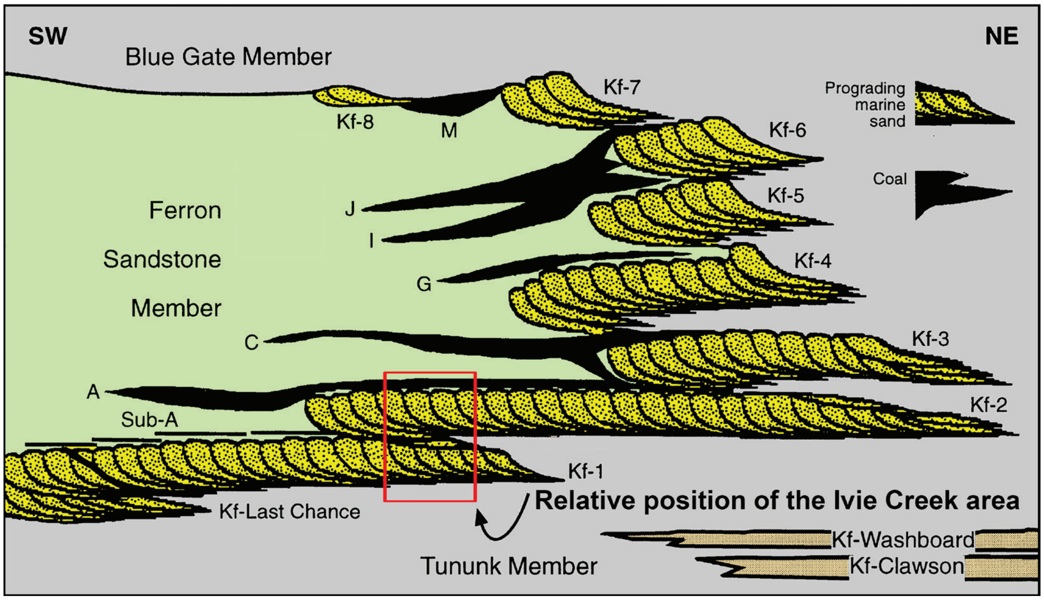

Figure 6. *Ferron Sandstone parasequence sets. There are nine parasequence sets in the Ferron referred to as Kf-Last Chance through Kf-8: "Kf" for Cretaceous Ferron Sandstone, followed by the first, second, third, etc. (Kf-LC, Kf-1, Kf-2…). The system of letter designations for major coal beds of Lupton (1916) is still followed. The green area represents coastal- and alluvial-plain deposits. After Ryer (1991), Anderson and others (1997), and Anderson and Ryer (2004).*

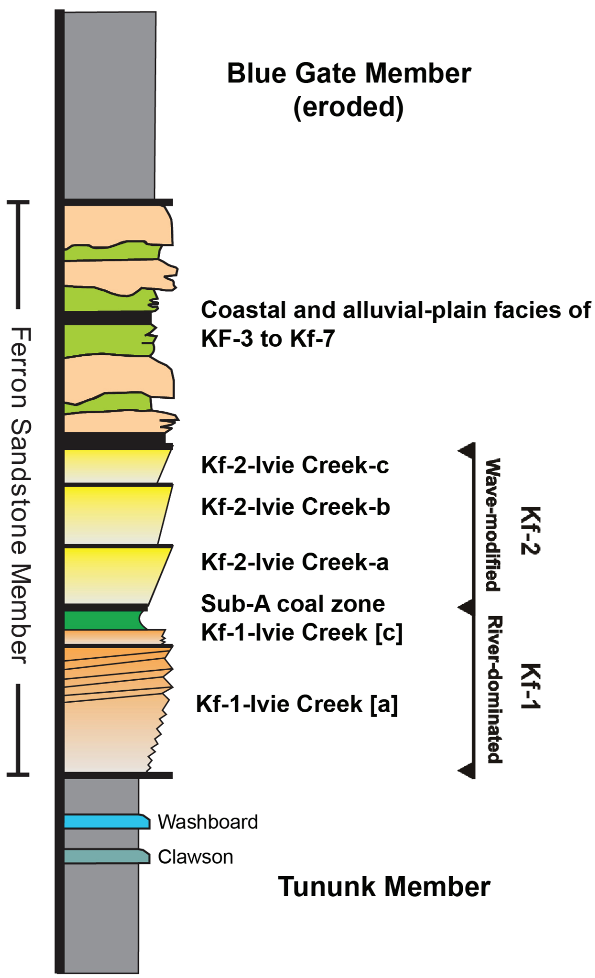

Figure 7. *Ivie Creek area Ferron stratigraphy including parasequence sets, parasequences, and named bedsets. Gray = marine shale, blue and gray-blue = marine siltstone, light orange and yellow = shoreface sandstone, green = bay-fill mudstone and siltstone, black = coal, grass green = coastal and alluvial plain siltstone and mudstone, tan = fluvial sandstone. After Anderson and others (2004).*

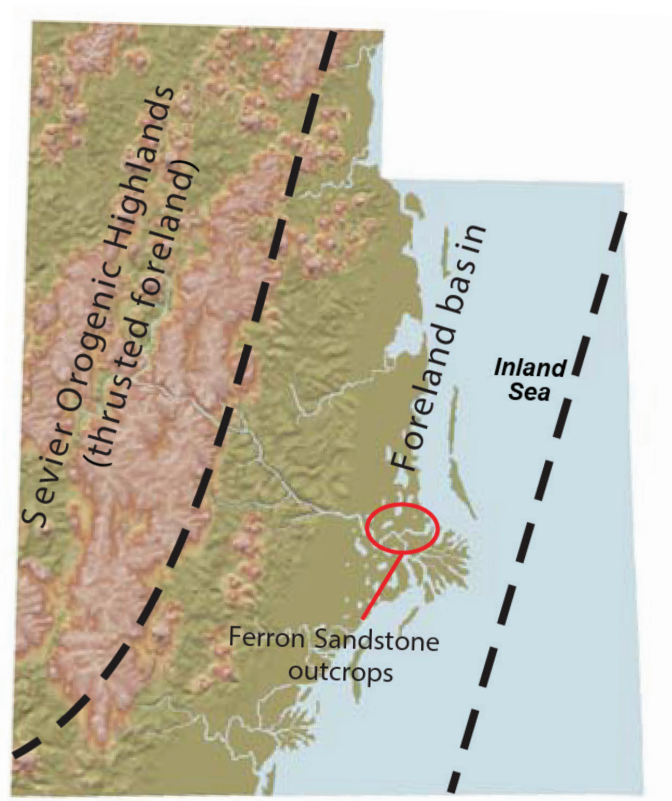

Figure 8. *Paleogeographic map of Utah about 85 Ma. Modified from Utah Geological Survey (1998).*

created lobate deltas consisting of delta-front deposits, distributary channels, splay complexes, and interdistributary bays. Later, conditions changed at Ivie Creek to wave-dominated or wave-modified deltaic deposition forming cuspate deltas that grade laterally into strandplains and barrier islands. Facies associated with wave-dominated or wave-modified deltas consist of prodelta deposits; lower, middle, and upper shoreface; foreshore; distributary channels; and distributary-mouth bars. The strandplains and barrier island facies include washover fans, lagoons, bays, and tidal inlets and associated flood-tidal deltas (Ryer, 1991; Ryer and Anderson, 2004). Elongate silty sand bodies, such as the Clawson and Washboard units (figure 6), represent offshore bars produced by longshore drift or sand plumes/turbidites that accumulated on the shallow-marine shelf to the east.

Landslides and Slumps

Landslides and slumps can occur when erosion oversteepens slopes and undercuts resistant bedrock. The Ferron Sandstone is highly jointed and underlain by shale beds of the Tununk Member of the Mancos Shale and thus very susceptible to rockfalls (figures 2 and 3). The Tununk contains significant amounts of swelling clay, particularly bentonite/smectite in volcanic ash beds. These unstable soft units cause joints in the overlying Ferron to further enlarge. Large Pleistocene-(?)-age (1,800,000 to 12,000 years ago) landslides can be observed along the south-facing slopes of the Ferron escarpment, east of Quitchupah Creek along the I-70 route (figure 2).

Emery Coalfield

The Emery coalfield is located along the west flank of the San Rafael Swell from the Limestone and Coal Cliffs continuing into the subsurface under Castle Valley and Wasatch Plateau (figure 1). The coalfield consists of 13 coal beds contained in the Ferron Sandstone that are given letter designations from A to M in ascending order based on Lupton's (1916) Ferron description system (figure 6); this system is still used by geologists working the Ferron over 100 years later.

Ferron coal beds are lenticular, which has limited their commercial development. Seven seams exceed 4 feet (1.2 m) in thickness; the maximum coal seam thickness is 30 feet (9 m) (Doelling, 1972). However, several seams coalesce to form a single, thicker coal with at least one at 25 feet (8 m) thick (Doelling, 1972, 1976). Coal beds A (exposed in the Ivie Creek area), C, I, and M are the most important (figure 6), and several are stratigraphically close to each other. Analyses of these beds indicate an overall high-volatile C bituminous coal (Doelling, 1972, 1976). Estimated available, in-place coal resources for the southern Emery coalfield are 2.2 billion short tons, based on coal beds greater than 4 feet (1.2 m) thick and less than 3000 feet (900 m) deep, of which about 500 million short tons are recoverable (Quick and others, 2004). Presently, one coal mine is extracting coal from the coalfield from the I seam.

SEQUENCE STRATIGRAPHY, FACIES, AND PALEOGEOGRAPHY OF THE FERRON SANDSTONE IN THE IVIE CREEK AREA

Kf-1 Parasequence Set

The Kf-1 parasequence set consists of river-dominated deltaic deposits that prograded from the south-southeast to the north-northwest, proximal to distal, as delta lobes across the Ivie Creek area. Progradation was parallel or onshore to the northwest-southeast regional shoreline trend. The Ivie Creek area is best known for its distinctive, steeply inclined bedsets or clinoforms dipping west-northwest 10° to 15° (figures 3 and 9). These unique sedimentary features have been the subject of major academic and industry studies and are incorporated in hydrocarbon reservoir simulation models (Anderson and others, 1997, 2004; Mattson, 1997; Forster and others, 2004; Jarrard and others, 2004; Mattson and Chan, 2004; Enge and Howell, 2010; Deveugle and others, 2011; Graham and others, 2013, 2015a, 2015b).

The Kf-1 parasequence set lies conformably upon the Tununk Member. In the Ivie Creek area the Kf-1 parasequence set consists of only one parasequence, Kf-1-Ivie Creek (Iv), with two bedsets referred to here as Kf-1-Ivie Creek[a] and Kf-1-Ivie Creek[c] (figures 3 and 7), that represent the two delta lobes sourced from a common point (Anderson and Ryer, 2004).

Kf-1-Iv[a] Bedset

The Kf-1-Iv[a] bedset can be traced on outcrop from landward to seaward pinchout for about 1.5 miles (2.4 km). Delta-front sandstones of a modified Gilbert delta make up these deposits, which change from proximal to distal as they pass from east to west across the Ivie Creek area. This bedset is a fan-like deposit that thickens to the east and was deposited into an area having minimal wave influence; therefore, the primary beds are preserved as clinoforms (figures 3 and 9). The clinoforms change characteristics from the shallower water, more proximal locations, to the deeper water, more distal locations. They thin rapidly to the west, as well as thin to the more typical seaward direction of north. This is anomalous for Ferron delta lobes.

The clinoforms are classified into four facies: proximal, medial, distal, and cap (figures 10 through 14) (Anderson and others, 1997, 2004; Mattson, 1997; Mattson and Chan, 2004). Clinoform facies are based on grain size, sedimentary structures, bedding thickness, inclination angle, and stratigraphic position.

- Clinoform proximal facies is sandstone, mostly fine to medium grained. The chief sedimentary structure is low-angle cross-stratification with minor horizontal and trough cross-stratification and rare hummocky bedding (figure 11). This facies is dominantly thick- to medium-bedded, well to moderately indurated.

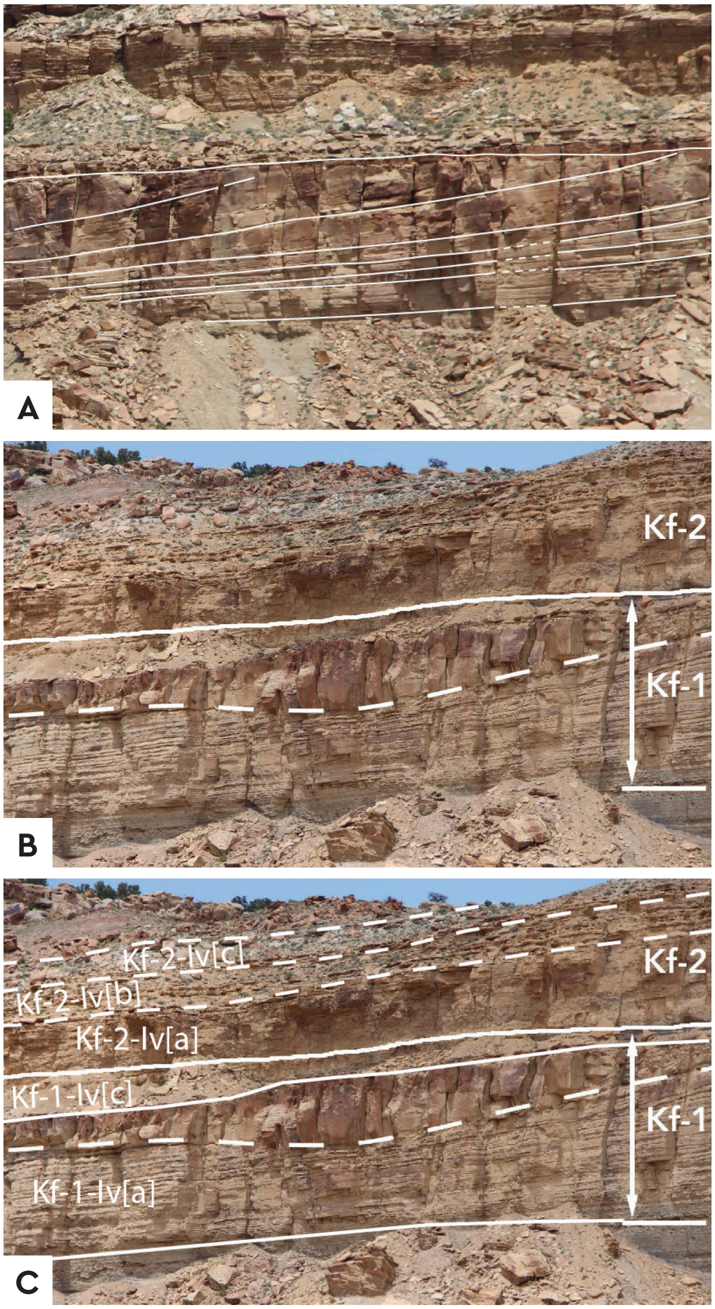

*Figure 9. Close-up photos of depositional features and stratigraphy of the Ferron Sandstone in the Ivie Creek area. **A** – Clinoforms in the Kf-1defined by pronounced bounding surfaces (see white box on figure 3 for location of figure 9A). **B** – Distributary channel cut into clinoforms within the Kf-1 parasequence set. The Kf-2 parasequence set above shows relatively thin bedding. **C** – Same photo as B annotated with Kf-1 bedsets and Kf-2 parasequences (see figure 7). Modified from Anderson and others (2004). Photographs by Michael Chidsey, Sqwak Productions Inc.*

Clinoform proximal facies is interpreted to be the highest energy and most proximal to the sediment supply. The steep inclinations are interpreted to represent deposition into a relatively localized deep portion of an open bay environment.

- Clinoform medial facies is dominantly sandstone with about 5% shale (figure 12). The sandstone is primarily fine grained with slightly more fine- to very fine grains than fine to medium grains. Horizontal beds dominate with some rippled, trough, and low-angle cross-stratified beds (figure 13). Bed thickness ranges from laminated to very thick, but most beds are medium. Clinoform medial facies is generally transitional between end members clinoform proximal and distal.

- Clinoform distal facies is sandstone (sometimes silty) and about 10% shale (figure 14). The sandstone grain size is dominantly fine to very fine grained, with considerable variation. Sedimentary structures in clinoform distal facies are chiefly horizontal laminations and ripples in medium to thin beds (figure 13). Clinoform distal facies is gradational with clinoform medial facies and represents the deepest water and lowest energy deposits within the clinoform. It can be traced distally into prodelta to offshore facies.

- Clinoform cap facies is sandstone, generally very fine to fine grained. The beds are horizontal, with some trough and low-angle cross-stratification in thick to medium beds (figure 11). The clinoform cap facies is interpreted to represent an eroded and reworked delta top.

The deposits of the Kf-1-Iv[a] bedset accumulated on an arcuate delta lobe that prograded into a deeper-water, fully marine bay. The main delta, located to the east and northeast, created a protected embayment in the northwest part of the Ivie Creek area (Anderson and others, 1997). The Kf-1 clinoforms represent deposition into the embayment fed by river channels from the southeast (figure 15A) (Anderson and others, 2004). The distributary complexes/delta front, shallow marine, and deep marine environments produced the clinoform proximal, medial, and distal facies, respectively.

Kf-1-Iv[c] Bedset

The Kf-1-Iv[c] bedset is sand rich and varies in thickness within the Ivie Creek area. In contrast to the Kf-1-Iv[a], delta-front, subtle clinoforms of the lower part of the bedset dip less than 5°. This sand-rich bedset thins in both up-depositional-dip and down-depositional-dip directions due to lateral facies changes. A major flooding surface is at the top of the Sub-A coal zone (figure 3 and 16) and corresponds to the boundary with the overlying Kf-2 parasequence set (figures 6 and 7).

The lower section of the Kf-1-Iv[c] laps onto the more distal parts of the Kf-1-Iv[a] in the western part of the area and represents the distal part of another delta lobe, probably sourced from the southwest. This lower section may be completely absent in some locations as a result of erosion and/or non-deposition. It also includes a distributary channel sandstone body, lenticular in cross section, deposited by a northwesterly flowing stream (figures 9B and 9C).

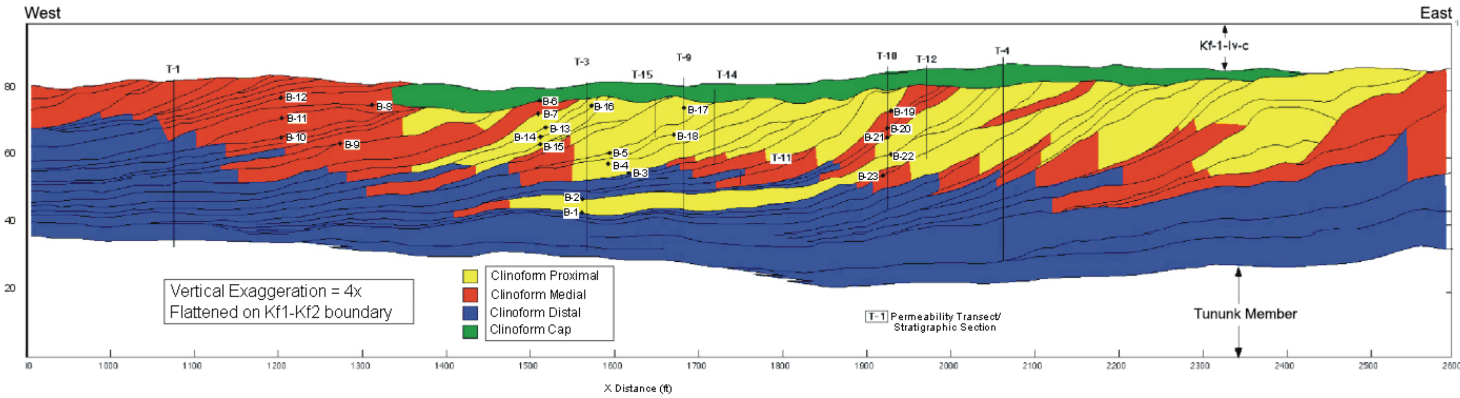

Figure 10. Scaled cross section, oriented west to east, of the Kf-1-Iv[a] bedset from the Ivie Creek amphitheater based on a portion of interpreted photomosaics showing clinoform facies distribution and bounding layer measurement locations (modified from Mattson, 1997; for data and detailed descriptions see Anderson and others, 2004). Figure 3, Kf-1 captures approximately the same area as the cross section. The artificially abrupt end of the medial facies is representative of most of the contacts portrayed between proximal, medial, and distal clinoform facies in this study because polygonal packages of rock are necessary for reservoir modeling and simulation. In reality, the transition from medial to distal (as well as medial to proximal) is gradational.

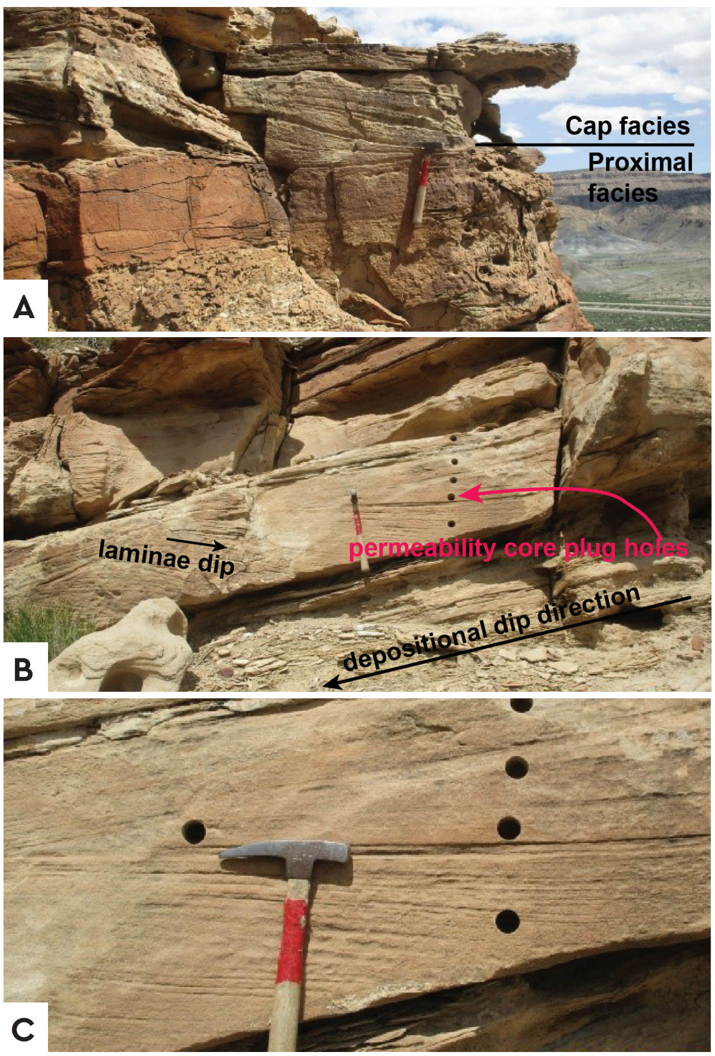

Figure 11. *Kf-1-Iv[a] bedset in the Ivie Creek amphitheater.* ***A*** *– Clinoform cap facies with trough cross-bedding exposed at the top of the photo. The head of the hammer is within the cap facies above a hard, reddish bed within the underlying clinoform proximal facies.* ***B*** *– Low-angle cross-beds are the primary sedimentary structure in the clinoform proximal facies. The general direction of the depositional dip is from right to left. Note the gentle up depositional dip inclinations of many laminae in the bed below the hammer. Holes in the rock are from outcrop permeability plugs taken in the unit.* ***C*** *– Close-up of low-angle trough cross-bedding in the clinoform proximal facies.*

Figure 12. *Clinoform medial facies in the Kf-1-Iv[a] bedset. The facies is dominated by horizontal bedding as found in the thicker bedded units. The recessive parts of the outcrop are typically ripple laminated and finer grained than the resistant sandstone beds.*

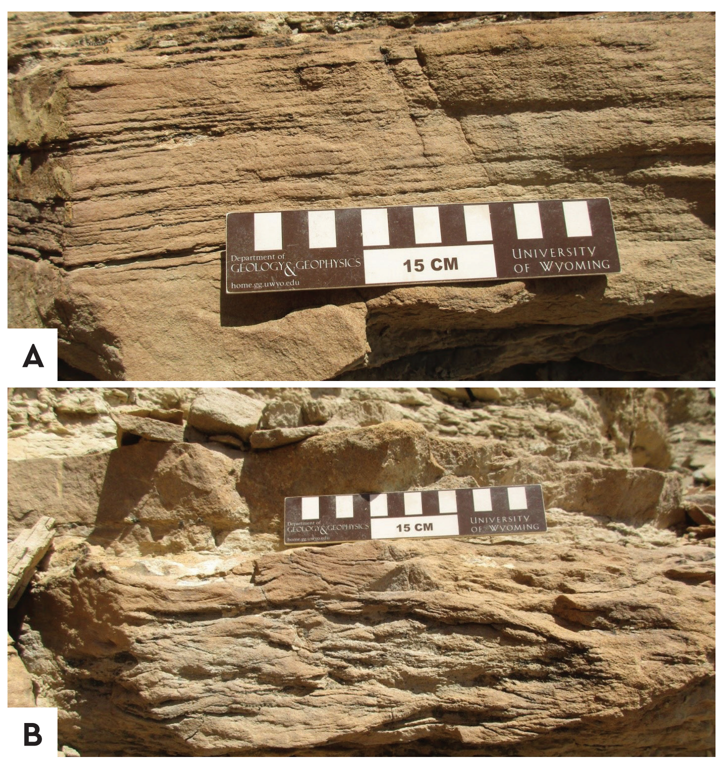

Figure 13. *Clinoform medial/distal facies showing close-up of* ***(A)*** *thin horizontal bedding and* ***(B)*** *ripple laminations.*

Figure 14. Clinoform distal facies in the Kf-1-Iv[a] bedset. The base of the Ferron Sandstone is exposed at the base of the interbedded sandstone, siltstone, and mudstone. Ripple and planar bedding are common; burrowing is sparse.

The uppermost section of the Kf-1-Iv[c] is continuous across the entire Ivie Creek area and has wave and fluvial influences (figure 3). It is capped by unidirectional, trough cross-bedded sandstone. The Kf-1-Iv[c] contains slump or rotated block features near the mouth of Ivie Creek Canyon. An excellent study of these features is presented in Braathen and others (2018).

In the Ivie Creek amphitheater, above the basal cross-bedded sandstone, are 10 to 15 feet (3–5 m) of coarsening- and bed-thickening-upward, brackish-water/bay-fill deposits consisting of carbonaceous mudstone; thin, rippled to horizontally laminated, sparsely to intensely burrowed sandstone and siltstone; fossiliferous mudstone to sandstone; oyster coquina; and ash-rich coal (figures 16 and 17). The presence of a brackish-water fauna (*Crassostrea, Corbula securis, Lucinid, Caryo corbulais*, aff. *Varia*, and *Serrthid*) is the distinguishing characteristic of this facies. This fauna is present within "dirty" sandstone, siltstone, mudstone, and carbonaceous mudstone. Oyster coquinas commonly are found within the brackish-water/bay facies (figure 17B). Typically, the rocks are rich in carbonaceous debris. The uppermost, carbonaceous mudstone or ash-rich coal is the Sub-A coal zone (figures 3 and 16). The coal zone (swamp [paludal] facies) shows considerable variation in thickness (0 to 1 foot [0–0.3 m]) and intertongues with underlying bay deposits. The paludal facies is commonly underlain and/or overlain by coastal plain facies (the top is frequently rooted) and may grade into shoreface deposits below.

At the mouth of Ivie Creek Canyon, the Kf-1-Iv[c] bedset is anomalously thick due to large slump features or rotated blocks that formed shortly after deposition. Failure of the rotated blocks is consistently toward the north to northwest, the direction that the delta lobe appears to have prograded.

KF-2 PARASEQUENCE SET

The Ferron sediment source switched from the east-southeast to the west going from Kf-1 to Kf-2 deposition. The Kf-2 parasequence set represents wave-modified deltaic deposits that generally coarsen east to west, consisting of shoreface and distributary complex facies gently inclined (< 3°) to the east (figure 3). These relatively clean, sand-rich deposits accumulated along a local north-south shoreline trend defined by a landward pinchout of marine shoreface facies (observed in the I-70 roadcut just to the west of the Ivie Creek area and farther east in Ivie Creek), as opposed to the more common regional northwest-southeast shoreline trend recognized in other Ferron cycles above and below Kf-2.

The Kf-2 parasequence set contains three parasequences: the Kf-2-Iv-a, Kf-2-Iv-b, and Kf-2-Iv-c (figures 7, 9B, and 9C). These parasequences show less lateral variation in lithofacies than the Kf-1 bedsets due to greater wave influence (reworking). Within the Ivie Creek area, there is also little lateral variation in thickness of sand-rich Kf-2 facies, even when lateral change occurs from one depositional subfacies to another. Kf-2 cycles accumulated in sheet-like bodies that pinchout laterally, forming a wedge due to wave-action along the delta front. The contact between Kf-1 and Kf-2 is generally drawn at the top of the Sub-A coal zone in the Ivie Creek area (figure 3). The top of Kf-2 lies near the top of the C coal and includes all of the A coal zone and delta-plain strata which separate the A and C coal zones (figure 6).

In general, the western part of the Ivie Creek area, east- to northeast-flowing distributary channels deposited large amounts of sand in north-south-trending distributary-mouth bars. Shallow- to moderate-depth marine conditions existed in the eastern part of the area. An uncommon transition from shoreface, to bay, to coastal plain/swamp occurred during the late stage of Kf-2 deposition (Anderson and others, 2004). Above the Kf-2 parasequence set are coastal-plain and alluvial-plain facies which represent the landward equivalents of the marine portions of Kf-3 through Kf-7 parasequence sets.

The wave-modified parasequences of the Kf-2 parasequence set consist predominantly of shoreface, distributary complex, and coastal plain/swamp facies.

Shoreface

The shoreface facies consists of a relatively steeply dipping zone (compared to the shelf/slope) from the subaerial beach to a poorly defined point where the slope flattens on the sea floor. Wave energy is sufficient to move sand-size grains in this zone. At the seaward end of the shoreface is the prodelta facies. This mud-dominated facies represents the area just seaward of the dominant influence of wave energy and typically interfingers with the lower shoreface defined below.

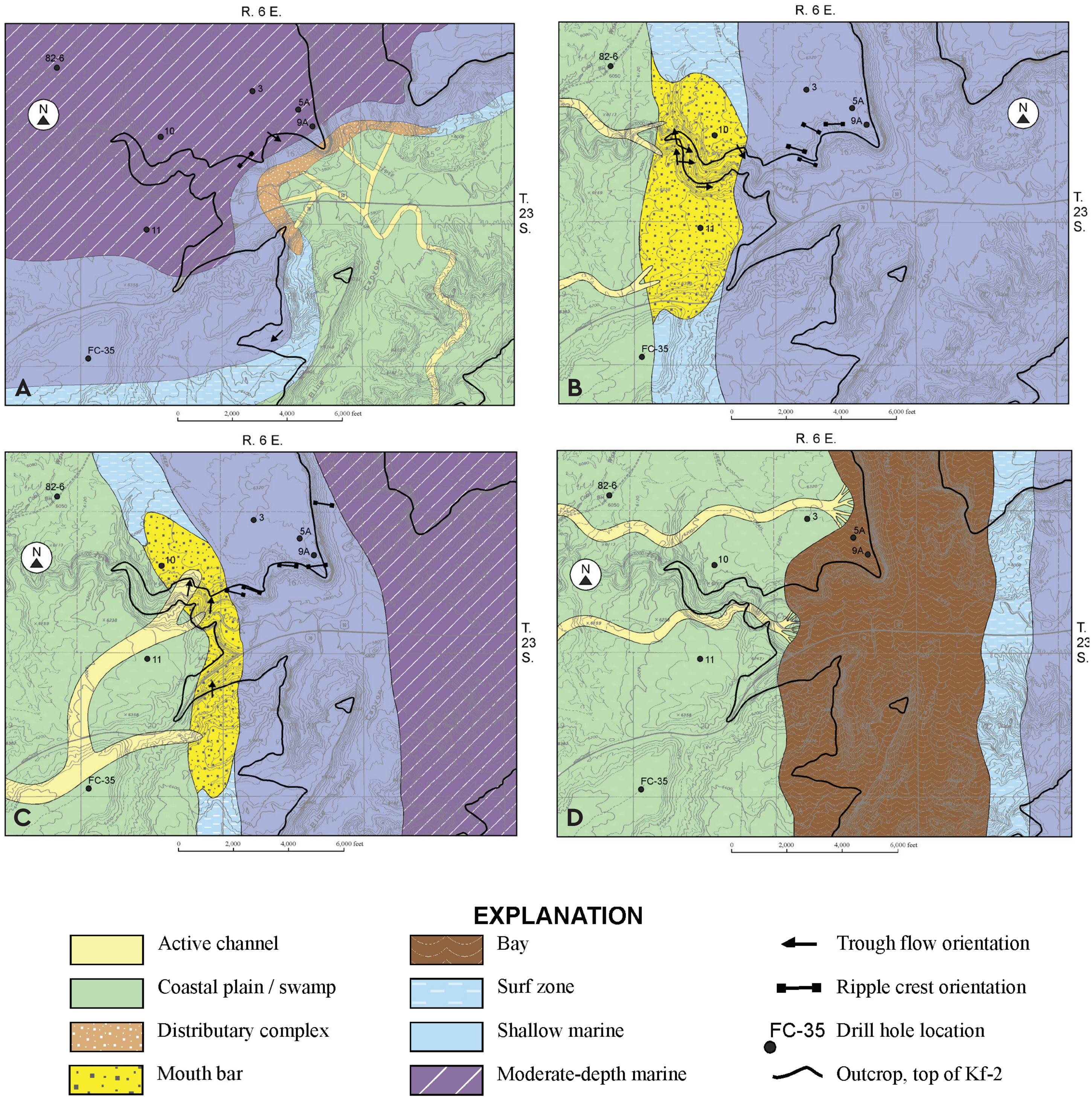

Figure 15. Paleogeographic interpretations of the Ferron Sandstone in the Ivie Creek area. A – Kf-1-Iv[a] bedset showing river channels flowing from the south and southeast that deposited sands into a protected embayment in the northwest part of the area. B – Kf-2-Iv-a parasequence showing a large distributary-mouth bar indicating the shoreline was probably not too far to the west and the shoreline was now primarily oriented north-south. C – Kf-2-Iv-b parasequence showing the continuation of the north-south-oriented shoreline where the landward area is dominated by distributary-mouth bar and distributary channels associated with a wave-modified delta which gives way seaward to shallow marine facies. D – Kf-2-Iv-c parasequence showing the north-south-oriented shoreline now farther east and a large bay with associated distributary channels and bay-head deltas. Late stages of this parasequence (not shown) include the development of large meander belt and channel system cut into coastal-plain deposits at the top of the Kf-2-Iv-c. See blue box on figure 2 for location of these maps. Modified from Anderson and others (2004).

The lower shoreface facies consists of thinly interbedded shale to siltstone and very fine to fine-grained sandstone having wave ripples to horizontal laminations; hummocky stratification is common (figure 16). Burrowing is generally found on the top of thin sandstone beds and the shale is often bioturbated.

Middle shoreface facies consists of very fine to fine-grained sandstone composed of hummocky, swaley, and planar laminations with minor ripple laminations (figure 18). This facies is generally thick, representing 50% or more of the shoreface sequence. The most common burrow types are *Thalassinoides* and *Ophiomorpha* with numerous other shallow marine traces and the amount of burrowing varies from moderately to intensely bioturbated.

Upper shoreface facies is characterized by fine- to medium-grained, multidirectional to bimodal, cross-stratified sandstone, in sets that are occasionally separated by planar laminations, and that is generally moderately to well sorted (figure 19). This facies is about 10 feet (3 m) thick, but greater in the vicinities of the landward pinchouts of the parasequences where the upper shoreface may reach 20 feet (6 m) in thickness. The upper shoreface facies is slightly to moderately burrowed and *Ophiomorpha* is the most common trace fossil.

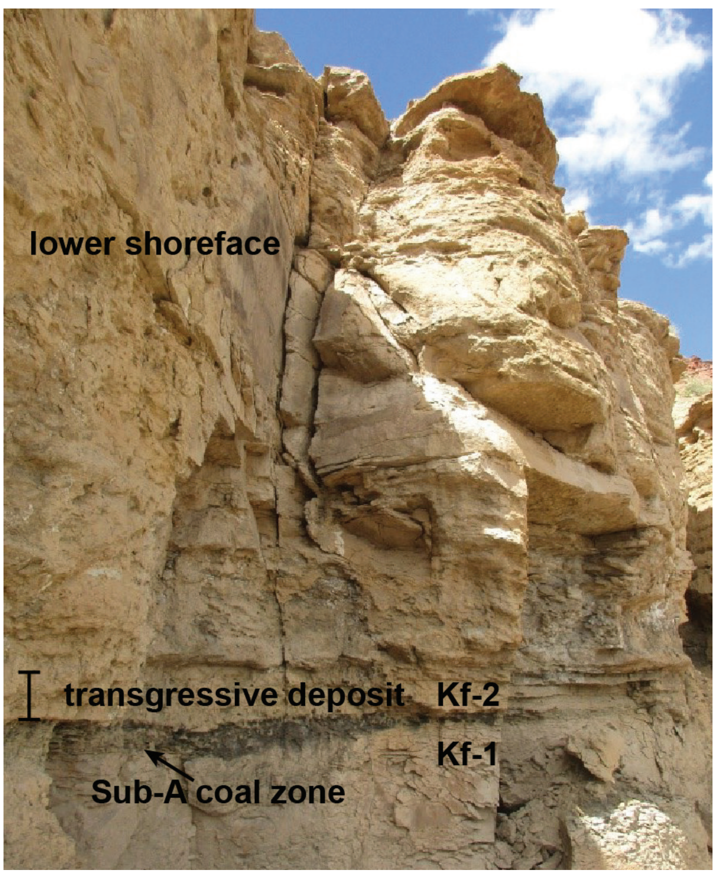

Figure 16. Lower shoreface facies found above the Kf-1/Kf-2 parasequence set boundary in the Ivie Creek area. Typically, the facies consists of interbedded very fine grained sandstone, siltstone, and shale, and grain size coarsens and beds thicken upward. This is stratigraphically the lowest facies in the wave-modified delta deposits in the area.

The foreshore facies consists of fine- to medium-grained sandstone with planar to inclined bedding, slightly to intensely burrowing, and is sometimes rooted (figure 19). This facies is sometimes absent at the top of the shoreface sequence due to erosion, but when present ranges up to a few feet in thickness.

Distributary Complex

The distributary complex facies is subdivided into distributary channel and distributary mouth-bar in the Ivie Creek area (figures 9B and 9C shows an example in the Kf-1). This facies is commonly characterized by the complicated geometry of cross-bedding and large-scale bounding surfaces that are related to cut-and-fill processes, in contrast to the flat to very gently inclined surfaces of the lower delta-front.

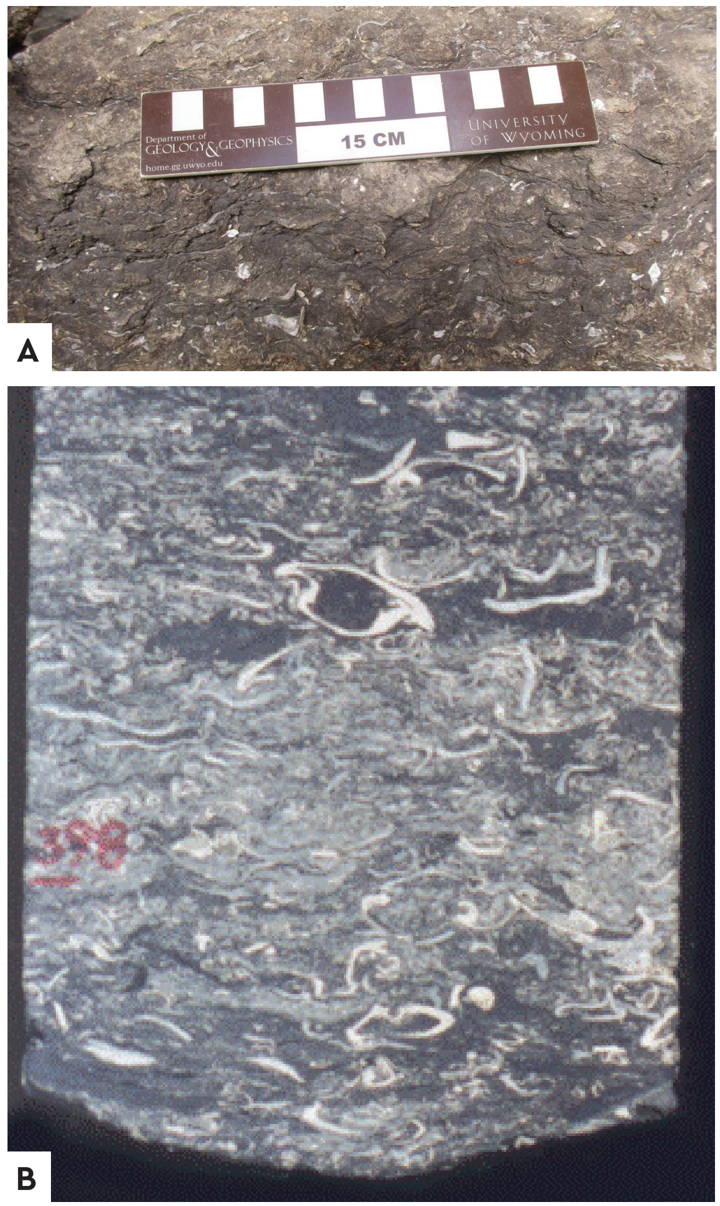

Figure 17. Brackish water/bay fill facies in the Kf-2-Iv-c in the Ivie Creek amphitheater. A – Carbonaceous mudstone, siltstone, and sandstone, intensely burrowed. B – Oyster coquina containing brackish-water fauna within carbonaceous mudstone. Core from UGS drill hole Ivie Creek no. 11 (see figure 15 for drill-hole location).

Figure 18. Middle shoreface facies in parasequence Kf-2-Iv-a usually forms a vertical cliff and consists of very fine to fine-grained sandstone that is horizontally bedded and often moderately burrowed to bioturbated. Note the horizontal bedding indicated by the light horizontal lineations in the photograph.

The distributary channel facies is common in river-dominated delta-front deposits and is also found within the wave-modified shoreline deposits of the Ivie Creek area (figures 9B and 9C). It is characterized by channels with high height-to-width ratios and unidirectional trough cross-stratified and current ripple cross-laminated deposits. Channel fills are sandstone-dominated, but heterolithic channel fills are also found. In sand-filled channels, the grain size is commonly coarser than the surrounding delta-front or shoreface and fines upward. Troughs in the channel base generally contain mud rip-up clasts, woody fragments, and rare shark teeth. This facies grades seaward into the distributary-mouth bar facies.

The distributary-mouth bar facies is found in the upper parts of delta-front sequences of Kf-2 and is associated with distributary channel deposits. This facies is characterized by fine-grained, or coarser, trough-cross-stratified sandstone, with moderate to intense burrowing in areas that had lower flow velocities and decreased sedimentation rate; some intervals between trough sets are completely bioturbated; *Ophiomorpha* is common. Paleoflow directions show a strong offshore component with the amount of scatter increasing with increased wave influence and distance from the distributary channel. Traced laterally and seaward, the facies commonly grades into middle shoreface or lower delta-front facies (fluvial-dominated shoreline).

Coastal Plain/Swamp

The coastal plain/swamp facies is represented by a sequence of non-marine rocks dominated by mudstone, carbonaceous mudstone, and siltstone with minor sandstone. Coal is commonly interstratified with the other rock types. These rocks are interpreted as inter-fluvial environments along a low-gradient coast.

Kf-2-Iv-a Parasequence

The oldest parasequence of the Kf-2 parasequence set in the Ivie Creek area is the Kf-2-Iv-a. The Kf-2-Iv-a thickens to 50 feet (15 m) westward across the area. The base of the Kf-2-Iv-a parasequence consists of interbedded sand and minor shale deposited in prodelta to lower-shoreface environments (figures 9C and 16). These deposits are thin, typically less than 10 feet (3 m) thick. The

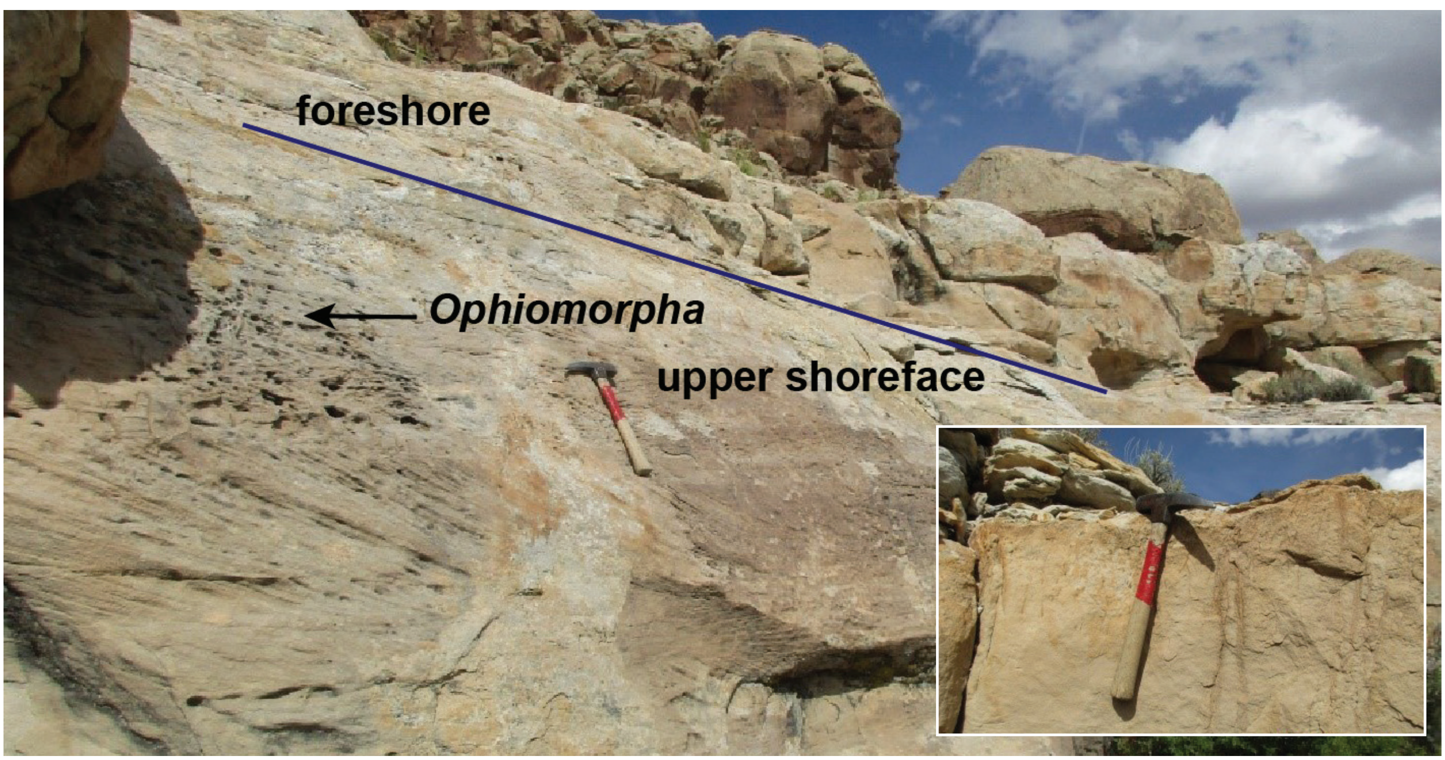

Figure 19. Upper shoreface and foreshore facies in parasequence Kf-2-Iv-C, exposed in Ivie Creek Canyon. Note the cross-beds in the base of the upper shoreface, typical of this facies. ***Ophiomorpha*** *is common in both facies. The foreshore bedding is horizontal to sometimes slightly inclined. Inset shows vertical rootlets penetrating the facies and originating from the overlying A coal.*

prodelta and lower-shoreface deposits are overlain by a 0.5- to 1-foot-thick (0.2–0.3 m) zone of highly carbonaceous to coaly sandstone which grades into 20 to 30 feet (6–9 m) of very fine grained, silty, and slightly carbonaceous sandstone representing a middle shoreface environment (figure 18). The middle-shoreface unit is moderately to intensely bioturbated.

Near the mouth of Ivie Creek Canyon, the Kf-2-Iv-a parasequence consists of a thin sequence of lower shoreface heteroliths overlain by about 28 feet (8 m) of middle-shoreface deposits (figure 18). The westernmost exposure of Kf-2-Iv-a is in Ivie Creek Canyon where the facies is a distributary-mouth bar. This indicates that the shoreline was probably not too far to the west. Utah Geological Survey (UGS) drill hole Ivie Creek no. 11 contained distributary-mouth bar facies of the unit (figure 15B), but interpretation of drill holes farther west indicate the shoreline has been crossed and only non-marine deposits are present. The shoreline orientation of the Kf-2-Iv-a parasequence was primarily north-south (figure 15B). Possible foreshore deposits are near the last outcrop of the Kf-2-Iv-a in the bottom of Ivie Creek.

Kf-2-Iv-b Parasequence

In the Ivie Creek amphitheater, the Kf-2-Iv-b parasequence was deposited in a middle- shoreface environment. Kf-2-Iv-b exhibits gently seaward-inclined beds that are very conspicuous when viewed from west to east along the outcrop. The Kf-2-Iv-b parasequence consists of horizontally bedded, silty sandstone at the base (middle shoreface) (figure 9C) and unidirectional, trough cross-bedded sandstone at the top (distributary channel to mouth-bar deposits). These units are moderately to intensely bioturbated.

Along Ivie Creek Canyon, Kf-2-Iv-b is dominantly unidirectional, trough cross-bedded sandstone of a mouth-bar complex which continues westward up the canyon and is present in the subsurface at UGS drill hole Ivie Creek no. 10 to the northwest (figure 15C). The unit thickens slightly from west to east, in contrast to the underlying parasequence.

Like the preceding unit, the shoreline orientation during deposition of the Kf-2-Iv-b parasequence was generally north-south. In the landward exposures at Ivie Creek Canyon, the unit is dominated by distributary-mouth bar and distributary channels associated with wave-modified delta deposits (figure 15C). Farther seaward, the distributary-mouth bar deposits give way to middle-shoreface deposits. Seaward (east) of the Ivie Creek area, a well-developed lower shoreface is present at the base of the unit. Paleoflow of several of the distributary channels indicates a general northerly trend in the local area.

At the I-70 road cut, a highway drainage channel was cut through solid rock to accommodate storm runoff. This cut provides superb views of Kf-2-Iv-b mouth-bar deposits. From the downstream end of the drainage channel, cross-bedded, mouth-bar deposits can be visually followed into distal bar or middle shoreface deposits to the east.

Kf-2-Iv-c Parasequence

The Kf-2-Iv-c parasequence is separated from the underlying Kf-2-Iv-b parasequence by a siltstone to shale interval that varies in thickness across the east part of the Ivie Creek area. Generally, the entire parasequence fines from west to east. In the Ivie Creek amphitheater, Kf-2-Iv-c is interpreted as a bay-fill deposit (although it is devoid of body fossils). There is evidence for bay-head deltas and tidal channels feeding the bay to the northeast in Quitchupah Canyon (figures 2 and 15D). At the top of this sequence is a thin, medium-grained carbonaceous sandstone, which may represent the migration of a low-energy beach (foreshore deposits) across the bay fill prior to capping by coastal-plain deposits and deposition of the overlying A-coal zone (which is locally burned). In Ivie Creek Canyon, Kf-2-Iv-c forms a 10-foot (3 m) cliff having excellent upper shoreface facies exposed (figure 19). The top of the unit is rooted by the overlying coastal-plain vegetation.

The landward pinchout of the marine facies of Kf-2-Iv-c trends just slightly east of south toward I-70. At the mouth of Ivie Creek Canyon, shoreline sandstone changes over a distance of about 300 feet (90 m) from a strongly wave-modified shoreface unit to a much lower energy unit that contains mud interbeds and finer sand and has a silvery gray color in outcrop, but is carbonaceous on a fresh surface. This suggests a change from a coast directly facing the sea to one that was sheltered from wave energy. The environment of this shoreline unit is a wave-modified coast, probably shoreface facies in the proximal part, transforming laterally to low-wave-energy bay facies.

A large meanderbelt channel system cuts into the top of the Kf-2-Iv-c parasequence just south of the immediate Ivie Creek area. The channel system flowed to the northeast, but much of this Ferron channel system has been removed by erosion. A late-stage episode of lateral channel migration across the top of the Kf-2-Iv-c delta-plain deposits is recorded by scours into the meanderbelt deposits. The best example of this channel system is exposed on the south side of I-70 across from the Ivie Creek amphitheater, just east of the road cut through the Ferron. This same channel is exposed in the road cut on the north side of I-70, but the channel orientation and the nature of its exposure in the cut face do not present the classic channel shape exhibited in the southern exposure. The meanderbelt and younger channel systems fed the continued progradation of Kf-2-Iv-c and stratigraphic equivalents to the east and northeast.

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