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MESOZOIC TO RECENT GEOLOGY OF UTAH

Edited by
Paul Karl Link and Bart J. Kowallis

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Cover photos taken by Paul Karl Link.

Top: Upheaval Dome, southeastern Utah.
Middle: Lake Bonneville shorelines west of Brigham City, Utah.
Bottom: Bryce Canyon National Park, Utah.

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Preface

Guidebooks have been part of the exploration of the American West since Oregon Trail days. Geologic guidebooks with maps and photographs are an especially graphic tool for school teachers, University classes, and visiting geologists to become familiar with the territory, the geologic issues and the available references.

It was in this spirit that we set out to compile this two-volume set of field trip descriptions for the Annual Meeting of the Geological Society of America in Salt Lake City in October 1997. We were seeking to produce a quality product, with fully peer-reviewed papers, and user-friendly field trip logs. We found we were bucking a tide in our profession which de-emphasizes guidebooks and paper products. If this tide continues we wish to be on record as producing "The Last Best Geologic Guidebook."

We thank all the authors who met our strict deadlines and contributed this outstanding set of papers. We hope this work will stand for years to come as a lasting introduction to the complex geology of the Colorado Plateau, Basin and Range, Wasatch Front, and Snake River Plain in the vicinity of Salt Lake City. Index maps to the field trips contained in each volume are on the back covers.

Part 1 "Proterozoic to Recent Stratigraphy, Tectonics and Volcanology: Utah, Nevada, Southern Idaho and Central Mexico" contains a number of papers of exceptional interest for their geologic synthesis. Part 2 "Mesozoic to Recent Geology of Utah" concentrates on the Colorado Plateau and the Wasatch Front.

Paul Link read all the papers and coordinated the review process. Bart Kowallis copy edited the manuscripts and coordinated the publication via Brigham Young University Geology Studies. We would like to thank all the reviewers, who were generally prompt and helpful in meeting our tight schedule. These included: Lee Allison, Genevieve Atwood, Gary Axen, Jim Beget, Myron Best, David Bice, Phyllis Camilleri, Marjorie Chan, Nick Christie-Blick, Gary Christenson, Dan Chure, Mary Droser, Ernie Duebendorfer, Tony Ekdale, Todd Ehlers, Ben Everitt, Geoff Freethey, Hugh Hurlow, Jim Garrison, Denny Geist, Jeff Geslin, Ron Greeley, Gus Gustason, Bill Hackett, Kimm Harty, Grant Heiken, Lehi Hintze, Peter Huntoon, Peter Isaacson, Jeff Keaton, Keith Ketner, Guy King, Mel Kuntz, Tim Lawton, Spencer Lucas, Lon McCarley, Meghan Miller, Gautam Mitra, Kathy Nichols, Robert Q. Oaks, Susan Olig, Jack Oviatt, Bill Perry, Andy Pulham, Dick Robison, Rube Ross, Rich Schweickert, Peter Sheehan, Norm Silberling, Dick Smith, Barry Solomon, K.O. Stanley, Kevin Stewart, Wanda Taylor, Glenn Thackray and Adolph Yonkee. In addition, we wish to thank all the dedicated workers at Brigham Young University Print Services and in the Department of Geology who contributed many long hours of work to these volumes.

Paul Karl Link and Bart J. Kowallis, Editors

Depositional Sequence Stratigraphy and Architecture of the Cretaceous Ferron Sandstone: Implications for Coal and Coalbed Methane Resources—A Field Excursion

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ABSTRACT

This Field Excursion will visit outcrops of the fluvial-deltaic Upper Cretaceous (Turonian) Ferron Sandstone Member of the Mancos Shale, known as the Last Chance delta or Upper Ferron Sandstone. This field guide and the field stops will outline the architecture and depositional sequence stratigraphy of the Upper Ferron Sandstone clastic wedge and explore the stratigraphic positions and compositions of major *coal zones.* The implications of the architecture and stratigraphy of the Ferron fluvial-deltaic complex for coal and coalbed methane resources will be discussed.

Early works suggested that the southwesterly derived deltaic deposits of the the upper Ferron Sandstone clastic wedge were a Type-2 third-order depositional sequence, informally called the Ferron Sequence. These works suggested that the Ferron Sequence is separated by a type-2 sequence boundary from the underlying 3rd-order Hyatti Sequence, which has its sediment source from the northwest. Within the 3rd-order depositional sequence, the deltaic events of the Ferron clastic wedge, recognized as parasequence sets, appear to be stacked into progradational, aggradational, and retrogradational patterns reflecting a generally decreasing sediment supply during an overall slow sea-level rise. The architecture of both near-marine facies and non-marine fluvial facies exhibit well defined trends in response to this decrease in available sediment.

Recent studies have concluded that, unless coincident with a depositional sequence boundary, regionally extensive *coal zones* occur at the tops of the parasequence sets within the Ferron clastic wedge. These *coal zones* consist of coal seams and their laterally equivalent fissile carbonaceous shales, mudstones, and siltstones, paleosols, and flood plain mudstones. Although the compositions of coal zones vary along depositional dip, the presence of these laterally extensive stratigraphic horizons, above parasequence sets, provides a means of correlating and defining the tops of depositional parasequence sets in both near-marine and non-marine parts of fluvial-deltaic depositional sequences. Ongoing field studies, based on this concept of *coal zone* stratigraphy, and detailed stratigraphic mapping, have documented the existence of at least 12 parasequence sets within the Last Chance delta clastic wedge. These parasequence sets appear to form four high frequency, 4th-order depositional sequences. The dramatic erosional unconformities, associated with these 4th-order sequence boundaries, indicate that there was up to 20–30 m of erosion, signifying locally substantial base-level drops. These base-level drops were accompanied by a basinward shift in paleo-shorelines by as much as 5–7 km. These 4th-order Upper Ferron Sequences are superimposed on the 3rd-order sea-level rise event and the 3rd-order, sediment supply/accommodation space driven, stratigraphic architecture of the Upper Ferron Sandstone. The fluvial deltaic architecture shows little response to these 4th-order sea-level events.

Coal zones generally thicken landward relative to the mean position of the landward pinch-out of the underlying parasequence set, but after some distance landward, they decrease in thickness. *Coal zones* also generally thin seaward relative to the mean position of the landward pinch-out of the underlying parasequence set. The coal is thickest in the region between this landward pinch-out and the position of maximum zone thickness. Data indicate that the proportion of coal in the *coal zone* decreases progressively landward from the landward pinch-out. The effects of differential compaction and differences in original pre-peat swamp topography have the effect of adding perturbations to the general trends. These coal zone systematics have major impact on approaches to exploration and production, and the resource accessment of both coal and coalbed methane.

INTRODUCTION

This Field Excursion is conducted in the northwestern portion of the Colorado Plateau in East-central Utah (fig. 1). Here uplift and erosion of the broad north-northeast-trending anticlinal structure of the San Rafael Swell along the northwestern margin of the Colorado Plateau exposes Cretaceous rocks. The focus of this Field Excursion will be the outcrops of the fluvial-deltaic Upper Cretaceous (Turonian) Ferron Sandstone Member of the Mancos Shale (fig. 2).

This field guide is organized in a fashion as to provide the field trip participant, and future workers in the Ferron Sandstone, with a comprehensive database and detailed field trip guide. A general introduction to the geology and stratigraphy of the Ferron Sandstone is presented and the major studies, that have contributed to our general understanding of the stratigraphy of the Ferron Sandstone, have been discussed to provide a general background. Any omissions of previous works are due to unintentional oversights. This field guide has at its core, the recent and ongoing studies of Garrison and van den Bergh (e.g., van den Bergh, 1995; Garrison and van den Bergh, 1996; 1997; van den Bergh and Garrison, 1996). The results of these studies, up to the time of the printing of this guidebook, are compiled and are included below in a short paper.

A detailed road log, through the outcrop belt of the Ferron Sandstone, is provided below. Each day of the two day field trip has its own road log. Each of the road logs starts and end in Price, Utah. The road logs attempt to provide the reader with geological, geographical, and cultural information, in hopes that the excursion through the Ferron Sandstone outcrops in the Castle Valley will both enjoyable and informative. The detailed discussions of the geology of each days field trip stops are presented separately from the road logs. They can be found immediately following each day's road log. This is done, first, to make it easier for the reader to follow the road log without interruptions, and secondly, to make it more easy to obtain the key points and background geology for each field trip stops. In order to preserve continuity and to have both the paper of Garrison and van den Bergh and the field trip stop descriptions able to stand alone, the reader may find some information, presented by Garrison and van den Bergh, reiterated in the field trip stop descriptions.

Energy Resources in Fluvial-deltaic Reservoirs

Fluvial-deltaic sandstones, such as the Ferron Sandstone, combined with their related strand-plain deposits, make up an estimated 45% of world's oil and gas reservoirs. The Ferron Sandstone produces natural gas; cumulative production exceeds 128 BCF (Laine and Staley, 1991), with a cumulative production of 8.8 MMCF from the Ferron Gas Field alone. In addition, the coals of the Ferron Sandstone have been targeted for coalbed methane production, resulting in a cumulative production of over 30 BCF of coalbed methane.

Most of the worlds coal reserves occur in fluvial-deltaic facies associations, such as the Ferron Sandstone. The Ferron Sandstone coals are analogous to, and similar in occurrence to, the coals of many coal fields in the eastern United States, Europe, Asia, and Australia. The Upper Ferron Sandstone of the Emery Coal Field has itself produced as much as 600,000 tons/year of bituminous B rank coal. Total cumulative coal production from the Emery Coal Field exceeds 9.5 million tons (Jahanbani, 1996). It is estimated that the Emery Coal Field has reserves in excess of 2.15 billion tons (Doelling, 1972). The Ferron Sandstone is but one of several formations in the Cretaceous of Central Utah to produce coal. Estimates are that total coal production exceeds 22 million tons/year in the Emery, Book Cliffs, and Wasatch Plateau Coal Fields of Central Utah (Semborski, 1991).

Coal Correlation and Geometry as a Tool in the Energy Industry

In fluvial-deltaic facies associations, coals are ubiquitous, although many times discontinuous, lithostratigraphic horizons. There is a natural tendency to connect together these compact, lithologically unique beds in outcrop and subsurface correlations. In the coal mining and the petroleum industries, performing subsurface coal correlations is an every day event. Even after years of industry experience, many subsurface correlations can still be problematic. This

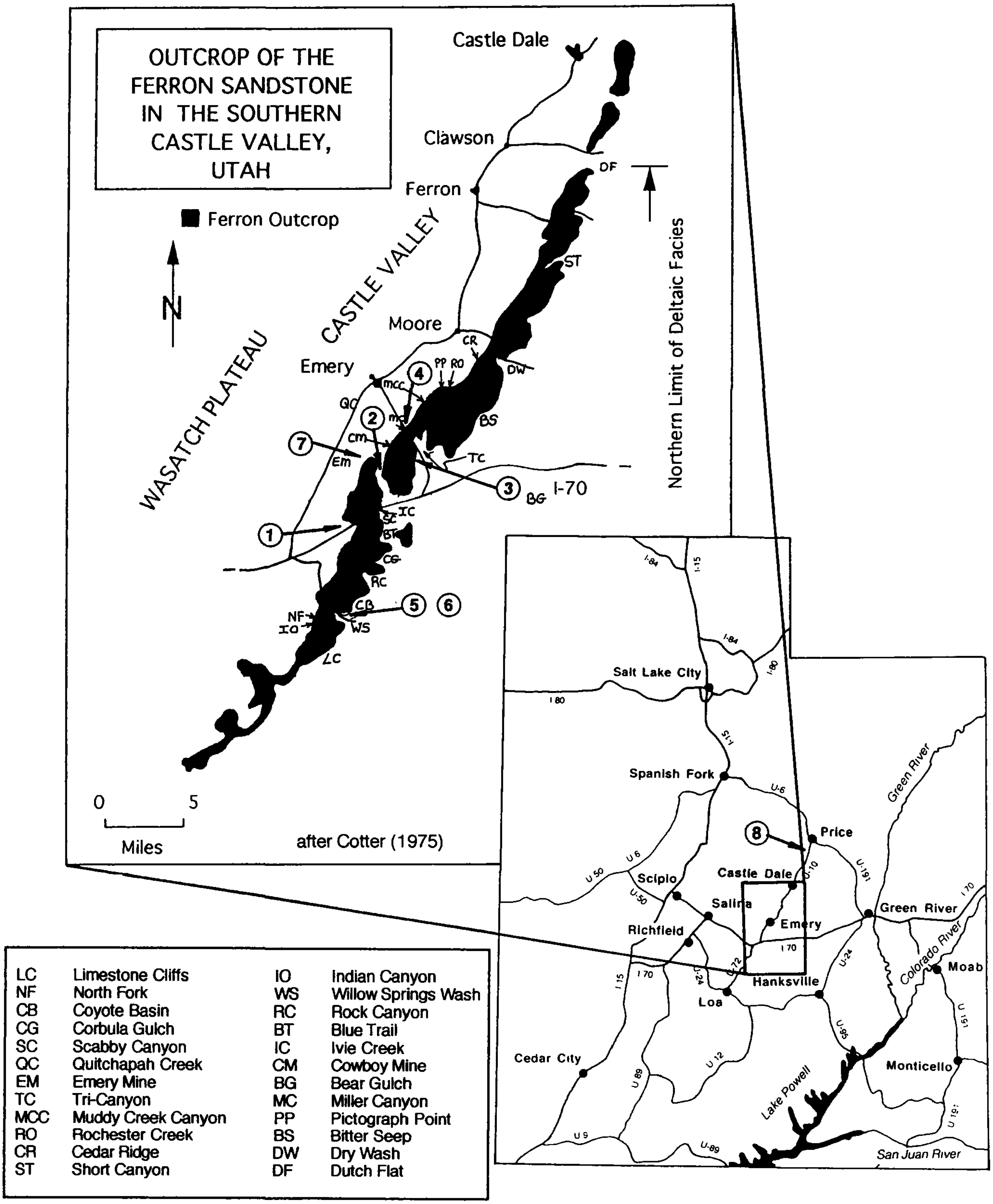


Figure 1. Location map for Ferron Sandstone outcrop belt and field trip stops.

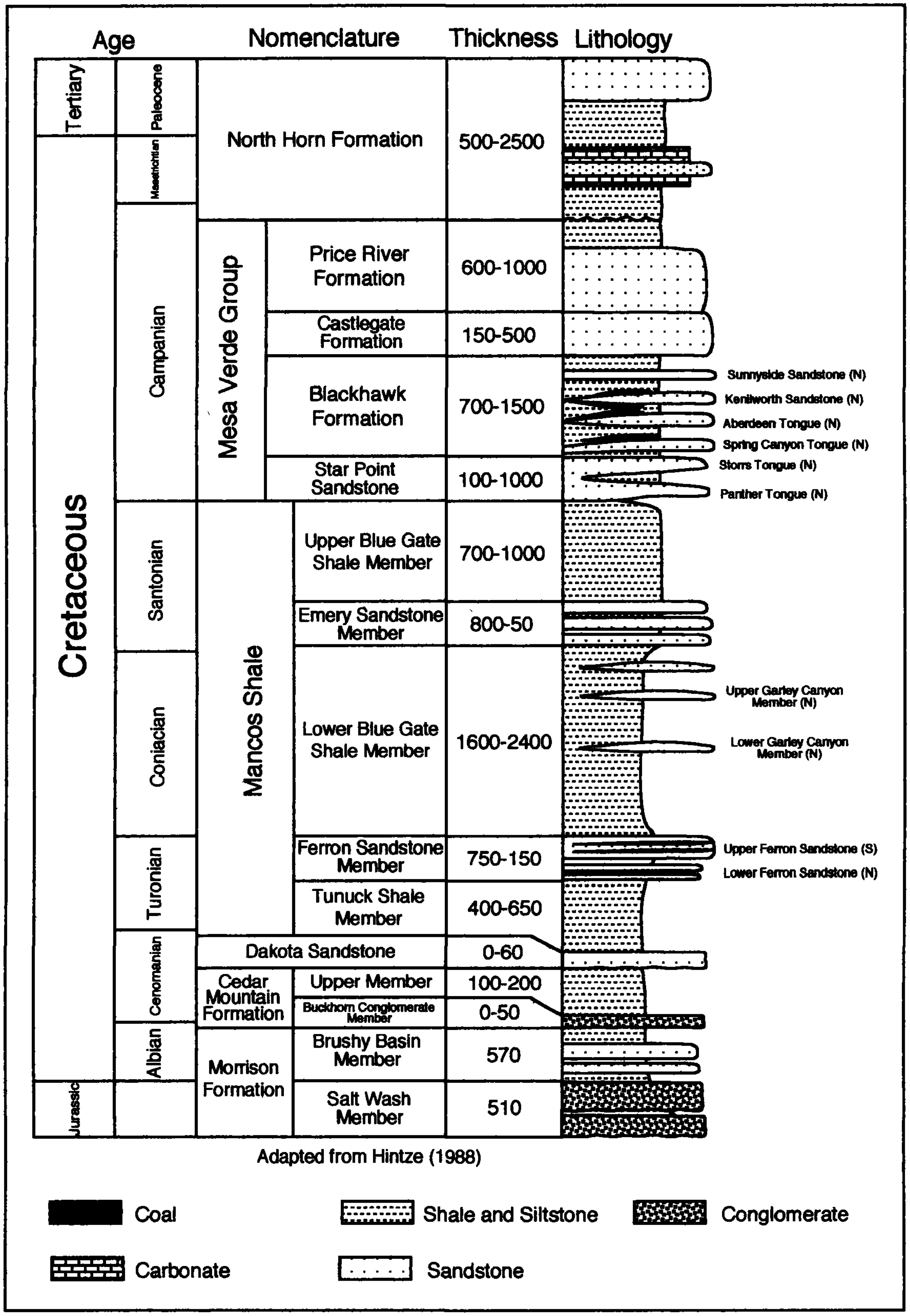


Figure 2. Stratigraphic column for the Cretaceous of the Castle Valley.

uncertainty introduces risk into exploration and production decisions. The desire to reduce this risk drives geologists to continue to investigate and to seek improved methodologies for making reliable subsurface correlations.

There appears to be a genetic relationship existing between the geometries of major coal beds and the geometries of the associated near-marine sediments in fluvial-deltaic deposits (e.g., see Ryer, 1981; Cross, 1988; Hamilton and Tadros, 1994). Numerous authors have proposed theories to utilize these relationships in lithostratigraphic, genetic sequence stratigraphic, depositional sequence stratigraphic, and/or regression/ transgression sequence stratigraphic correlations (e.g., see Ryer, 1981; Cross, 1988; Hamilton and Tadros, 1994; Aitken, 1994; Ryer et al., 1980; Garrison and van den Bergh, 1996).

Garrison and van den Bergh (1996) outlined, in a case study within the Upper Ferron Sandstone, stratigraphic relationships existing between the geometries of major coal beds and the geometries of the associated near-marine and non-marine sediments in Ferron fluvial-deltaic deposits. They describe this approach as *coal zone* stratigraphy and outline its use in depositional sequence stratigraphy.

This field excursion will examine the use of *coal zone* stratigraphy in high-resolution depositional sequence stratigraphic correlations of the Upper Ferron Sandstone. The stratigraphic positions and compositions of the Ferron coal zones will be discussed, in the context of this stratigraphy. The implications of this stratigraphy for coal and hydrocarbon exploration and production will also be addressed.

GENERAL GEOLOGY AND STRATIGRAPHY OF THE FERRON SANDSTONE

Introduction

The Upper Cretaceous (Turonian) Ferron Sandstone Member of the Mancos Shale is one of several eastward thinning clastic wedges that prograded into the Mancos Sea along the western margin of the Interior Cretaceous Seaway, between 89 and 90 million years ago (Gardner, 1992). The Ferron deltaic complex was deposited into the Mancos Sea in response to the abundant supply of sediments shed from the thrust-faulted and uplifted Sevier Orogenic belt located to the west in southeastern Nevada, western Utah, and southern Idaho. It reaches a thickness of over 1100 feet in the western area beneath the Wasatch Plateau and extends over 10,500 square kilometers (Tripp, 1989). The Ferron Sandstone is exposed along the approximately 170 kilometer length of the northeasterly trending outcrop belt.

The Ferron Sandstone can be divided into two distinct clastic wedges (Ryer, 1981). The lower portion of the Ferron Sandstone is a thin, northerly derived storm- and wave-dominated shoreline/deltaic complex, informally called the Vernal delta. The upper portion of the Ferron Sandstone is a younger, thicker, and more north-northeasterly prograding deltaic complex, informally called the Last Chance delta. The Last Chance deltaic complex is exposed along the outcrop belt generally parallel to the deltaic progradational direction. There is almost a complete 92 km long dip section exposure of the deltaic complex. The width of the outcrops of the Ferron Sandstone perpendicular to the trend of the outcrop belt is generally less than about 5 km, thus allowing very little opportunity to examine the deltaic deposits in the strike direction (Ryer, 1981) (fig. 1). In this discussion, only the upper clastic wedge of the Ferron Sandstone known as the Ferron Last Chance delta complex or the Upper Ferron Sandstone (Ryer, 1981) will be addressed, unless otherwise noted.

Stratigraphy

Ryer and McPhillips (1983) recognized that the Ferron deltaic complex was composed of sediments deposited during a series of transgressions and regressions of the Cretaceous shoreline. Ryer (1981;1982) recognized five deltaic cycles within the Last Chance deltaic complex of the southern Ferron Sandstone outcrop belt. These delta-front sandstones were referred to as sandstones 1–5. Ryer (1981; 1982) noted that the delta-front sandstone 2 had both a seaward and landward limit displaced further seaward than delta-front sandstone 1 and that delta-front sandstones 3–5 each have seaward limits displaced successively landward. In a subsurface well-log study, Ryer and McPhillips (1983) identified delta-front sandstones 1–5 in the subsurface beneath the Castle Valley and the Wasatch Plateau. Subsequent work by Gardner (1992; 1993) and Ryer (1991) led to the identification of two more, stratigraphically higher, delta cycles in the outcrop belt, referred to as 6–7; both have seaward limits displaced successively landward. The Ferron Sandstone was subdivided into 7 major deltaic events (Gardner, 1992; 1993). Gardner also suggested that an eighth delta-front sandstone occurred in the subsurface further south. Gardner's eighth, subsurface, deltaic unit will not be discussed in this paper. Recent works have subsequently delineated an additional eighth delta-front sandstone in the outcrop belt.

Major coal beds occur within the Ferron sandstone complex and generally mark the top of the deltaic events. The coal nomenclature was first developed by Lupton (1916) and retained by Ryer (1981; 1982) and Gardner (1993). These coal beds can be easily correlated through the Ferron delta-front complex and can be further correlated as discontinuous zones of coal and carbonaceous shale into the distributary channel dominated delta-plain setting (Garrison and van den Bergh, 1996). Many of the major coal beds within the Ferron Sandstone contain one or more layers of kaolinitic/bentonitic material representing altered volcanic ash falls (Ryer et. al., 1980). The coal beds together with altered volcanic ash layers can be generally used as chronostratigraphic indicators.

Sequence Stratigraphy—Historical Development

Gardner (1992; 1993) examined these deltaic events and placed them into a sequence stratigraphic framework. He recognized the upper portion of the Ferron Sandstone to be a Type-2 third-order depositional sequence, called the Ferron Sequence. A Type-2 sequence boundary is physically expressed by a downward shift in coastal onlap, onlap of overlying strata, and subaerial exposure with minor erosional truncation at the top or base of the progradational, parasequence set (Van Wagoner et. al., 1990). The southwesterly derived deltaic deposits of the 3rd-order Ferron Sequence contains *Scaphites ferronensis* and is separated by a type-2 sequence boundary from the underlying 3rd-order Hyatti Sequence, which contains the ammonite *P. hyatti* (Gardner, 1992). The Hyatti Sequence has its sediment source from the northwest (Gardner, 1993). Gardner (1993) places the sequence boundary at the base of the Upper Ferron Sandstone above the Hyatti condensed section. Ryer (1994) suggested that the fluvial-deltaic sandstones of the lower Ferron Sandstone (i.e., the Hyatti Sequence) probably formed in response to a dominantly eustatic sea level change. Leithold (1994) also suggested that the Hyatti Sequence (i.e., Lower Ferron Sandstone and its correlative siltstones and shales of the Tununk Member of the Mancos Shale) was formed as a result of a high frequency (i.e., 3rd-order) eustatic sea level change superimposed on the tectonically induced 2nd-order Greenhorn sea level cycle. Leithold (1994) also suggested that the Lower Ferron Sandstone, of the Hyatti Sequence, probably formed during the regressive phase of the Greenhorn sea level cycle (i.e., at the point of maximum sea level regression). Ryer (1994) postulated that the Upper Ferron Sandstone (i.e., the Ferron Sequence) probably formed in response to an increase in sediment supply associated with increased tectonic activity in the Sevier orogenic belt, during a period of slow sea level rise (i.e. during a 3rd-order slow sea level rise). These 3rd-order cycles are postulated to be on the order of 400,000 years in duration (Leithold, 1994).

Leithold (1994) hypothesized that the higher frequency Greenhorn events (i.e., parasequence sets and parasequences) are probably associated with local autocyclic events, although many of these events appear to be more basin-wide in extent and thus, may be associated with climatic changes or Malankovitch cycles. van den Bergh and Sprague (1995) and van den Bergh (1995) first discussed the possibility of additional high frequency (i.e., 4th-order) sequences within the 3rd-order Ferron Sequence deltaic complex.

Gardner (1992; 1993) described the individual deltaic events, within the 3rd-order Ferron Sequence, as genetic sequences (Galloway, 1989). Recent workers have described them as depositional parasequence sets (e.g., van den Bergh, 1995; Anderson and Ryer, 1995; Ryer and Anderson, 1995; Garrison and van den Bergh, 1996). After examining the seaward and landward limits of the delta-front complexes, Gardner (1993) recognized that genetic sequences 1–3 successively stepped seaward recording an overall regressive event and genetic sequences 4–7 recorded a relative transgression, with genetic sequences 4–5 being aggradational and genetic sequences 6–7 back-stepping sharply landward. Although described as depositional parasequence sets, the stacking pattern of the delta cycles was later confirmed by Ryer and Anderson (1995). van den Bergh and Sprague (1995) postulated that these parasequence sets may be grouped into high-frequency 4th-order depositional sequences within Gardner's 3rd-order Ferron Sequence.

Coals, where preserved within the Ferron Sandstone, generally occur below the flooding surface at the top of each of the delta cycle or parasequence sets (e.g., see Garrison and van den Bergh, 1996). Garrison and van den Bergh (1997) have noted that in a few instances, that in addition a transgressive lag or a high-order depositional sequence boundary may occur at the top of a parasequence set. Based on the Ferron *coal zone* stratigraphy and detailed stratigraphic mapping, Garrison and van den Bergh (1996; 1997) have subsequently documented the existence of at least 12 parasequence sets (i.e., including single hierarchically equivalent parasequences) which form four high frequency, 4th-order depositional sequences (fig.3). These 4th-order events are superimposed on the slow 3rd-order sea-level rise event discussed by Gardner (1993) and Leithold (1994). The work of Garrison and van den Bergh (1997) suggests that the 3 stratigraphically lowest parasequence sets, within the Ferron clastic wedge, may actually belong to the underlying 3rd-order Hyatti Sequence. Widespread condensed sections lie stratigraphically above (Garrison and van den Bergh, 1997) and below (Gardner, 1993) the Upper Ferron Sandstone clastic wedge.

COAL ZONE AND HIGH-RESOLUTION DEPOSITIONAL SEQUENCE STRATIGRAPHY AND ARCHITECTURE OF THE UPPER FERRON SANDSTONE

James R. Garrison, Jr. and T.C.V. van den Bergh

Introduction

In the petroleum industry, performing subsurface correlations is an every day event. Uncertainty in subsurface correlations introduces risk into exploration and/or production management decisions. The desire to reduce this risk drives geoscientists to continue to investigate and to seek improved methodologies for making reliable subsurface correlations.

Coals are intuitively excellent stratigraphic correlation horizons because they are easily recognizable in outcrop, core, and on logs, they tend to be laterally extensive, and generally chronostratigraphic markers. In fluvial-deltaic facies associations, coal seams are ubiquitous, although many times discontinuous, lithostratigraphic horizons. There is an intuitive tendency to connect together these compact, lithologically unique beds in outcrop and subsurface correlation exercises.

There appears to be a clear genetic relationship between the geometries of major coal beds and the geometries of the associated near-marine sediments in fluvial-deltaic deposits. Numerous authors have proposed theories to utilize these relationships in lithostratigraphic, genetic sequence stratigraphic, depositional sequence stratigraphic, and/or regression/transgression sequence stratigraphic correlations (e.g., see Cross, 1988; Hamilton and Tadros, 1994; Ryer, 1981; Aitken and Flint 1994, 1995, van den Bergh, 1995; Garrison and van den Bergh, 1996). This paper details the high-resolution depositional sequence stratigraphy of the Upper Ferron Sandstone and outlines the ideas for the use of *coal zone* stratigraphy as a tool in high-resolution depositional sequence stratigraphic correlations, as proposed by Garrison and van den Bergh (1996).

Coal zones—An Extension of Coal Seam Stratigraphy

Flint et al., (1995), Aitken and Flint (1995), Gastaldo et al., (1993), Garrison and van den Bergh (1996) and van den Bergh (1995) have examined coal stratigraphy in a depositional sequence stratigraphic context. Aitken (1994) pointed out that in many situations coals may become thin and laterally restricted, commonly becoming poorly developed, with carbonaceous mudstones, shales, and siltstone and paleosols becoming more prevalent. The observation that coal seams, in the Ferron Sandstone, are commonly associated with carbonaceous siltstone and shales and paleosols, has suggested to the authors that *coal zones* (i.e. coals and their lateral equivalents) may prove useful tools in sequence stratigraphic correlations in fluvial-deltaic systems.

Garrison and van den Bergh (1996) define *coal zones* as coal seams and their laterally equivalent fissile carbonaceous mudstones, shales and siltstones, paleosols (e.g., rooted horizons), and flood plain mudstones. It should be noted that a *coal zone* may, vertically or laterally, consist of any combination of these components. This concept of *coal zones* has evolved as an outgrowth of the challenge of correlating coal horizons from within the lower delta plain/ near-marine transition landward into the delta plain /alluvial plain environments. It is well known that lower delta plain coals are generally laterally extensive and thin, with variable geometry, associated with back barrier environments, while coals in the upper delta plain to alluvial plain become thicker, more elongate, and associated with lacustrine and fluvial deposition systems (e.g., Fielding, 1985). This paper extends the well documented coal seam stratigraphy, as discussed above, to more non-marine, continental environments. Garrison and van den Bergh (1996) explain where these *coal zones* reside in the shoaling upward facies tracts outlined by Van Wagoner et. al. (1990) and developed a methodology for using *coal zones* in high resolution depositional sequence stratigraphy.

In the study of Garrison and van den Bergh (1996), a model was proposed in which peat accumulations and their laterally equivalent delta plain/alluvial plain facies associations, occur, generally time synchronously, in a variety of depositional situations ranging from back barrier (near-marine) peat swamps (i.e., generating true coal seams as defined by Hamilton and Tadros (1994) and Ryer, (1981)), to local to sub-regional ephemeral organic-rich swamp/lacustrine environments to very localized abandoned fluvial channel settings. All of these organic-rich peat or organic-rich mud accumulations are time synchronous, although not necessarily connected in space, either in elevation or geographic proximity. Ye (1995) also describes rooted paleosols that can also be correlated, for many kilometers, in fluvial flood-plain settings. This "South Louisiana" bayou/swamp model is most common in temperate to tropical delta plain and distal alluvial plain settings. Ryer (1981), McCabe (1993), Shanley and McCabe (1993), Cross (1988), and Vail (1987) have also discussed the occurrences of coal bearing strata in relation to their stratigraphic positions within a fluvial-deltaic sequence and hypothesized that the thickest accumulations of coal occur in areas landward of aggradational or landward-stepping shorelines.

The *coal zone* stratigraphic model has been successfully tested in a 3 km strike cross-section of the delta plain/alluvial plain facies association of the Ferron Sandstone. This *coal zone* correlation has also been further tested by constructing of a 40 km dip section, both north and south of the strike section, in the delta plain/alluvial plain to near-marine facies associations. It has been clearly demonstrated that coal seams occurring above near-marine parasequence sets are transitional into *coal zones* as they are traced landward into the non-marine facies associations (van den Bergh, 1995; Garrison and van den Bergh, 1996).

A Case Study in the Upper Ferron Sandstone

The Upper Cretaceous Ferron Sandstone Member of the Mancos Shale accumulated during late Turonian time as a series of river- and storm-dominated deltaic depositional episodes (e.g., see Ryer, 1981). Offshore marine, delta-front, delta-plain, and alluvial-plain depositional facies are recognized within the Ferron delta complex. Ryer and McPhillips (1983) recognized that the Ferron deltaic complex was composed of sediments deposited during a series of transgressions and regressions of the Cretaceous shoreline of the Mancos Sea. The upper clastic wedge of the Ferron Sandstone, known ad the Last Chance delta, can be subdivided into 7 major deltaic events (Ryer, 1991). Gardner (1993) described these deltaic events as genetic sequences. Recent workers have described them as parasequence sets (e.g., van den Bergh, 1995; Anderson and Ryer, 1995; Garrison and van den Bergh, 1996; 1997). Major coal beds occur within the Ferron Sandstone complex and, generally, mark the top of parasequence sets (van den Bergh, 1995; Garrison and van den Bergh, 1996). The coal nomenclature was first developed by Lupton (1916) and retained by Ryer (1981) and Gardner (1993). These coal beds can be easily correlated through the Ferron delta-front complex. Most of the major coal beds within the Ferron Sandstone contain one or more layers of kaolinitic/bentonitic material representing altered volcanic ash falls (Ryer et. al., 1980; Garrison and van den Bergh, 1996). The coals together with altered volcanic ash layers can be used as time line indicators.

The studies of Garrison and van den Bergh (1996; 1997) resulted in the construction of a short 3 km strike cross-section in Willow Springs Wash, Willow Springs Quadrangle, to document the uses of *coal zones* as tools for delineating parasequence sets in non-marine sections, and in the construction of a 40 km long sub-regional dip cross-section from the Limestone Cliffs, north of Last Chance Creek, to Dry Wash, in Willow Springs, Walker Flat, Mesa Butte, Emery East, and Short Canyon Quadrangles to test the *coal zone* stratigraphy model. The strike cross-section is based on 11 measured sections, seven of which are detailed sedimentological measured sections and four are geometric (i.e., only thicknesses of lithologic units are recorded with grain-size and sedimentary structures generalized). The dip cross-section is a projected 40 km long section based on 45 measured sections, five of which are geometric, and one core. The emphasis in the construction of these cross-sections was the application of *coal zone* stratigraphy and its relationship to the architecture and stacking patterns of parasequences and parasequence sets in a depositional sequence stratigraphic framework. Parasequence sets were delineated, and where possible, parasequences were broken out. The nature of the upper boundaries of parasequences and parasequence sets was determined.

The original delta cycle and/or genetic sequence and/or depositional sequence nomenclature (e.g., cycles 1–7, genetic sequences 1–7, and parasequence sets 1–7) is so prevalent in the literature (e.g., Ryer, 1991; Gardner, 1993; Ryer and Anderson,1995;, and Garrison and van den Bergh, 1996), that the authors have chosen to retain this numeric scheme in this study, although more than seven events have been identified by the authors. How this will be accomplished is described below. For example, multiple parasequences identified within the original delta cycle 2 will be consecutively denoted as Parasequences 2a, 2b, 2c, etc. (Parasequence denoted as upper case). Furthermore, multiple parasequence sets identified within delta cycle 2 will be consecutively denoted as Parasequence Sets 2A, 2B, 2C, etc. (Parasequence Set denoted as upper case). This convention will retain the connection to the original Ferron nomenclature and make discussions of the newer depositional sequence stratigraphy easier. The only exception to this scheme is that the oldest identified parasequence in Parasequence Set 1 is given the non-sequential, designation of Parasequence 1z. This was done, in part, because its entire dip length has not yet been quantified in the studies of Garrison and van den Bergh (1996).

Ferron Sandstone Depositional Sequence Stratigraphy

These detailed cross-sections have delineated 12 parasequence sets within the Upper Ferron Sandstone (fig. 3). In the cross-sections, 12 near-marine parasequences have been identified within Ferron Parasequence Set 1 (denoted 1z, 1a–1k); 4 occur within Ferron Parasequence Set 2A (denoted 2a–2d). Parasequence Set 2B contains only Parasequence 2e. Parasequence Set 2C contains 5 parasequences (denoted 2f–2j). Parasequence Set 3 contains only two parasequences. Both Parasequence Sets 4A and 4B contains only one parasequence. Parasequence Set 5A contains 2 parasequences and Set 5B contains only one. Parasequence Set 6 contains one parasequence. Parasequence Set 7 contains 4 parasequences. Parasequence Set 8 contains two parasequences. The single parasequences of Parasequence Sets 2B, 4A, 4B, 5B, and 6 have been given hierarchical equivalence to a parasequence set. Parasequence Sets 3–8 are represented along the Ferron Sandstone outcrop belt as dominantly delta plain facies associations (fluvial channel belts, crevasse splays, delta plain mudstones, and carbonaceous shale/coals). Fluvial channel belts have width/thickness that varies as a function of parasequence set stacking pattern (van den Bergh and Garrison, 1996). These systematics are honored in the *coal zone* stratigraphy and parasequence set delineations.

The 12 parasequence sets form four high frequency, 4th-order depositional sequences (denoted FS1–4) (fig. 3). The lowest 4th-order sequence FS1 consists of three parasequence sets. FS2 also consists of three parasequence sets. FS3 consists of two parasequence sets and FS4 consists of four parasequence sets. In general, the 4th-order depositional sequences consist of progradational and/or aggradational parasequence sets, with the upper-most, highstand (back-stepped) parasequence set lying stratigraphically above a transgressive lag deposit. The upper boundaries of

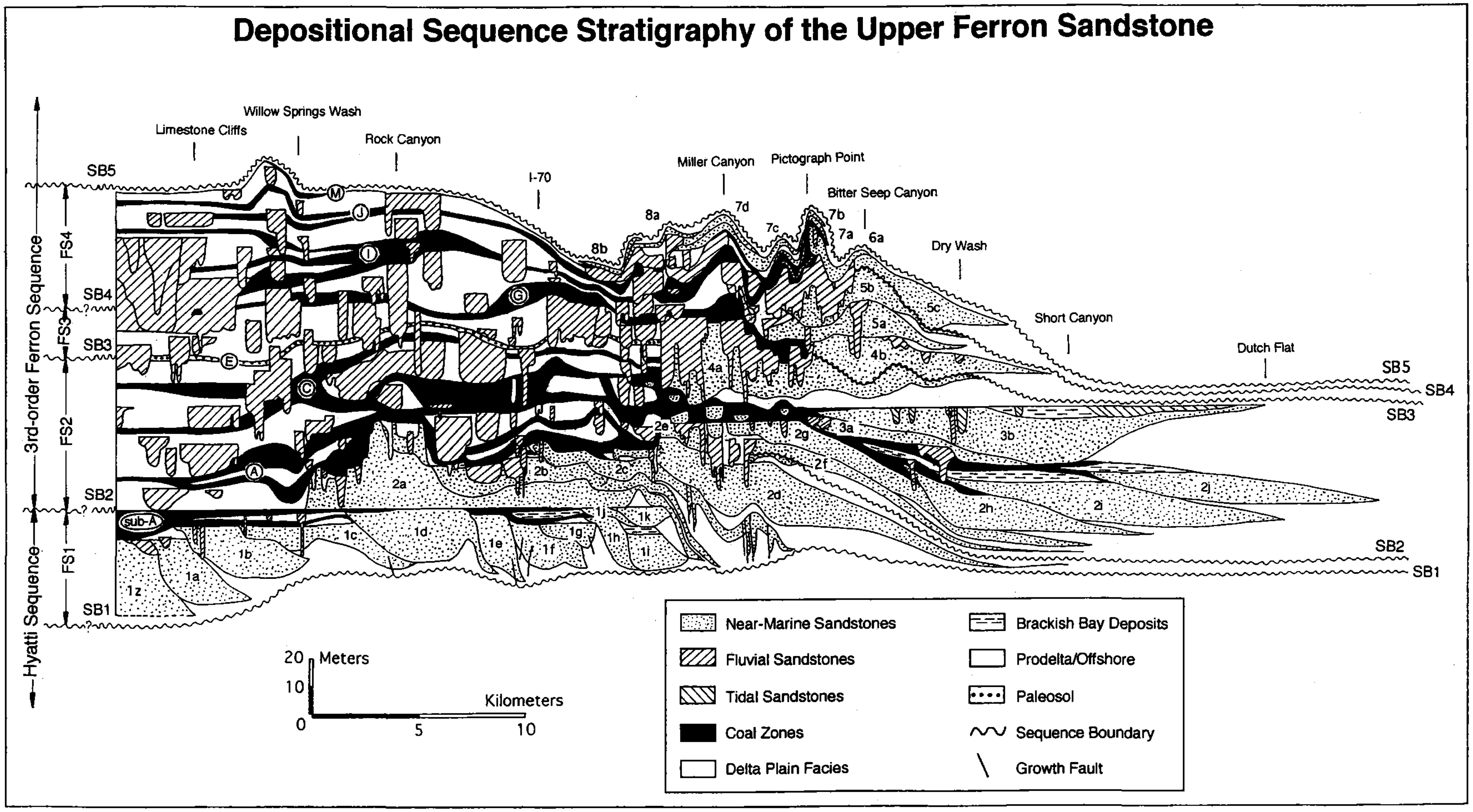


Figure 3. Cross-section showing the depositional sequence stratigraphy of the Upper Ferron Sandstone. Between Limestone Cliffs and the Emery Mine is datum is the top of the sub-A coal zone; *from the Emery Mine to Pictograph Point the datum is the base of the composite A-C* coal zone; *from Pictograph Point to Dry Wash the datum is the top of the C coal zone/base of the transgressive lag at the top of Parasequence Set 3; north of Dry Wash the datum is the top of Parasequence Set 3.*

parasequence sets, when not coincident with sequence boundaries, are *coal zones.*

The upper boundaries of 4th-order depositional sequences FS1, FS2, and FS3, are marked by regionally extensive erosional unconformities produced by major fluvial events that record major basinward shifts in depositional facies. It appears that erosion along these sequence boundary surfaces has removed most, if not all, of any previously deposited coals. The up-dip correlative surface of the upper boundary of FS2 is an extensive rooted zone in the non-marine part of the section. The up-dip correlative surfaces of FS1 and FS3 are still problematic. The lower boundary of FS1 is immediately above the Hyatti condensed section (Gardner, 1993) suggesting that it is actually a correlative conformity/condensed section boundary in this part of the basin. The upper boundary of FS4 is a below a concretion-bearing condensed section a few m above the uppermost sandstones of FS4. Based on this interpretation, FS1 should probably be assigned to the 3rd-order Hyatti Sequence of Gardner (1993) and FS2, FS3, and FS4 assigned to the 3rd-order Ferron Sequence of Gardner (1993). FS1 would be the 4th-order highstand depositional sequence of the 3rd-order Hyatti Sequence. FS2 and FS3 would be the 4th-order progradational to aggradational sequences of the 3rd-order Ferron Sequence (i.e., representing a shelf-margin systems tract) and FS4 is the 4th-order transgressive depositional sequence of the Ferron Sequence. The 4th-order highstand sequence of the Ferron Sequence is not located in the study area, but is only represented by condensed section sediments.

Seaward-Stepping Parasequence Sets

In the context of the larger scale 3rd-order Ferron Sequence defined by Gardner (1992; 1993), each of the delta cycles represented by Ferron Parasequence Sets 1, 2A–2C, and 3 progressively step seaward. The landward pinch-out of the near-marine sandstones (i.e., location of paleo-shorelines) of each younger parasequence set is progressive further down-dip. Internally, within each of these parasequence sets, the parasequences themselves exhibit a progradational, seaward-stepping stacking pattern. *Coal zones* typically occur at or near the top of these depositional parasequence sets, with the thickest portion of the *coal zones* occurring near the landward pinch-out of the near-marine delta-front sandstones of the depositional parasequence sets. The sub-A *coal zone* caps Ferron Parase- quence Set 1; the A *coal zone* caps Parasequence Set 2; the C *coal zone* caps Parasequence Set 3. It is common for these *coal zones* to split near the top of a depositional parasequence set.

Parasequence Set 1

Ferron Parasequence Set 1 contains at least 12 river-dominated, fluvial-deltaic parasequences (denoted 1z, 1a–1k), that exhibit a seaward-stepping stacking pattern (fig. 3). Within Parasequence Set 1, the landward pinch-out of the near marine facies of each successively younger parasequence steps seaward by an average of about 2–5 km, relative to the landward pinch-out of the near marine facies of immediately underlying parasequence. The near-marine sandstones of Parasequence Set 1 extend at least 27 km in the dip direction.

The near-marine parasequences in Ferron Parasequences Set 1 exhibit both vertical and lateral facies changes from (1) stream mouth bar (SMB), to (2) proximal delta front (pDF), to (3) distal delta front (dDF), to (4) prodelta (PD) (figs. 4 and 5). Both proximal and distal delta front deposits, as denoted here, represent subdivisions of the distal bar facies of Ryer (1981). Distributary channels (DC) and delta plain (DP) facies associations are commonly present as well. Distal prodelta/shelf slumping, indicating instability as a result of rapid deposition, is common. Contorted bedding, flame structures, escape burrows, and the cannibalizing of distal stream mouth bar by proximal stream mouth bar (or distributary) channels also suggests generally a rapid rate of deposition (van den Bergh, 1995). In general, Parasequence Set 1 delta front deposits exhibit little to mild evidence of wave influence. They locally exhibit poorly developed hummocky stratification and only rare bi-directional ripple stratification.

Parasequences 1z–1d appear to represent a series of delta lobes prograding seaward in a northeasterly direction (25°–40° azimuth), each of which progressively steps seaward and rises stratigraphically relative to the immediately underlying parasequence. The outcrop belt is approximately along the depositional dip direction. The landward pinch-out of the near marine facies, of each successively younger parasequence, steps seaward by an average of about 2–5 km, relative to the landward pinch-out of the near marine facies of immediately underlying parasequence. The near-marine facies of Parasequences 1a, 1b, 1c, and 1d are approximately 4.9 km, 6.3 km, 8.4 km, and 7.5 km, in dip length, respectively, and maximum thicknesses are 24 m, 20 m, 10 m, and 17 m, respectively. Parasequence 1c is a composite delta with 2–3 mouth bars. Parasequences 1e, 1f, 1g, and 1i appear to have formed in response to the northwesterly (310°–335° azimuth) progradation of very small, river-dominated sub-delta lobes. The outcrop belt cuts these parasequences in a strike-oblique direction. Parasequences 1e, 1f, 1g, and 1i are approximately 2.9 km, 3.7 km, 2.7 km, and 2.5 km in strike width, respectively, and the maximum thicknesses are 22 m, 17 m, 9 m, and 13 m, respectively. Parasequence 1f appears to be a composite delta with two mouth bars. Parasequences 1h and 1k appear to represent small delta lobes prograding seaward in a northeasterly direction. Parasequence 1k pinches out into a split of the sub-A *coal zone*. The dip lengths of 1h and 1k are approxi-

Figure 4. Photograph of the Upper Ferron Sandstone Parasequence Set 1 at Ivie Creek/I-70 outcrop.

mately 2.5 km and 2.4 km and maximum thicknesses are 15 m and 7 m, respectively.

Parasequence 1j, occurs within a split in the sub-A *coal zone*, and is represented in the outcrop belt as a brackish water bay mudstone, to the south near I-70, and as a small 2.9 km, 3 m thick delta front sandstone body, to the north in Quitchapah Creek Canyon.

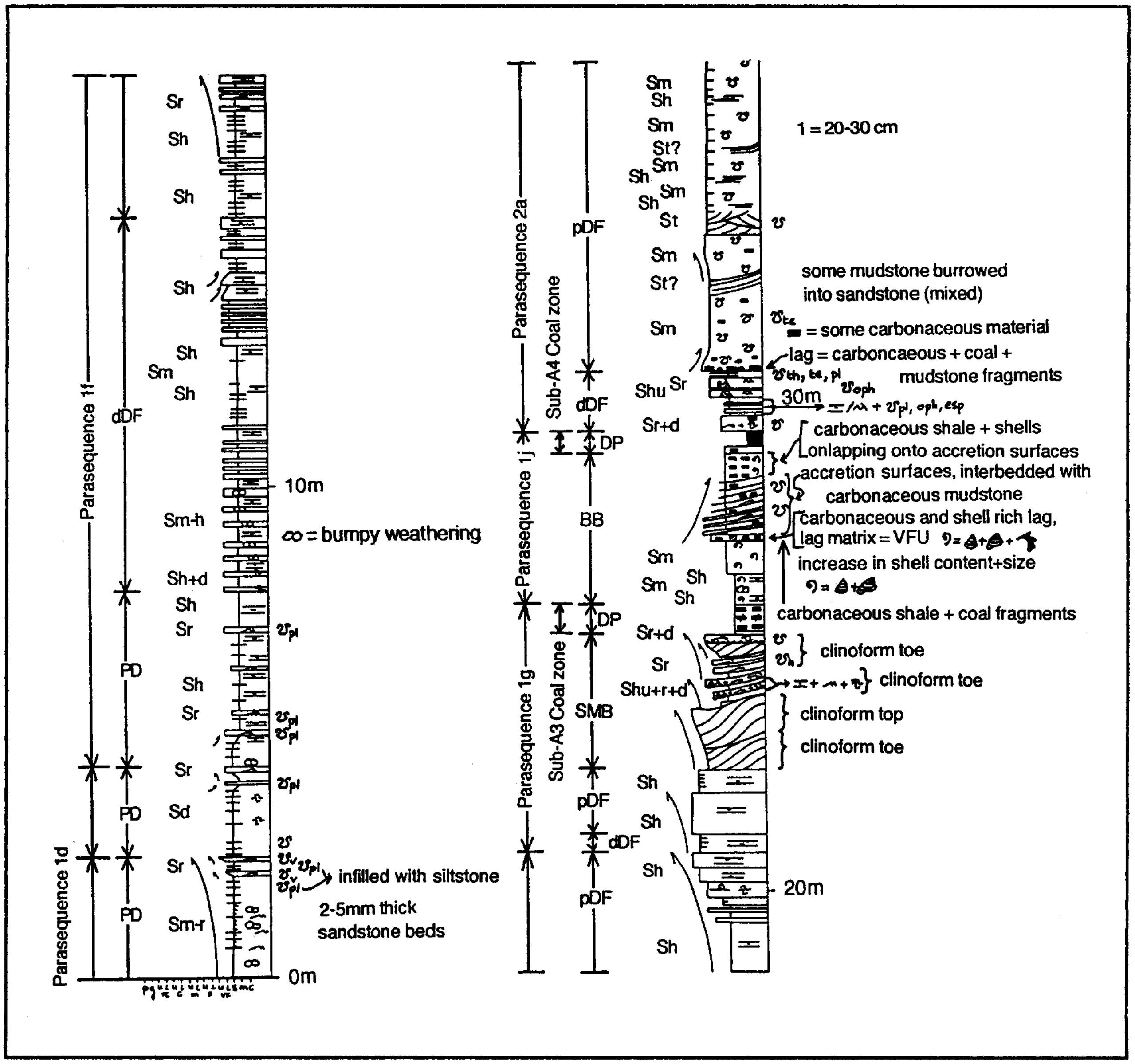
In the Limestone Cliffs, the sub-A *coal zone* is approximately 15 m thick and splits into two components denoted sub-A1 and sub-A2. The sub-A1 *coal zone* disappears in Coyote Basin and the Sub-A2 *coal zone* disappears in Rock Canyon. A *coal zone* stratigraphically equivalent to the Sub-A2 reappears in Blue Trail Canyon and splits into two components near I-70, where they are designated the sub-A3 and sub-A4. The sub-A3 and sub-A4 section of the sub-A *coal zone* extends some 8.5 km, from Blue Trail Canyon to North Quitchapah Creek. The total dip length for the sub-A *coal zone* is at least 27 km. In the Limestone Cliffs, the sub-A2 *coal zone* contains a very well-developed tonstein. This sub-A2 tonstein has not been identified further down-dip.

Parasequence Sets 2A, 2B, and 2C

Parasequence Set 2A contains 4 wave-modified, river-dominated parasequences (2a–2d), that exhibit a seaward-stepping stacking pattern (fig. 3). The near-marine sandstones of Parasequence Set 2A extend about 36 km in the dip direction. Parasequence 2e is hierarchically equivalent to a parasequence set and is placed in Parasequence Set 2B. Parasequence Set 2B is severely truncated by sequence boundary erosion, such that its true extent cannot be ascertained. Parasequence Set 2C contains 5 parasequences (2f–2j). The near-marine sandstones of Parasequence Set 2C extend about 29 km in the dip direction.

The near-marine parasequences in Ferron Parasequence Set 2A, 2B, and 2C all exhibit both vertical and lateral facies changes from (1) stream mouth bar and reworked stream mouth bar (frequently preserved as upper shoreface deposits (USF)), to (2) reworked delta front (pDF and dDF) (frequently preserved as middle (MSF) and lower shoreface (LSF) deposits), to (3) prodelta (figs. 6 and 7). South of Willow Springs Wash, distributary channels and delta plain facies associations are present as well. In general, Parasequence Set 2 stream mouth bar and distal bar (i.e., pDF and dDF) deposits exhibit evidence of moderate wave influence. The stream mouth bar deposits are frequently moderately burrowed (ichnofacies *Skolithos*) and may exhibit well-developed trough and herringbone stratification. The distal bar deposits are frequently moderately burrowed (ichnofacies *Skolithos* and *Cruziana*), but exhibit well-developed hummocky and planar stratification and bi-directional ripple-stratification (van den Bergh, 1995).

Parasequences 2a and 2b appear to represent large wave influenced, river-dominated delta lobes prograding seaward in a northeasterly direction. South of I-70, Parasequence 2a progrades northeast (034° azimuth) (van den Bergh, 1995). In the vicinity of I-70 and Ivie Creek, Parasequence 2a progrades northeast (025° azimuth). Parasequence 2b is actually



SMB	stream mouth bar	pDF	proximal delta front	dDF	distal delta front
PD	prodelta	DC	distributary channel	DP	delta plain
BB	brackish bay deposit		horizontal bedding		ripples
	grain-size change		trough crossbeds		contorted bedding
	hummocky stratification	1	bed	2	bedset
Sm	massive	Sh	horizontal bedding	Sr	ripple stratification
St	trough cross-stratified	Sd	deformed stratification	Shu	hummocky stratification
Sta	tabular stratification		bumpy weathering		load cast
	coal		carbonaceous material		roots
	log		coal fragments		intrabasinal pebbles
	brackish water fossil		gastropod		oyster
	bivalve		burrow (trace fossil)		horizontal burrow
	vertical burrow		escape burrow		*Ophiomorpha*
	Thalassinoides		*Planolites*		*Teichichnus*

Figure 5. Measured section through the Upper Ferron Sandstone Parasequence Set 1 at the I-70 roadcut.

a composite delta lobe with a more easterly progradation direction. In the vicinity of Scabby Canyon and I-70, Parasequence 2b progrades northeast (045° azimuth). The landward pinch-out of the near-marine facies of Parasequence 2b steps seaward 3.5 km, relative to the landward pinch-out of the near-marine facies of the immediately underlying Parasequences 2a. Near-marine Parasequence 2c appears to be a deltaic lobe prograding northeast (025° azimuth) into a quiet brackish-water bay. The landward pinch-out of near-marine facies of Parasequence 2c occurs almost 7.5 km seaward of the landward pinch-out of the underlying Parasequence 2b. Parasequence 2d is a major delta lobe prograding northeast (050° azimuth). The landward pinch-out of Parasequence 2d steps seaward almost 2.7 km from the pinch-out of Parasequence 2c. There is slight stratigraphic rise associated with each seaward step. The near-marine facies of Parasequences 2a, 2b, 2c, and 2d are approximately 18.0 km, 15.1 km, 11.4 km, and 24.0 km in dip length, respectively and maximum thicknesses are 31 m, 16 m, 10 m, and 19 m, respectively.

Parasequence 2e has its landward pinch-out, in Quitchapah Creek Canyon, about 0.5 km seaward from the pinch-out of Parasequence 2d. In Bear Gulch, Parasequence 2e lies upon a highly bioturbated transgressive lag deposit. This transgressive lag deposit can be traced over 3 km northward into Muddy Creek Canyon, where it goes into the subsurface. Parasequence 2e has a very small stream mouth bar deposit and for much of its length. In Muddy Creek Canyon, it has distal delta front and prodelta facies lying stratigraphically above the stream mouth bar deposits of Parasequence 2d, suggesting a slight back-stepping relative to Parasequence 2d. Based on these observations, Parasequence 2e has been assigned to the stratigraphically higher Parasequence Set 2B. Due to severe degrees of erosional truncation by overlying fluvial deposits, it cannot be determined whether additional parasequences existed in Parasequence Set 2B prior to Parasequence Set 2C fluvial erosion.

From North Quitchapah Creek Canyon, near the Emery Mine, to Muddy Creek Canyon, Parasequence Set 2C consists of a major fluvial channel belt complex that incises up to 25 m deep into Parasequence 2A and 2B. South of I-70, this incision is represented only as an erosional unconformity, with up to 30 m of relief, as most of the sediment was by-passed some 5 km seaward to the northeast. This fluvial system marks a basinward shift of 3 km and a substantial base level fall. The wave-modified, river dominated, near-marine sandstones of Parasequence 2C, represented by Parasequences 2f, 2g, 2h, 2i, and 2j have their landward pinch-outs in South Muddy Creek Canyon, Muddy Creek Canyon, north of Bitter Seep Wash on the Molen Reef, Dry Wash, and near Short Canyon, respectively. Parasequences 2f and 2g are near vertically stacked. Parasequences 2h, 2i, and 2j represent seaward steps of 6.7 km, 1.2 km, and 7.5 km respectively. The near-marine facies of Parasequences 2f, 2g, 2h, 2i, and 2j are approximately 16.2 km, 16.8 km, 11.6 km, 16.7 km, and 13.3 km in dip length, respectively and maximum thicknesses are 8 m, 10 m, 13 m, 15 m, and 11 m, respectively. Locally, in the Miller Canyon area, the upper part of Parasequence Set 2C contains small laterally restricted flood tidal delta deposits. These deposits are intimately associated with the A *coal zone.*

Parasequence Set 2C is capped by the A *coal zone* (fig. 3). In Blue Trail Canyon, the A *coal zone* splits into three components denoted A1, A2, and A3; the A1 *coal zone* disappears near I-70; only the A2 and A3 *coal zones* can be seen in Quitchapah Creek Canyon. In the region from just south of Bear Gulch to Muddy Creek, the A *coal zone* lies conformably below the C *coal zone.* The A *coal zone* extends over 40 km, from the Limestone Cliffs to just north of Dry Wash. Most of the coal deposited at the top of Parasequence Sets 2A and 2B was probably subsequently removed by erosion and is now represented only by the unconformity between FS1 and FS2. This will be discussed in more detail below.

Parasequence Set 3

Parasequence Set 3 contains 2 wave-modified, river-dominated parasequences, that exhibit an aggradational to seaward-stepping stacking pattern (fig. 3). The near-marine sandstones of Parasequence Set 3 extend about 22 km in the dip direction. Parasequence Set 3 contains 2 parasequences, denoted Parasequences 3a and 3b. In the southern half of the outcrop belt, Parasequence Set 3 is represented by non-marine delta plain facies associations composed of delta plain mudstones, large distributary channel belts, crevasse splay sandstones, over-bank deposits, and carbonaceous shales and siltstones.

The near-marine parasequences in Ferron Parasequence Set 3 exhibit both vertical and lateral facies changes from (1) stream mouth bar and reworked stream mouth bar (frequently preserved as upper shoreface deposits (USF)), to (2) reworked delta front (pDF and dDF) (frequently preserved as middle (MSF) and lower shoreface (LSF) deposits), to (3) prodelta. From Cedar Ridge Canyon to Dry Wash, Parasequence Set 3 also contains tidal inlet and channel deposits.

Parasequences 3a and 3b represent delta lobes with a general east-northeastern progradational direction (075° azimuth). This paleoshoreline is much north-south oriented (approximately 345° azimuth) than that of underlying and overlying parasequence sets. Parasequence 3a and 3b have near-marine facies that are 10.8 km and 20.8 km in dip length, respectively, and maximum thicknesses of 5 m and

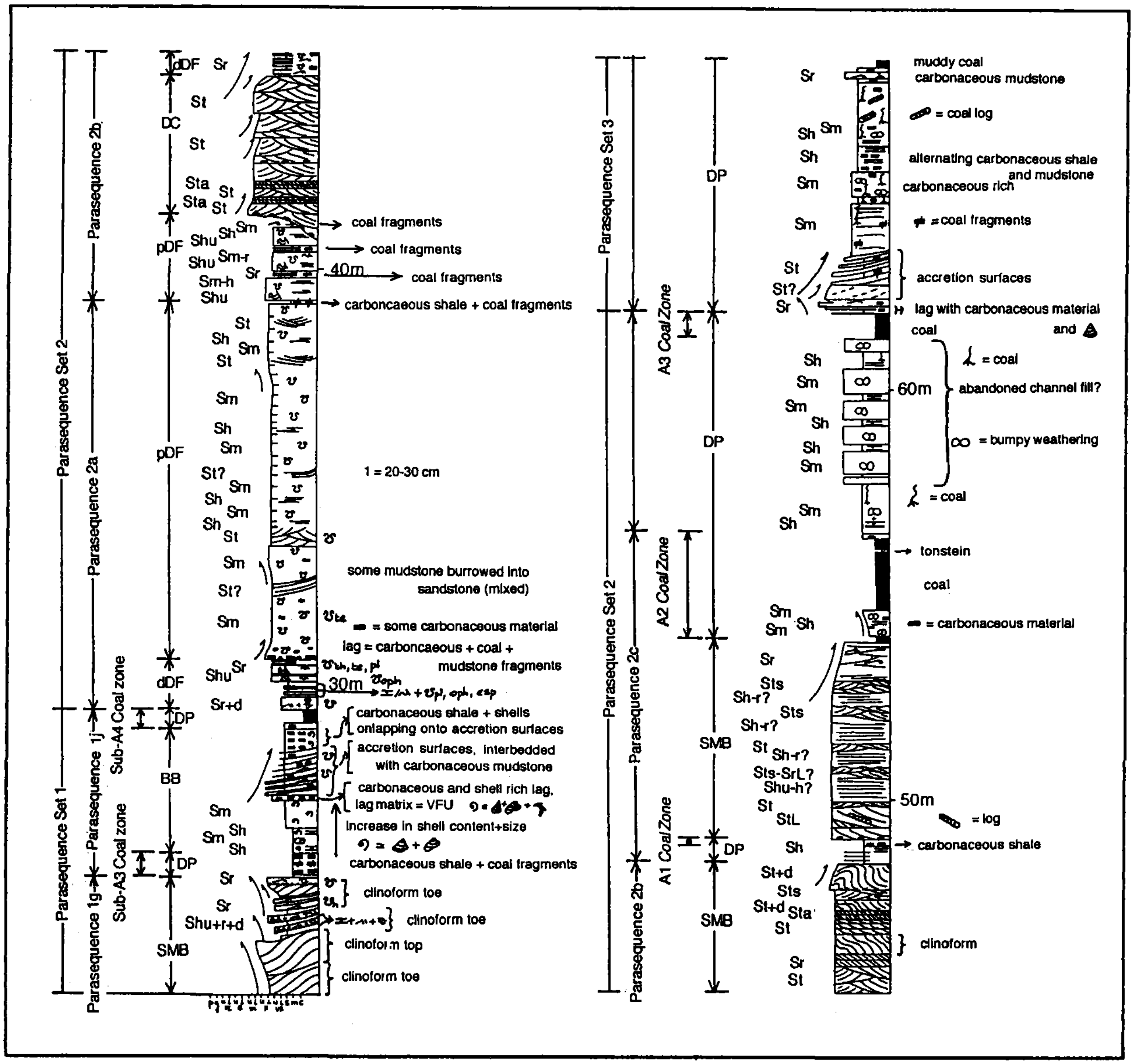
Figure 6. Photograph of the Upper Ferron Sandstone Parasequence Set 2A at the I-70 roadcut.

16 m, respectively. Parasequence 3b steps seaward less 1 km relative to Parasequence 3a. Parasequence 3a steps landward 13 km relative to the youngest parasequence in Parasequence Set 2C.

Parasequence Set 3 is capped by the C *coal zone.* The C *coal zone* extends over 35 km from the Limestone Cliffs to it seaward pinch-out in Cedar Ridge Canyon. In Willow Springs Wash, the C *coal zone* splits into two components denoted C1 and C2; the C2 *coal zone* appears to not be present further down-dip than north Quitchapah Creek; the C1 *coal zone* locally splits into two components near Rock Canyon, but merges at Blue Trail Canyon and splits again at Ivie Creek, but merges again just south of Bear Gulch. The C *coal zone* has multiple tonstein layers. The C2 *coal zone* tonstein can be traced from Ivie Creek to its pinch-out in north Quitchapah Creek. The thickest tonstein in the C1 *coal zone* can be traced from Corbula Gulch, just south of Blue Trail, northward to northern portions of Muddy Creek, near Pictograph Point. Numerous smaller tonsteins can also be correlated from north of I-70 to Muddy Creek.

Aggradational Parasequence Sets

In the context of the larger scale 3rd-order Ferron Sequence defined by Gardner (1993), the delta cycles represented by Ferron Parasequence Sets 4A–4B and 5A–5B are essentially vertically stacked (i.e., aggradational) (fig. 3). In the southern 25 km of the outcrop belt, Parasequence Sets 4A, 4B, 5A, and 5B are represented by non-marine delta plain facies associations composed of delta plain mudstones, large distributary channel belts, crevasse splay sandstones, over-bank deposits, and carbonaceous shales and siltstones. *Coal zones* occur at or near the top of Parasequence Sets 4B and 5B, with the thickest portion of the *coal zones* occurring near the landward pinch-out of the near-marine delta-front sandstones. Parasequence Set 4B is capped by the G *coal zone* and Parasequence Set 5B is capped by the I *coal zone.* The near-marine facies of Parasequence Set 4A and 5A are sub-regionally bounded above by erosional unconformities representing 4th-order depositional sequence boundaries.



SMB	stream mouth bar	pDF	proximal delta front	dDF	distal delta front
PD	prodelta	DC	distributary channel	DP	delta plain
BB	brackish bay deposit		horizontal bedding		ripples
	grain-size change		trough crossbeds		contorted bedding
	hummocky stratification	1	bed	2	bedset
Sm	massive	Sh	horizontal bedding	Sr	ripple stratification
St	trough cross-stratified	Sd	deformed stratification	Shu	hummocky stratification
Sta	tabular stratification	∞	bumpy weathering		load cast
	coal		carbonaceous material		roots
	log		coal fragments		intrabasinal pebbles
	brackish water fossil		gastropod		oyster
	bivalve		burrow (trace fossil)		horizontal burrow
	vertical burrow		escape burrow		*Ophiomorpha*
	Thalassinoides		*Planolites*		*Teichichnus*

Figure 7. Measured section through the Upper Ferron Sandstone Parasequence Set 2A at the I-70 roadcut.

Parasequence Set 4A and 4B

Parasequence Sets 4A and 4B appears to contain only one parasequence (fig.3). The near-marine facies of the single parasequence in each Parasequence Sets 4A and 4B represent wave-dominated, wave-reworked delta front deposits. Near-marine facies of the parasequences in Parasequence 4a is 15.0 km, and the maximum thickness is approximately 28 m. Near-marine facies of the Parasequences 4b, in Parasequence Set 4B, is 11.2 km in dip length with a maximum thicknesses of approximately 20 m. The near-marine facies of both parasequences exhibit vertical and lateral facies changes from (1) stream mouth bar and reworked stream mouth bar (frequently preserved as upper shoreface deposits (USF)), to (2) reworked delta front (pDF and dDF) (frequently preserved as middle (MSF) and lower shoreface (LSF) deposits), to (3) prodelta. The stream mouth bar and reworked stream mouth bar deposits contain trough and herringbone stratification and frequently contain the ichnofossil *Ophiomorpha.* The reworked delta front deposits (pDF and dDF) contain hummocky, planar, and ripple cross-stratification and frequently the ichnofossils *Ophiomorpha, Teichichnus, Chondrites, Cylindrichnus, Arenicolites, Diplocraterion, and Thalassinoides.*

In Miller Canyon, Parasequence 4a of Parasequence Set 4A rests on a transgressive lag deposit. This deposit reworks the upper part of the C *coal zone* and exhibits extreme bioturbation. This transgressive deposit can be traced northward over 13 km to Dry Wash. The paleoshoreline of the near-marine facies of Parasequence 4a shifts landward approximately 7 km relative to the paleoshoreline of underlying Parasequence 3b. In Miller Canyon and southward into Bear Gulch, there is approximately 20 m of erosional relief developed on Parasequence Set 4A, as fluvial channel belts of Parasequence Set 4B scour down into the underlying parasequence (fig 8). The paleoshoreline of the near-marine facies of Parasequence Set 4B shifts basinward some 7 km relative to the paleoshoreline of Parasequence Set 4A and is accompanied by at least 32 m of erosion. This change in shoreline position and baselevel and the development of the erosional unconformity indicate that the boundary between Parasequence Sets 4A and 4B is the sequence boundary between 4th-order depositional sequences FS2 and FS3. In the non-marine part of the Parasequence Set 4A, south of Bear Gulch, Parasequence Set 4A is capped by a very laterally extensive rooted zone (designated the E Rooted Zone). This rooted zone can be traced from just north of Last Chance Creek northward to just south of Bear Gulch, where it is correlative with the erosional unconformity between Parasequence Set 4A and 4B cropping out in Bear Gulch and Miller Canyon.

The G *coal zone* caps Ferron Parasequence Set 4B. South of Indian Canyon, in the Limestone Cliffs, the G *coal zone* is completely scoured out by distributary channel belts and does not occur further south than Mussentuchit Wash. Curiously, the G *coal zone* does not split within the study area. The G *coal zone* extends over 27 km from its erosional limit in the Limestone Cliffs to it seaward limit north of Bitter Seep Canyon.

Parasequence Set 5A and 5B

Parasequence Set 5A is a progradational to aggradational set containing two parasequences (fig. 3). The near-marine facies of the parasequences in each Parasequence Sets 5A and 5B represent wave-dominated, wave-reworked delta front deposits. They all exhibit both vertical and lateral facies changes from (1) stream mouth bar and reworked stream mouth bar (frequently preserved as upper shoreface deposits (USF)), to (2) reworked delta front (pDF and dDF) (frequently preserved as middle (MSF) and lower shoreface (LSF) deposits), to (3) prodelta. The stream mouth bar and reworked stream mouth bar deposits contain trough stratification and frequently contain *Ophiomorpha.* The reworked delta front deposits (pDF and dDF) contain hummocky, planar, and ripple cross-stratification and are commonly contain the ichnofossils *Ophiomorpha and Thalassinoides* and occasionally *Skolithos.*

The landward pinchout of Parasequence 5b is truncated by fluvial channels of Parasequence Set 5B, but can be located to within 1 km. This erosion makes estimates of maximum length and thickness problematic. Near-marine facies of the Parasequences 5a, and 5b, in Parasequence Set 5A, are approximately 10.4 km, and 9.6 km in dip length, respectively, and maximum thicknesses are approximately 14 m, and 15 m, respectively. The estimated overall dip length of Parasequence Set 5A is approximately 11 km with a maximum thickness of approximately 33 m. The near-marine facies of the Parasequence 5c, in Parasequence Set 5B, is 8.5 km in dip length and has a maximum thickness of 16 m.

Parasequence Set 5A backsteps landward about 2.2 km, from the position of the landward pinch-out of Parasequence Set 4B. From the southern goosenecks of Muddy Creek Canyon to Picture Flats, the top of Parasequence Set 5A has from 10 to 20 m of erosional relief developed, as fluvial channel belts of Parasequence Set 5B scour down into the underlying parasequence set. This represents a basinward shift of at least 3 km. Within progradational to aggradational Parasequence Set 5A, Parasequence 5b steps seaward 0.7 km, relative to the underlying Parasequences 5a.

The I *coal zone* caps Ferron Parasequence Set 5B. South of Indian Canyon, in the Limestone Cliffs, the I *coal zones* are completely scoured out by distributary channel belts and does not occur further south than Mussentuchit Wash.

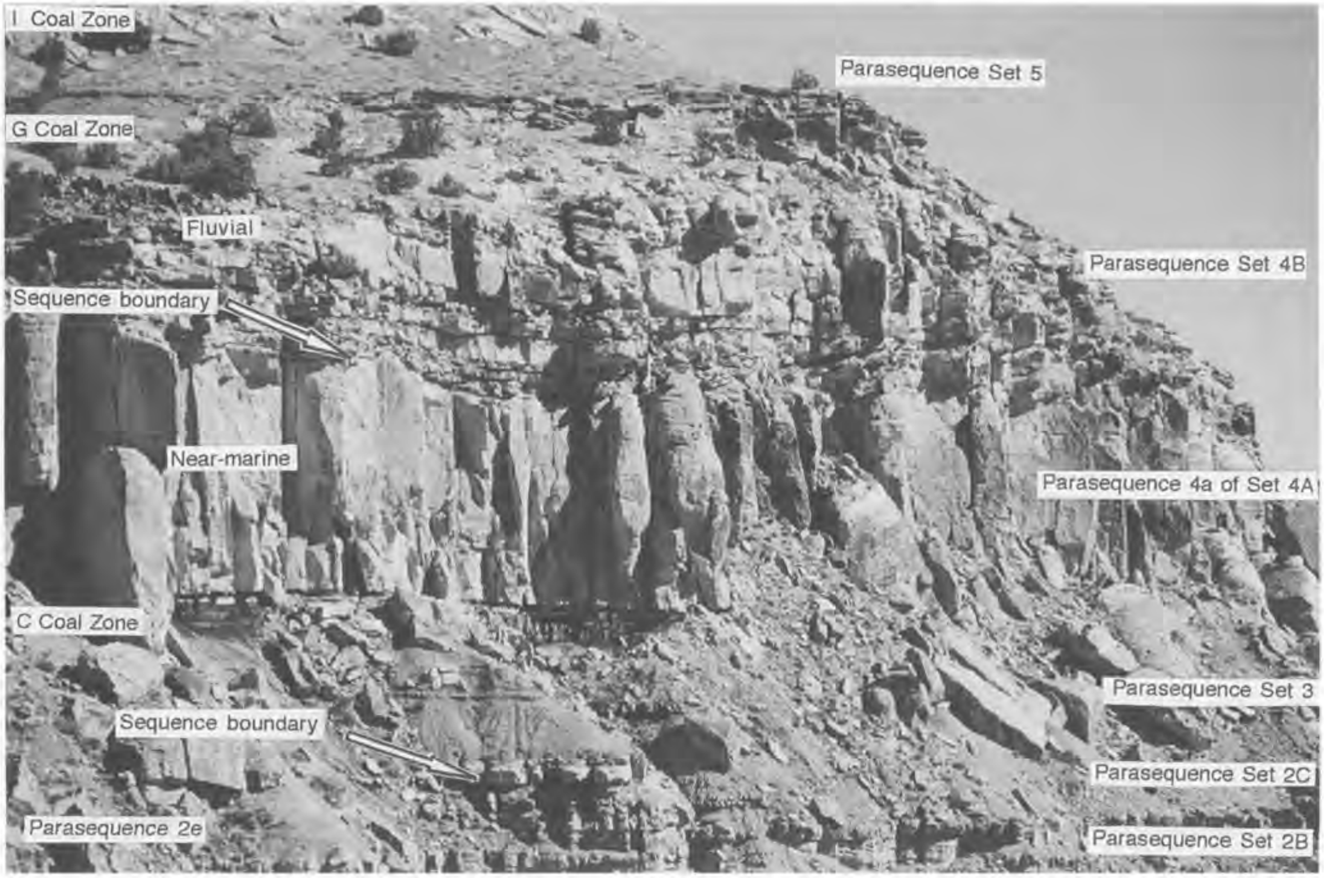


Figure 8. Photograph showing the sequence boundary separating Upper Ferron Parasequence Sets 4A and 4B in Bear Gulch.

South of Coyote Basin, the I *coal zone* splits into three zones, denoted as the I_1, I_2, and I_3 *coal zones.*

Landward-Stepping Parasequence Sets

Ferron Parasequence Sets 6, 7, and 8 each progressively step landward, relative to the older, underlying parasequence sets (Gardner, 1993) (fig. 3). Along most of the outcrop belt, Parasequence Sets 6, 7, and 8 are represented by delta plain facies associations composed of delta plain mudstones, wide distributary channel belts, crevasse splay sandstones, over-bank deposits, and carbonaceous shales and siltstones. Parasequence Sets 6, 7, and 8 contain one, four, and two parasequences, respectively. The near-marine facies of the parasequences in each Parasequence Sets 6, 7, and 8 represent a wave-dominated, wave-reworked delta front deposit. They all exhibit both vertical and lateral facies changes from (1) stream mouth bar and reworked stream mouth bar (frequently preserved as upper shoreface deposits (USF)), to (2) reworked delta front (pDF and dDF) (frequently preserved as middle (MSF) and lower shoreface (LSF) deposits), to (3) prodelta. The stream mouth bar and reworked stream mouth bar deposits contain trough stratification and frequently contain *Ophiomorpha* and *Arenicolites.* The reworked delta front deposits (pDF and dDF) contain hummocky, planar, and ripple cross-stratification and commonly contain the ichnofossils *Ophiomorpha and Thalassinoides.* Locally, the base of Parasequence Set 7, resting on the J *coal zone*, contains the trace fossils *Teichichnus, Thalassinoides, Planolites,* and *Rhizocorallium.*

Near-marine facies of Parasequence Sets 6, 7, and 8 are approximately 2.8 km, 6.7 km, and 5.4 km, in dip length, respectively. The thicknesses of the near-marine facies of the Parasequence Sets 6, 7, and 8 are 6 m, 8 m, and 7 m, respectively. Parasequence 6a of Parasequence Set 6 is 2.8 km in dip length and has a maximum thickness of 6.4 m. Parasequence 6a backsteps 2 km relative to Parasequence Set 5B. Parasequences 7a, 7b, 7c, and 7d of Parasequence Set 7 are 1.3 km, 2.4 km, 3.2 km, and 3.8 km in dip length and have maximum thicknesses of 3.6 m, 2.1 m, 8.5 m, and 3.6 m, respectively. Parasequence Set 7 is a retrogradational parasequence set with the near-marine facies of Parasequence 7d back-stepped landward 2.9 km, relative to Parasequence 7c. Parasequence 7c backsteps 1.4 km landward, relative to Parasequence 7b and Parasequence Set 7b backsteps 1.7 km landward, relative to 7a. Parasequence 7a steps landward 0.2 km, relative to Parasequence Set 6. Parasequences 8a and 8b of Parasequence Set 8 are 2.8 km and 3.4 km in dip length and have maximum thicknesses of 3.2 m and 3.4 m, respectively. Parasequence Set 8 is a retrogradational parasequence set with the near-marine facies of Parasequence 8b back-stepped landward 2.0 km, relative to Parasequence 8a. Between south Quitchapah Creek and the Emery Mine, Parasequence 8 is separated from Parasequence Set 7 by a extra-basinal pebble lag. The pebbles range from 1 cm up to 10 cm in length and are found nowhere else in the Upper Ferron Sandstone. In some areas, these pebbles are found floating throughout the near-marine facies of Parasequence Set 8.

Coal zones occur at or near the top of these depositional Parasequence Sets 6 and 7. The J *coal zone* caps Ferron Parasequence Set 6; the M *coal zone* caps Ferron Parasequence Set 7. The M *coal zone* capping Parasequence Set 7 is only exposed from North Fork Canyon to Willow Springs Wash and from Ivie Creek to south Quitchapah Creek Canyon. North of Willow Springs Wash, the top of Parasequence Set 7 is represented only as a burrowed transgressive surface; the burrows are marine *Thalassinoides* belonging to the *Skolithos* ichnofacies. South of North Fork Canyon the surface is rooted and is burrowed by non-marine Scoynia. In the Muddy Creek Canyon area, Parasequence Set 7 is capped by a thin shale interval containing septarian nodules. Parasequence Set 8 is locally capped by lag of oyster fragments and a thin shale interval containing septarian nodules.

Architectural Systematics of Near-Marine Facies

A plot of dip length versus thickness for Ferron Parasequence Sets and Parasequences is shown in figure 9. Examining the dimensions of parasequence sets and parasequences, clear trends can be discerned. When classified according to their delta cycle stacking arrangement in the 3rd-order Ferron Sequence (Gardner, 1993), the total near-marine facies of the parasequence sets occupy distinct fields on the plot of dip length versus thickness. The 3rd-order seaward-stepping Parasequence Sets 1, 2A–2C, and 3 have mean dip lengths of 24 km with mean thicknesses of 24 m; the mean aspect ratio (i.e., length/thickness) is 1180. The 3rd-order aggradational Parasequence Sets 4A–4B and 5A–5B have mean dip lengths of 11 km with mean thicknesses of 24 m; the mean aspect ratio is 490. The 3rd-order landward-stepping Parasequence Sets 6, 7, and 8 have mean dip lengths of 5 km with mean thicknesses of 7 m; the mean aspect ratio is 682. This suggests that the general trend in 3rd-order delta cycle evolution within the Ferron Sequence (Gardner, 1993) is one of first seaward-stepping of thick, long parasequence sets, followed by the aggradation of thick, short parasequence sets, and finally followed by the back-stepping of thin, short parasequence sets. When considered in the context of the slow 3rd-order sea-level rise, this overall trend can be explained by a systematic decrease in sediment supply. In the seaward-stepping parasequence sets, sediment supply is large relative to available accommodation space, resulting in substantial seaward-stepping (i.e., progradation) of the deltas. Very early in this period (i.e., Parasequence Set 1 time), the deltas were extremely river dominated, with little wave-reworking. Later, there is an increase in the degree of wave-reworking, but still an abundance of sediment for major seaward progradation. Midway through the Ferron deposition (i.e. the aggradational phase of the 3rd-order cycle), sediment supply declined. This, coupled with substantial wave reworking slowed the seaward progradation, allowing aggradation of several delta cycles. In the final phase (i.e., during the back-stepping phase of Ferron deposition), sediment supply decreased dramatically resulting in small retrogradational deltas and a retreat of the paleoshorelines. These well defined trends suggest that the 4th-order depositional sequence events, described above, are superimposed on the 3rd-order sediment supply/accommodation space driven trends and that the superimposed 4th-order internal stacking patterns have little overall geometrical effects.

Examination of the dip length and thickness systematics, at the parasequence scale, reveals groupings based on the degree of wave-reworking (fig. 9). In particular, in the seaward-stepping phase of the 3rd-order cycle where both river-dominated parasequences and wave-reworked parasequences occur, the effects of degree of wave-reworking is very evident. In the very river-dominated Parasequence Set 1, the average near-marine facies of the parasequences is 15 m thick and 5.4 km long, with a mean aspect ratio of 400. The strike dimensions of parasequences suggest that these deltas had dip length/strike width aspect ratios near 1.8. These systematics are reasonable in light of the typical morphology and avulsion frequency exhibited by river-dominated deltas. The river-dominated, but wave-reworked near-marine facies of parasequences of Parasequence Sets 2A, 2C, and 3 are similar in thickness, with a mean thickness of 15 m, but have substantially longer dip lengths, averaging 15.9 km, and higher aspect ratios (e.g., mean aspect ratio is 1124). The length and thickness systematics of the parasequences belonging to the 3rd-order aggradational phase of Ferron deposition are somewhat thinner than the wave-reworked seaward-stepping deltas (i.e. mean thickness is 19 m), and shorter in dip length (i.e., mean dip length is 11 km); mean aspect ratio is 602. This decrease in progradational length reflects the overprint of a declining sediment supply, as discussed above. The parasequences

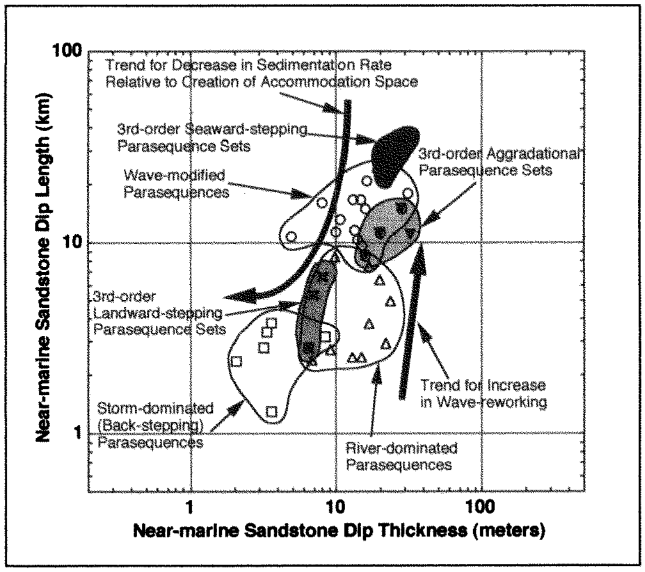


Figure 9. Plot of dip length versus thickness for Upper Ferron Sandstone Parasequence Sets and Parasequences.

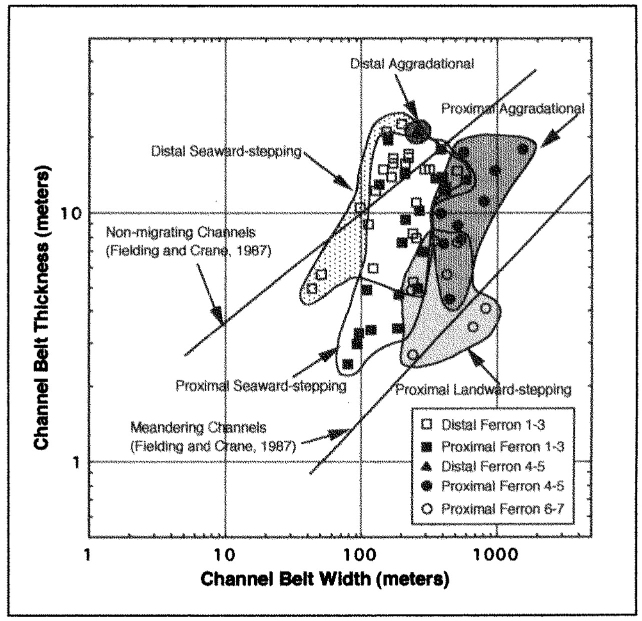


Figure 10. Plot of thickness versus width of Upper Ferron Sandstone channel belts.

belonging to the back-stepping phase of Ferron deposition have lengths and thickness that appear to be mainly controlled by the continued, but dramatic, decrease in sediment supply. They are shorter in dip length, with mean lengths of only 2.8 km, and are thin, with mean thicknesses of only 4 m, resulting in a mean aspect ratio of 754.

It is clear from these dimensional data that the volume of sediment progressively decreased throughout Ferron deltaic deposition. No relationship can be found with the positions of parasequences or parasequence sets within the higher frequency 4th-order sequences. Therefore, it can be assumed that the effects of the 4th-order sea-level fluctuations were over-shadowed by the overwhelming effects of a constantly varying sediment supply.

Architectural Systematics of Non-marine Channel Belt Sandstones

A favorable strike outcrop section that exposes almost the complete delta plain facies association of the Ferron Sandstone stratigraphic interval is located in Willow Springs Wash, Willow Springs Quadrangle, Emery and Sevier Counties (fig. 1). Outcrop studies to quantify the sizes and shapes of Ferron Sandstone fluvial channel belts were conducted by the authors in Willow Springs Wash, along both the north and south canyon walls (van den Bergh, 1995; van den Bergh and Garrison, 1996). These data represent the majority of the data for the following discussion and subsequent statistical analyses. Barton (1994) and Lowry and Jacobsen (1993) acquired data for some fluvial channel belts farther north from Willow Springs Wash; this data is also included in the following analysis.

Examination of the channels belts in Willow Springs Wash reveals clear differences in channel belt internal and external architecture as a function of channel position within the stacking arrangement in the 3rd-order Ferron Sequence (fig. 10). The fluvial channel belts of seaward-stepping parasequence sets are generally laterally restricted and multi-storied with channel filling elements (i.e., macroforms and/or barforms) generally stacked vertically within the channel belt boundaries. The fluvial channel belts of aggradational parasequence sets are generally quite laterally extensive and multi-storied with channel filling elements generally stacked en echelon laterally within the channel belt boundaries. The fluvial channel belts of landward-stepping parasequence sets are laterally extensive and sheet-like with channel filling elements generally stacked vertically within the channel belt boundaries.

The proximal seaward-stepping fluvial channel belts (i.e., those channel belt cross-sections that are located near the upper delta plain and adjoining the alluvial plain) in Willow Springs Wash have a bimodal thickness distribution ranging in thickness from 2.4 m to 20.1 m with thicknesses between 3–5 m and 12–14 m being most common. Their widths range from 77 m to 580 m, with widths near 90–220 and 360–430 m being most common. The width/thickness aspect ratios range from 7.8 to 52.9, with an average of 29.5 (fig. 10). The distal distributary channel belts (i.e., those near the paleoshoreline) are generally narrower and thicker than the proximal channel belts with widths ranging from 43 m to 510 m, averaging 195 m, and thicknesses ranging from 4.9 m to 22.9 m, with thickness of 5–9 and 15–18 m being most common. The aspect ratios of the distal distributary channel belts are also much less than those of the proximal channel belts ranging from 7.1 to 45.5, averaging 16.6. This change in size and shape of the seaward-stepping distributary channel belts is consistent with the change in channel morphology resulting from river bifurcation.

The proximal aggradational distributary channel belts in Willow Springs Wash have a bimodal thickness distribution ranging in thickness from 4.6 m to 18.3 m, with thicknesses between 8–11 m and 17–18 m being most common. Their widths range from 380 m to 1448 m, with widths near 380–580 m being most common. The width/thickness aspect ratios range from 31.9 to 97.4, with an average of 57.2 (fig. 10). The distal distributary channel belt, reported by Barton (1994) at Cedar Ridge, is generally narrower and thicker than the proximal channel belts with a width of 255 m, and a thickness of 21.3 m. The aspect ratio of 12.0 for the distal distributary channel belt at Bitter Seep Canyon is also much less than those of the proximal channel belts. This change in size and shape of the aggradational fluvial channel belts is consistent with the change in channel morphology resulting from river bifurcation. The proximal aggradational fluvial channel belts in Willow Springs Wash are generally much wider than the seaward-stepping channel belts, while the thicknesses are generally slightly greater; aspect ratios of the aggradational fluvial channel belts are a factor of two higher that those of the proximal channel belts.

The proximal landward stepping fluvial channel belts in Willow Springs Wash have a thickness distribution ranging in thickness from 2.7 m to 7.9 m, averaging 5 m in thickness. Their widths are uniformly distributed from 228 m to 809 m. The width/thickness aspect ratios range from 43.8 to 195.0, with aspect ratios near 65–90 and 185–195 being most common (fig. 10). The landward-stepping channel belts in Willow Springs Wash are similar in width to the proximal channel belts, but generally much wider than the seaward-stepping channel belts; these channel belts are generally thinner that either the aggradational or seaward-stepping channel belts; aspect ratios of the landward-stepping fluvial channel belts are generally higher that those of the aggradational and seaward-stepping channel belts.

The aspect ratio distributions for the individual channel fill elements within the fluvial channel belts, are similar, regardless of position within the deltaic stacking pattern, suggesting that only channel belt internal stacking patterns vary between the fluvial channel belts within the Ferron seaward-stepping, aggradational, and landward-stepping stacking pattern. The proximal channel belt fill elements are generally thicker and wider than the distal channel belt fill elements. This change in size of the distal fluvial channel belt macroforms is also consistent with the change in channel morphology resulting from river bifurcation.

The channel belts, in context of their position within the Ferron stacking pattern, exhibit clear differences in channel belt internal and external architecture as a function of stacking pattern. Channel belts evolve through the spectrum from supplying the purely river-dominated to the lobate wave-dominated to the strand/beach type strongly wave-dominated deltaic systems. As they move from river-dominated, seaward-stepping deltaic systems to more wave-dominated aggradational systems, they change from multi-storied belts with channel fill elements stacked vertically within the channel belt boundaries to increasingly wider and quite laterally extensive multi-storied channel belts with channel fill elements generally stacked in echelon laterally within the channel belt boundaries. As the deltas begin to step landward during strong (relative) transgressions, the channel belt morphology responds by becoming thinner and narrower, yet still quite laterally extensive.

Lithologic Composition of Coal Zones

Analysis of the *coal zone* thicknesses and compositions obtained from detailed measured sections has allowed some quantification of *coal zone* systematics as a function of dip length along the Ferron delta cycles (i.e., parasequence sets). Choosing an appropriate datum, with respect to which systematics are to be examined is difficult and problematic. One might choose the landward pinch-out of the near-marine facies of a parasequence set, or the landward pinch-out of the stratigraphically highest parasequence in the parasequence set, or the mean paleoshoreline position for the parasequence set, or the mean position of the paleoshoreline of the highest parasequence in the parasequence set. In this paper, the *coal zone* systematics are examined as a function of position along the dip cross-section of Garrison and van den Bergh (1996; 1997) (fig. 1), but the details of the *coal zones* are discussed in terms of the general architecture of the underlying parasequence set. In this analysis, the coal seam and *coal zone* thicknesses are the sums of all coal seams and *coal zone* thicknesses of all splits of the *coal zone* at the sampling location. The total *coal zone* thickness is the sum of the thicknesses of the coal seams, the carbonaceous shales, mudstones, and siltstones, tonsteins, paleosols, and delta plain mudstones and siltstones included within the coal zone.

Coal zones generally thicken landward relative to the mean position of the landward pinch-out of the underlying parasequence set, but after some distance landward, they decrease in thickness. This can be seen well in a plot of *coal zone* thickness and coal thickness versus distance for the C

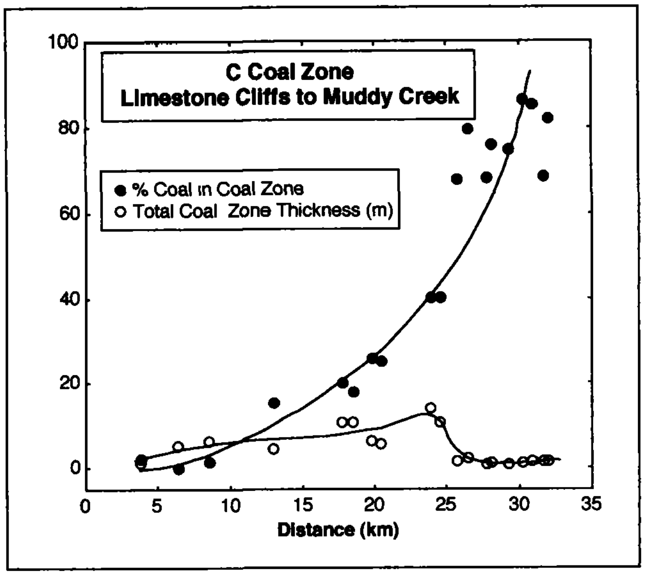


Figure 11. Thickness profile of Upper Ferron C coal zone *along its dip length.*

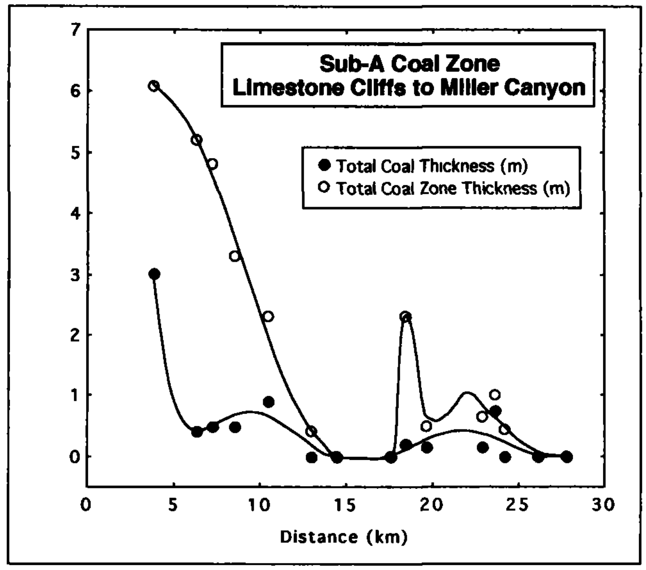


*Figure 12. Thickness profile of Upper Ferron sub-*A coal zone *along its dip length.*

coal zone, from Limestone Cliffs to Muddy Creek Canyon (fig. 11). In this plot, the C *coal zone* progressively increases in thickness in a landward direction until it reaches a maximum thickness of 13.8 m, at Cowboy Mine Canyon, about 6 km landward of the approximate projected position of the landward pinch-out of Parasequence 3a in Parasequence Set 3; further south the zone continually decreases in thickness. The coal is thickest in the region between this landward pinch-out and the position of maximum zone thickness. The data indicate that the proportion of coal in the *coal zone* decreases progressively landward from the landward pinch-out of Parasequence Set 3 (fig. 11). The balance of the *coal zone* is composed of carbonaceous shale and mudstone; with tonstein and delta plain mudstone and siltstone occurring as minor constituents.

Coal zones generally thin seaward relative to the mean position of the landward pinch-out of the underlying parasequence set. This is particularly well shown in the data for the sub-A *coal zone* (fig. 12). The landward extent of the sub-A *coal zone* cannot be determined because it occurs south of the Ferron outcrop belt. Therefore, the outcrops of the sub-A are seaward of the landward pinch-out of the oldest near-marine rocks of Parasequence Set 1. The sub-A *coal zone* appears to have two distinct parts, the southern most part is composed of the sub-A1 and sub-A2 splits and overlies Parasequences 1z–1d, and the northern part consists of the sub-A3 and sub-A4 splits and overlies Parasequences 1e–1k. The composite sub-A1+A2 portion of the sub-A *coal zone* decreases dramatically in thickness in a seaward direction, from 6.1 m in the Limestone Cliffs to 0.5 m in Rock Canyon, before pinching out in Corbula Gulch. The composite sub-A3+A4 portion of the sub-A *coal zone* also decreases dramatically in thickness in a seaward direction, from 2.4 m in Scabby Canyon to 0.5 m in north Quitchapah Creek Canyon, before pinching out near Bear Gulch. These systematics suggest that the sub-A should actually be divided into 2 distinct *coal zones*. Examining composite sub-A1+A2 coal thickness, in light of the position of the near-marine pinch-out of Parasequence 1d, in Coyote Basin, it appears that the coals become thicker just landward of this position. The same is true of the composite sub-A3+A4 coal thickness, where it becomes thicker near the landward pinch-out of Parasequence 1k in Quitchapah Creek Canyon.

The effects of differential compaction and differences in original pre-peat swamp topography have the effect of adding perturbations to the general trends discussed above. The A *coal zone* illustrates this particularly well (fig. 13). Almost the entire A *coal zone* is exposed in the outcrop belt from Limestone Cliffs, where it is only 0.7 m thick, to its seaward pinch-out just north of Dry Wash. In Dry Wash, the A *coal zone* is 1.9 m thick and contains 0.45 m of coal. This zone represents the seaward extension of the A *coal zone.* The A *coal zone* has its minimum thicknesses near its landward limit and then again as it approaches its seaward limit. The most notable feature of the A *coal zone* is that it does not thicken to a maximum and then thin seaward, but has at least 4 distinct maxima. The A *coal zone* has its thick-

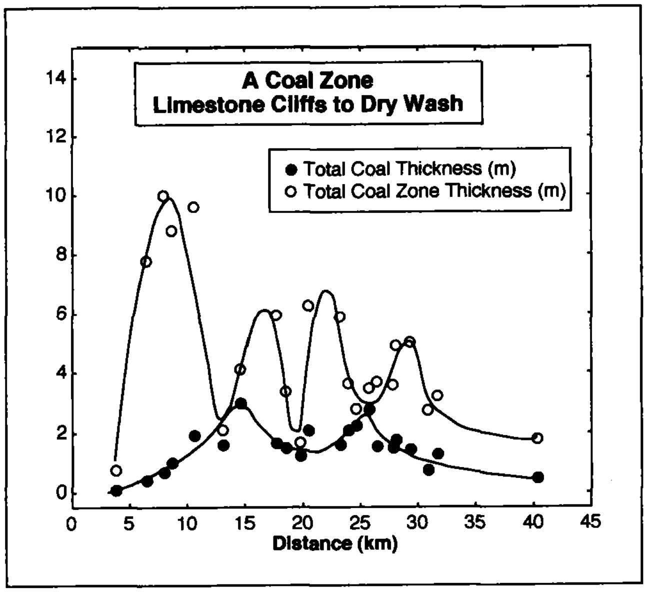


Figure 13. Thickness profile of Upper Ferron A coal zone *along its dip length.*

est accumulations just south of Coyote Basin (8.8 m thick) and just north of Ivie Creek and Quitchapah Creek Canyon (6.4 m thick). In the vicinity of Rock Canyon and Corbula Gulch and at I-70, the A *coal zone* appears to be abnormally thin. The coal is thickest in the area near Rock Canyon and to the north in Quitchapah Creek Canyon. In the vicinities of Rock Canyon and I-70, the A *coal zone* is composed of about 75% coal. The compaction of the *coal zone* (i.e., the original peat accumulation) was greater in these areas than in Coyote Basin, where it is composed of 20% coal, 56% carbonaceous shale, and 24% interlayered delta plain mudstones, and north of Ivie Creek area, where it is composed of 58% coal, 17% carbonaceous shale, and 25% delta plain mudstones. The A *coal zone* appears to be associated with the landward pinch-out of Parasequence Set 2C, because, except for a small A coal "split" between South Blue Trail Canyon and I-70, the A *coal zone* lies above the erosional unconformity on Parasequence Sets 2A and 2B, marking the sequence boundary between FS1 and FS2. Most of the older coals associated with Parasequence Sets 2A and 2B must have been removed by erosion. The only exceptions may be in the area south of Willow Springs Wash, where the zone becomes extremely thick, and in the area immediately south of I-70.

Altered Volcanic Ash Layers in *Coal Zones* (Tonsteins)

In the Ferron Sandstone, *coal zones* frequently contain volcanic ash layers (Ryer et al., 1980; Garrison and van den Bergh, 1996). These volcanic ash horizons are characterized as laterally continuous kaolinitic claystone partings called "tonsteins" (Williamson, 1970). These tonsteins are greenish-white to gray in color and contain kaolinite booklets, beta quartz, volcanic K-feldspars, Fe-oxide and Ti-oxide minerals, and zircons (fig. 14) (van den Bergh, 1995). Tonsteins have been found in all major *coal zones* in the Ferron Sandstone (Garrison and van den Bergh, 1997). Many *coal zones* contain multiple tonstein layers. The tonsteins associated with these *coal zones* document near time synchroneity of the *coal zone* horizons, but splits in *coal zones* clearly indicate significant time represented by these deposits.

In the 7 Ferron Sandstone *coal zones*, 13 distinct tonsteins have been identified. In the Limestone Cliffs, the sub-A2 *coal zone* contains a very well-developed tonstein. This sub-A2 tonstein has not been identified further down-dip. Both the A1 and A2 splits of the A *coal zone* contain tonstein layers. The tonstein in the A1 *coal zone* extends as far up-dip as the Limestone Cliffs and as far down-dip as Blue Trail Canyon. The tonstein in the A2 *coal zone* has been identified in Coyote Basin and at I-70/Ivie Creek. North of I-70, the A2 *coal zone* contains two tonsteins that can be traced northward to at least Bear Gulch. North of I-70, the C *coal zone* contains at least 2 tonsteins and occasionally up to four tonsteins. The thickest tonstein in the C *coal zone* has been traced from Corbula Gulch to Muddy Creek Canyon, a distance of over 16 km. No tonsteins have been identified in the C *coal zone* south of Corbula Gulch. A tonstein occurs in the G *coal zone* from Willow Springs Wash to Muddy Creek. A tonstein was identified in the I *coal zone* from Rock Canyon to Bear Gulch. The J *coal zone* contain a tonstein from Willow Springs Wash to Rochester Creek, a distance of about 23 km. From the South Goosenecks of Muddy Creek to Rochester Creek, the J *coal zone* also contain an additional tonstein layer. A tonstein has been identified in the discontinuous M *coal zone* in Willow Springs Wash and in Coal Wash, north of Ivie Creek.

Landward and seaward of near-marine pinch-outs of parasequence sets, preservation potential of volcanic ash layers decreases dramatically, as illustrated well by the sub-A1-A2 and C *coal zones*. The southern most 15 km of the C *coal zone*, in the outcrop belt, is devoid of tonstein. From Corbula Gulch to I-70 only a single tonstein is present in the C *coal zone*, in Bear Gulch four tonsteins are assigned to the C *coal zone*, in Miller Canyon 3 tonsteins occur, and about 4 km north of Miller Canyon, near Pictograph Point, where the C *coal zone* goes into the subsurface, it still contains 2 tonsteins. This is approximately 20 km landward of the seaward pinch-out of Parasequence Set 3. The composite sub-A1-A2 *coal zone* is devoid of tonstein seaward from the Limestone Cliffs to its seaward limit in Rock Canyon, a distance of over 8 km.

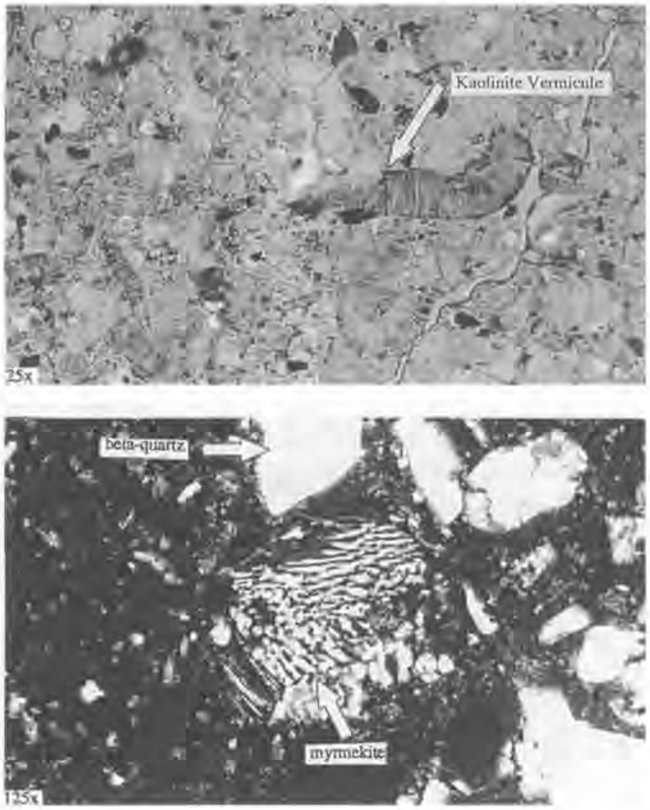


Figure 14. Photomicrographs of tonsteins within the A coal zone *(top) and the J* coal zone *(bottom).*

Depositional Sequence Stratigraphic History of the Last Chance Delta

Based on radiometric age dates of Obradovich (1991) and ammonoidea and inoceramadae faunal zonations, Gardner (1992) suggested that the Upper Turonian Ferron Sandstone Last Chance Delta was deposited between 89.8 and 88.8 m.y.b.p. During this period, the eustatic sea-level curves indicate a slow 2nd-order sea-level fall event, upon which are superimposed two 3rd-order sea-level cycles (Gardner, 1992). The tectonic activity in the Sevier orogenic belt was relative quite during this period, although a period of foreland basin expansion was occurring (Gardner, 1992). Based on the geochronology and faunal zone correlations, Gardner (1992) developed a relative sea-level curve for Central Utah and hypothesized that tectonic subsidence, coupled with the eustatic events, produced a local slow 3rd-order sea-level rise event in Central Utah during the Upper Turonian. The 3rd-order Ferron Sequence was deposited during this slow Upper Turonian 3rd-order sea-level rise.

Based on the geochronology and the sea-level curve developed by Gardner (1992), it is possible to speculate on the timing and durations of the depositional episodes occurring within the Ferron clastic wedge. The earliest deposition of Ferron Parasequence Set 1 occurred during the beginning of this slow sea-level rise, near 89.8 m.y.b.p. The youngest parasequence set of the outcrop belt, Parasequence Set 8, was deposited in earliest Coniacian time at about 88.8 m.y.b.p., while the local relative sea-level was still rising. Ryer (1994) suggested that this sea-level rise event was accompanied by an increase in sediment supply from the Sevier Orogenic Belt. The available stratigraphic and architectural data, for both near-marine and nonmarine facies, as quantified by Garrison and van den Bergh (1996; 1997) and van den Bergh and Garrison (1996), indicate that, when taken in the context of 3rd-order deltaic parasequence set stacking patterns, the over-all Ferron Sandstone Last Chance Deltaic deposition is controlled by sediment supply. This is also confirmed by the calculations of Gardner (1992), in which he demonstrated that the total volume of sediment progressively decreased during each successive depositional episode. The increased sediment supply, in the early stages of deltaic development, resulted in a volume of sediment that exceeded the available accommodation space, with subsequent deltaic events stepping seaward at a dramatic rate. During each successive deltaic cycle, less sediment was available, resulting in aggradation and eventual back-stepping of the final delta cycles (i.e. transgression), as the sediment supply could no longer keep pace with the rise in relative sea-level.

The 4th-order Upper Ferron Sequences FS1-FS4 are superimposed on the 3rd-order sea-level rise event and the 3rd-order stratigraphic architecture of the Ferron Sandstone. The dramatic erosional unconformities associated with the sequence boundaries at the tops of Upper Ferron Sequences FS1, FS2, and FS3, indicate that there was up to 20–30 m of erosion, signifying locally substantial base-level drops. These base-level drops were accompanied by a basinward shift in paleoshorelines by as much as 5–7 km.

The internal architecture of the 4th-order depositional sequences FS1–FS4, of the Ferron clastic wedge (fig. 3), also reflect the progressive change in the ratio of sediment supply to available accommodation space. 4th-order sequence FS1, formed during a period in which available sediment supply was much greater than available accommodation space. It has an internal architecture dominated by progradational parasequence sets. The transgressive phase is probably only represented by the transgressive lag deposit. The highstand parasequence set is poorly developed. 4th-order sequence FS2 formed during a period in which available sediment was initially greater than available accommodation space, but later became more balanced. It has an internal architecture consisting of a progradational parasequence set overlain by an aggradational parasequence set. A transgressive lag is well developed and is overlain by a well-developed highstand parasequence set. 4th-order sequence FS3 developed during a period when sediment supply was balanced with the rate of development of accommodation space. Its internal architecture is dominated by aggradational parasequences. The oldest parasequence set consists of a single parasequence overlain by a poorly developed transgressive lag deposit. The highstand parasequence set is slightly progradational to aggradational. 4th-order sequence FS4 developed during a period when the sediment supply was waning and could not keep up with the development of accommodation space. Its internal architecture is dominated by retrogradational (back-stepping) parasequence sets. The oldest parasequence set consists of a single (slightly progradational to aggradational) parasequence (i.e. its dip length is consistent with older aggradational parasequences). The transgressive phase is represented by retrogradational (back-stepping) parasequence sets. A transgressive lag is not apparently developed. A highstand parasequence set was either apparently not developed or has not been identified within the outcrop belt.

As stated above, FS1 actually belongs to the Hyatti Sequence and FS2, FS3, and FS4 belong to the Ferron Sequence. FS1 would be the 4th-order highstand sequence of the 3rd-order Hyatti Sequence. The lower boundary of FS1 is immediately above the Hyatti condensed section (Gardner, 1993) suggesting that it is actually a "correlative conformity/condensed section boundary" in this part of the basin. FS2 and FS3 would be the 4th-order progradational to aggradational sequences of the 3rd-order Ferron Sequence and FS4 is the 4th-order transgressive sequence of the Ferron Sequence. The upper boundary of FS4 is a below a concretion-bearing condensed section a few m above the uppermost sandstones of FS4, suggesting that the 4th-order highstand sequence of the Ferron Sequence is not located in the study area, but is only represented by condensed section sediments. On balance, these 4th-order events are most easily explained as forming as a result of small, rapid, sea-level fall and rise events. These events are superimposed on the overall 3rd-order patterns of the Upper Ferron Last Chance Delta, as described by Gardner (1992; 1993).

Within the clastic wedges of the Cretaceous interior seaway, conglomerates can mark major basinwide unconformities (Ryer, 1994). Within the Upper Ferron Sandstone only two major occurrences of extrabasinal pebble and conglomeratic lags have been identified. The channel belts of Ferron Parasequence Set 4B contain extrabasinal pebbles with a maximum long dimension of up to 4 cm. Extrabasinal pebbles (up to 15 cm) occur at the base of, and occasionally floating within, Ferron Parasequence 8a. The pebbles, in both Parasequence Sets 4B and 8 are quartzite, chert, sandstone, siltstone, volcanic-derived lithics, and large, rounded K-feldspar crystals. The pebbles, within Parasequence Set 4B, appear to occur in response to base-level drop during sequence boundary development. The pebbles in Parasequence Set 8 may be related to sedimentological events that areÊcorrelative with the events that produced the Calico Beds of southern Utah and the Coalville Conglomerate of Northern Utah (e.g. see Ryer, 1994).

Based on stratigraphic data (Garrison and van den Bergh, 1996; 1997) and faunal zonations (Gardner, 1992), the Upper Ferron 4th-order Sequences would have each been deposited over about a 250,000 year period. The individual depositional events that produced the parasequences within the Upper Ferron Sandstone, would have been deposited over, on average, about a 20,000–30,000 year period. It is estimated that the parasequence sets within the Upper Ferron Sandstone, would have been deposited, on average, during a 60,000–100,000 year period of time. The duration of the Upper Ferron 4th-order depositional sequence events is similar to the duration of older 3rd-order events within the Tununk Shale (i.e., the Woolgari and Hyatti Sequences), observed by Leithold (1994). The duration of the depositional episodes that resulted in the Upper Ferron Parasequences and Parasequence Sets is similar to the 20,000–100,000 year durations postulated for 4th-order events in the Tununk Shale (Leithold, 1994).

DAY 1 ROAD LOG

Int. Miles	Cum. Miles	
0.0	0.0	Leave parking lot of Holiday Inn in Price, Utah. Travel east on Utah Highways 6 and 191.
0.6	0.6	Price River.
0.7	1.3	Exit 241. Junction with Utah Highway 10. Travel south on Utah Highway 10 through Huntington, Castle Dale, Ferron and Emery to Fremont Junction.
1.5	2.8	Industrial Park. The Book Cliffs can be seen to the north. The reddish coal burns are in the Blackhawk Formation that overlies ledges of Star Point Formation and the Aberdeen Tongue (fig. 2).
0.5	3.3	Four Mile Hill. The Blue Gate Shale in the road cut contains thin sandstone lenses probably representing small channels.
0.6	3.9	Junction with Ridge Road. Continue south on Utah Highway 10. To the southeast, Cedar Mountain and the San Rafael Swell can be seen. Cedar Mountain is capped by the Lower Cretaceous Buckhorn Conglomerate Member of the Cedar Mountain Formation (fig. 2).
1.0	4.9	Miller Creek.

0.5	5.4	Junction with Stake Farm Road on east. Continue south on Utah Highway 10. To the west, the northwest dipping Garley Canyon Sandstone can be seen (fig. 2). Pump jacks and well heads of the Drunkards Wash Coalbed Methane Field can be seen in the foreground to the west.
0.9	6.3	Pinnacle Peak. A pinnacle of Blue Gate Shale.
0.3	6.6	Junction with Utah Highway 122 to the west. Continue north on Utah Highway 10. The Plateau Coal Mine is visible to the west on the Wasatch escarpment. The first prominent cliff former on the Wasatch escarpment is the Panther Tongue of the Star Point Formation (fig. 2).
0.4	7.0	Road cut in Blue Gate Shale. Note the sandy nature of the upper part of the outcrop.
0.4	7.4	Emery-Carbon County Line. Enter Carbon County.
0.3	7.7	Road cut in Blue Gate Shale. Note the sandy nature of the Blue Gate Shale and the thin sandstone lenses that are about 1 foot thick and 30–40 feet wide.
0.4	8.1	Broad Valley Wash.
1.3	9.4	Road cut in Blue Gate Shale.
0.2	9.6	Washboard Wash.
0.1	9.7	Road cut exposes small lamprophyre dike cut by a small thrust fault.
0.2	9.9	North junction with Utah Highway 155 to Cleveland (pop. 498). Cleveland was established in 1885 by Samuel Alger and Henry Oviatt (Geary, 1996). Continue south on Utah Highway 10.
1.7	11.6	Wildcat Draw.
0.5	12.1	Road cut in Blue Gate Shale. Trail to the west up the steeply sloping Poison Spring Bench. The Hiawatha Coal Mine is at the head of Poison Spring Bench.
0.4	12.5	Top of Hill. View of Castle Valley with Wasatch Plateau to the west and the Book Cliffs to the north and northeast and Cedar Mountain to the east. Low outcrops of the reddish Jurassic Morrison Formation can be seen in the middle ground (fig. 2).
0.8	13.3	Potter Wash. To the west the Panther Tongue is well exposed on the Wasatch escarpment.
2.4	15.7	Huntington International Airport on the east.
1.7	17.4	South junction with Utah Highway 155. Continue south on Utah Highway 10. Utah 155 provides access to the Cleveland-Lloyd Dinosaur Quarry. The Cleveland-Lloyd Dinosaur Quarry is managed by the BLM. More than 12,000 bones from at least 70 dinosaurs representing 14 species, including two previously unknown species, have been recovered.
1.2	18.6	Huntington Creek. Huntington Creek is a major tributary of the San Rafael River that dissects the San Rafael Swell.
0.4	19.0	Junction with Utah Highway 31 to the west. Continue south on Utah Highway 10.
1.0	20.0	Huntington. Huntington (pop. 1875, elev. 5791 feet) was established in 1879 by Elias Cox. Proceed south on Utah Highway 10.
1.0	21.0	Junction with north road to Lawrence. Continue north on Utah Highway 10.
0.7	21.7	Five Mile Wash Bridge. Prominent topographic feature on the western skyline is Red Point. The lower slope of the Wasatch escarpment is the Blue Gate Shale, overlying the Emery Sandstone at the base of the escarpment. The three sandstone benches overlying the shale are the Panther, Storrs, and Spring Canyon Tongues of the Star Point and Blackhawk Formations. The Spring Canyon Tongue and the overlying Blackhawk Formation are reddish in color due to coal burns in the Blackhawk Formation (fig. 2).
1.3	23.0	Wilberg Wash. Junction with south road to Lawrence (pop. 80, elev. 5652 feet). Lawrence was established in 1885 (Geary, 1996). Continue south on Utah Highway 10.
1.3	24.3	Junction with Utah Highway 29 to the west to Joe's Valley Reservoir. Continue south on Utah Highway 10.
2.0	26.3	Junction with the Old Spanish Trail to the east. Continue south on Utah Highway 10.
0.5	26.8	Roadcut through dark gray Blue Gate Shale, containing no sand or silt.
0.9	27.7	100 East Street in Castle Dale. Castle Dale, Utah (pop. 1707, elev. 5600 ft) was originally settled in 1877 by Orange Seely. Castle Dale lies in the central part of the Castle Valley located between the Wasatch Plateau to the west and the San Rafael

Swell to the east and is the county seat of Emery County. Proceed south on Utah Highway 10 through the Castle Valley.

0.4 28.1 Cottonwood Creek. Cottonwood Creek is a major tributary of the San Rafael River.

2.0 30.1 Hunter Power Plant. The power plant is fueled by local coal.

0.6 30.7 Junction with Utah 57 on right to Orangeville (pop. 1459, elev. 5772 ft). Orangeville, named after Orange Seely, was established in 1880 (Geary, 1996). Continue on Utah Highway 10.

1.5 32.2 Old Rest Area in Rock Canyon Flat. On the right, cliffs exposing the Cretaceous age Mesaverde Group can be seen. The Blackhawk Formation overlies the cliff-forming Star Point Sandstone mid-way up the escarpment. The escarpment is capped by the Castlegate Member of the Price River Formation (fig. 2). The lower part of the Star Point Formation become more sandy as the correlative Panther and Storrs Tongue Members are developed. The "reddish" area marking a coal burn is on the uppermost Spring Canyon Tongue Member of the Blackhawk Formation.

2.0 34.2 Junction with Main Street of Clawson (pop. 151, elev. 5950 feet). Continue on Utah Highway 10.

0.7 34.9 South access road to Clawson. Continue on Utah Highway 10.

1.1 36.0 "Castles" within the Blue Gate Shale along the Castle Valley. These "castles" are held up by thin sandstone tongues of the Garley Canyon Sandstone, can be seen in the foreground to the west and southwest. The Emery Sandstone can also be seen, in the background, up Garley Canyon. Note the down thrown fault block up the canyon, demarking the Joe's Valley fault system.

1.8 37.8 Ferron (pop. 1606 and elev. 5934 feet). Ferron was established in 1880 by Abram Conover (Geary, 1996).

0.6 38.4 Ferron Creek. Ferron Creek is a major tributary of the San Rafael River.

0.6 39.0 Ferron Creek Drainage. View to the west, toward Ferron Canyon, that dissects the Wasatch Plateau escarpment, showing the units of the Upper Cretaceous Mesaverde Group. The Blue Gate Shale is the slope-former near the base of the escarpment, which is overlain by the cliff-forming Star Point Sandstone. The Star Point Sandstone is overlain by the coal-bearing Blackhawk Formation. The Castlegate Member of the Price River Formation caps the escarpment. Nelson Mountain (9070 feet) is the highest peak along the escarpment.

0.2 39.2 Ferron Gas Field. West of the highway, the pumping unit of the Pan American Ferron Unit 3 well within the Ferron Gas Field (10,022 ft TD) can be seen. This well produced over 36,000 bbl oil from the Permian Kaibab Formation and over 10 BCF gas from the Ferron Sandstone and the Kaibab Formation.

2.2 41.4 Top of Hill. Roads cuts expose the Blue Gate Shale Member of the Mancos Shale. Note the lack of sandstone, siltstone, or concretions in the Blue Gate Member.

1.1 42.5 Junction with old Utah Highway 10 to Moore (pop. 6, elev. 6269 feet). Moore, originally named Rochester, was established about 1903 (Geary, 1996). To the west, Youngs Peak (9005 feet) is the high peak along the Wasatch escarpment. Continue south on Utah Highway 10.

1.3 43.8 View of Dry Wash to the east. Dry Wash is formed by a major drainage that dissects the western limb of the San Rafael swell, a prominent north-south trending anticlinal structure, and exposes sandstones of the Upper Ferron Sandstone Member of the Mancos Shale. The Upper Ferron Sandstone (figs. 1 and 2) in this area is represented by the the more distal near-marine sandstones of the Last Chance Delta complex. Coal deposition was very minimal in this portion of the Upper Ferron Sandstone. Only the A *coal zone* remains in this northern portion of the outcrop belt.

2.7 46.5 The town of Moore is visible in the foreground, to the east. In the foreground, the western limb of the anticlinal San Rafael Swell containing outcrops of the Upper Ferron Sandstone, can be seen dipping westward, while the eastern skyline is dominated by the distant peak-forming outcrops of Jurassic Navajo Sandstone.

1.6 48.1 South road to Moore and to the "Rochester Panel" Fremont Indian rock art site. A

		replica of the rock art panel is on display at the Museum of the San Rafael. Continue on Utah Highway 10.
0.3	48.4	Muddy Creek. One of the three major drainages that dissects the San Rafael Swell. It provides drinking and irrigation water for both Moore and Emery. At its confluence with the Fremont River near Hanksville, they become the Dirty Devil River which flows into the Colorado River near Hites Crossing at Lake Powell.
0.4	48.8	Camp Muddy Creek Monument. From 1885–1888, early settlers, led by Heber Petty and Casper Christensen, dug a 1200 foot long tunnel through the Blue Gate Shale to bring waters from Muddy Creek to supply the settlement of Emery.
2.0	50.8	In the middle ground to the east, Miller Canyon can be seen cutting through the Molen Reef, a topographic escarpment whose western slopes are defined by the anticlinal San Rafael Swell. The Molen Reef rises almost 1,000 feet above the desert floor. In the background through the gap of Miller Canyon, the peaks of the Henry Mountains can be seen. The highest peak on the skyline to the south is Mount Hilgard (elev. 11,527 feet) in the Wasatch Mountains south of I-70.
0.2	51.0	Junction with 300 East Street to Miller Canyon road and Interstate-70. Continue south on Utah Highway 10.
0.3	51.3	Emery (pop. 300, elev. 6250 ft). Emery was established in 1884 by Samuel Williams. Rest Area on the west side of Utah Highway 10.
4.0	55.3	Junction with road to Emery Coal Mine. The mine, inactive since about 1990, is owned by Consolidation Coal Company (Consol). Continue south on Utah Highway 10.
1.0	56.3	Sevier-Emery County Line. Enter Sevier County. Coal beds can be seen in the Blackhawk Formation in the Wasatch Plateau escarpment to the west.
0.3	56.6	Junction with BLM access road to the east. In the middle ground to the east the Emery Coal Mine can be seen at the confluence of Quitchapah Creek and Christiansen Wash.
1.6	58.2	To the west, the Joe's Valley fault system can be seen veering off to the north. In this area, the fault system has developed a graben system that is manifest as a saddle in the mountains to the north.
1.1	59.3	Junction with paved road, to the east, to the Hidden Valley Coal Mine. The mine, currently owned by Consol, has been reclaimed. The Hidden Valley Mine is in the Ferron A *coal zone*.
1.2	60.5	Northern limit of Miocene basalt boulder field. These boulders were fluvially transported from Miocene basalt flows to the southwest.
1.7	62.2	Junction with BLM access road to the east of Utah Highway 10. This road follows part of the historic Spanish Trail, a major trading route that wound through Utah, New Mexico, Arizona, Nevada, and California during the period from 1800–1850. Portions of the trail were first penetrated by Juan Maria de Rivera in 1765, and late in 1776 by Padres Dominquez and Escalante.
0.5	62.7	Sandstone cliffs on the west side of Utah Highway 10 are formed by the Emery Sandstone Member of the Mancos Shale. The Emery Sandstone is another fluvial-deltaic wedge that prograded eastward into the Mancos Sea and is 3–4 million years younger than the Ferron Sandstone deltaic complex (fig. 2).
0.9	63.6	Fremont Junction. Proceed under the overpass to the south side of I-70 and immediately turn left onto the east-bound entrance ramp. Proceed east onto I-70.
0.6	64.2	Road cuts expose the Blue Gate Shale Member of the Mancos Shale.
1.7	65.9	To the north and northwest, the skyline is dominated by the Wasatch Plateau. The Castle Valley lies to the east of the plateau and is floored by the Mancos Shale. The northeastern skyline is Coal Cliffs outcrops of the fluvial-deltaic Ferron Sandstone. Note the gently westward dipping western limb of the north-south trending anticlinal San Rafael Swell.
0.9	66.8	Sevier-Emery County Line. Enter Emery County and continue east on I-70.
1.1	67.9	To the south of the highway, a Ferron Parasequence Set 5 channel belt occurs within a split in the I *coal zone. Coal zones* such as this occur at the tops of parasequence sets within the Upper Ferron Sandstone. Splits such as seen here are common in the *coal zones.* Note

		the accretionary surfaces within the channel complex and the mud-filled channel margin on the west side of the channel. Continue east on I-70 through the Ferron Sandstone outcrops.
0.8	68.7	On the north side of I-70 near Mile Marker 94, the C *coal zone.* is well exposed and consists of several coal seams, layers of carbonaceous shale, delta plain mudstones and siltstones, and volcanic ash (tonstein).
0.1	68.8	On the south side of I-70, the upper split of the A2 *coal zone.* is very well exposed and contains a thick white tonstein layer. Continue east on I-70 descending through the massive cliffs of Upper Ferron Parasequence Set 2A near-marine sandstones and the more mud-rich delta-front sandstones of Upper Ferron Parasequence Set 1. The gray shale underlying the Ferron Sandstone is the Tununk Shale Member of the Mancos Shale.
2.2	71.0	Ivie Creek Canyon. Note the slope-forming gray Tununk Shale exposed in the mesas to the south of the highway. The Coal Cliffs can be seen to the north of the highway. Mesa Butte is the high butte to the south of the highway. The amphitheater at the mouth of Ivie Creek Canyon exposes the near-marine rocks of Ferron Parasequence Sets 1 and 2.
0.6	71.6	Turn right off I-70 at exit 97. Intersect the north-south Ranch Road, turn north, and cross over I-70. Where the Ranch Road intersects the I-70 entrance ramp, turn west and proceed west onto I-70.
2.2	73.8	Mouth of Quitchapah Creek Canyon is located to the north of I-70. The mouth of Blue Trail Canyon can be seen on the south side of I-70 to the southeast. Note the intense red color of the canyon walls, to the north, due to coal burns in the A and C *coal zones.*
0.8	74.6	**STOP 1: I-70 Road Cut at Ivie Creek** (fig 1). (no facilities). Pull off I-70 on the north side of the highway, midway up the narrow road cut. The massive cliffs of the road cut expose the sand-rich Upper Ferron Parasequence Set 2A near-marine sandstones and more mud-rich delta-front sandstones of Upper Ferron Parasequence Set 1 (figs.3, 4 and 6). Two splits of the sub-A (sub-A3 and sub-A4) *coal zone.* separate these two parasequence sets. Parasequence Set 2A is capped by the A *coal zone.* Ferron Parasequence Set 3 is chiefly represented by the C *coal zone.*
0.0	74.6	Carefully pull back onto I-70 and proceed west.
2.7	77.3	Sevier-Emery County Line. Enter Sevier County.
2.8	80.1	Exit I-70 to north at exit 89. Stop sign at junction of I-70 exit ramp to Utah Highway 10. Turn north onto Utah Highway 10 and proceed north to Emery.
12.6	92.7	Junction with 300 East Street in Emery. Turn south and proceed south down 300 East Street.
0.8	93.5	Junction with Miller Canyon Road on east side of 300 East Street. Proceed south on 300 East Street. Leave paved road and continue on dirt road south. Miller Canyon can be seen to the east cutting through the Coal Cliffs and Molen Reef to the southeast.
1.0	94.5	Junction with Emery County Road to east. Continue south on dirt road.
0.6	95.1	Cattle guard. Junction with Cowboy Mesa County Road. Turn east on the County Road and proceed up the dip slope of Cowboy Mesa. Cowboy Mesa, expressed as the gently sloping topographic feature in the middle ground, is the west side of the topographic Molen Reef and marks the western limb of the San Rafael Swell, in this area.
0.7	95.8	Christiansen Wash. Continue on County Road up the dip slope of Cowboy Mesa. The low sandstone outcrop to the north of the road is the retrogradational (backstepping) near-marine facies of Ferron Parasequence Set 7.
1.1	96.9	Cattle guard.
0.5	97.4	Intersection with jeep trail to the south. Turn south and continue along Cowboy Mesa. The sandstone ridges to the east of the road are fluvial channel belts of Ferron Parasequence Sets 5A and 5B.
0.7	98.1	Cowboy Mine Canyon. Intersection with jeep trail to east and west. Turn east and proceed up switchback, on jeep trail across Cowboy Mesa.
0.4	98.5	Intersection with jeep trail to west. Turn west onto jeep trail and proceed along the south side of Cowboy Mine Canyon.

0.9	99.4	**STOP 2: Overlook of Quitchapah Creek Canyon** (fig 1). (no facilities).
0.0	99.4	Retrace road back to Cowboy Mesa County Road.
2.0	101.4	Junction of jeep trail with Cowboy Mesa County Road. Turn east onto Cowboy Mesa County Road and proceed up the dip slope of Cowboy Mesa.
0.3	101.7	Junction with jeep trail to the north. Turn north on jeep trail to Bear Gulch.
0.1	101.8	**STOP 3: Bear Gulch** (fig 1). (no facilities).
0.0	101.8	Retrace road back to Cowboy Mesa County Road.
0.1	101.9	Intersection of jeep trail with Cowboy Mesa County Road. Turn west onto Cowboy Mesa County Road and proceed down the dip slope of Cowboy Mesa.
2.7	104.6	Junction with Emery County Road. Turn north on County Road and proceed north.
0.6	105.2	Junction with Emery County Road to the east. Turn east and proceed east along County Road.
0.7	105.9	Junction with paved Miller Canyon Road. Turn southeast on Miller Canyon Road and proceed.
1.0	106.9	Cattle guard. Enter Miller Canyon and descend along paved road. The massive sandstone outcrops are fluvial channel belt sandstones of Ferron Parasequence Sets 5A and 5B.
0.3	107.2	Midway up the canyon walls, outcrops of the Ferron G *Coal zone* can be seen. In Miller Canyon, the G *coal zone* is dominantly carbonaceous shale and contains only three thin coal seams.
0.2	107.4	On the east side of the Canyon, near the base of the cliffs, a small mine shaft into the C *coal zone* can be seen. Whitish-gray tonstein layers can be seen in this 2.6 m thick coal seam.
0.1	107.5	**STOP 4: Miller Canyon** (fig 1). (no facilities).
0.0	107.5	Pull back on Miller Canyon Road and proceed on paved road northwest back to Emery.
2.8	110.3	Junction with Emery 300 East Street. Turn north on 300 East Street and proceed.
0.8	111.1	Junction with Utah Highway 10. Turn east and proceed along Highway 10 through Ferron, Castle Dale, and Huntington and back to Price.
49.7	160.8	Junction of Utah Highway 10 with Utah Highways 6 and 191. Turn west onto Utah Highways 6 and 191.
1.3	162.1	Pull into parking lot of the Holiday Inn in Price.

DAY 1 STOPS

Stop 1: I-70 Road Cut at Ivie Creek

Vertical Sedimentology and Architecture of the Near-Marine facies of Ferron River-Dominated Parasequence Set 1 and Wave-modified Parasequence Set 2A

The road cut of I-70 through the Ivie Creek Bench, near Mile Marker 94, and the canyon incised by Ivie Creek, near Mile Marker 95, provide excellent 3-D exposures of Upper Ferron Parasequence Sets 1 and 2A (figs. 3, 4, 5, 6, and 7). Ferron Parasequence Set 1 is strongly river-dominated. Parasequence Set 2A is also river-dominated, but it exhibits evidence of substantial wave reworking.

Ferron Parasequence Set 1 contains at least 12 river-dominated, fluvial-deltaic parasequences. The near-marine parasequences in Ferron Parasequences Set 1 exhibit both vertical and lateral facies changes from (1) stream mouth bar (SMB) to, (2) proximal delta front (pDF) to, (3) distal delta front (dDF) to, (4) prodelta (PD) (fig.5). Distributary channels (DC) and delta plain (DP) facies associations are commonly present as well. Distal prodelta/shelf slumping, indicating instability as a result of rapid deposition, is common. In general, Parasequence Set 1 delta front deposits exhibit little to mild evidence of wave influence. The high proportions of shale present in the near-marine facies of the parasequences within Parasequence Set 1, are characteristic of river-dominated delta front deposits.

At the I-70 road-cut and along Ivie Creek, Parasequences 1e, 1f, 1g, and 1j are exposed. Parasequences 1e–f are represented by distal bar delta front deposits consisting of steeply dipping (310°–335° azimuth) prograding clinoforms (fig. 4). These clinoforms average about 3 m thick at their thickest part. Parasequence 1g also exhibits dipping, prograding clinoforms, although these clinoforms are of a much smaller scale (<1.5 m). The uppermost parasequence (Parasequence 1j) occurs within a split in the sub-A *coal zone,* and is represented at this outcrop as a thick succession of brackish water mudstones, containing fragments of gastropods and molluscs, as well as crevasse splay deposits. A selected portion of a measured section from I-70 showing Parasequences 1f, 1g, and 1j is shown in figure 5.

Ferron Parasequence Set 2A contains 4 wave-modified, river dominated, fluvial-deltaic parasequences (denoted as

2a–2d). The near-marine facies of these parasequences exhibit both vertical and lateral facies changes (1) stream mouth bar and reworked stream mouth bar (frequently preserved as upper shoreface deposits (USF)), to (2) reworked delta front (pDF and dDF) (frequently preserved as middle (MSF) and lower shoreface (LSF) deposits), to (3) prodelta (figs. 6 and 7). The mouth bar deposits exhibit well-developed trough stratification. The distal bar deposits are moderately burrowed (*Ophiomorpha, Teichichnus, and Thalassinoides*) and locally exhibit well-developed hummocky stratification and planar stratification.

Figure 6 is a photograph of an outcrop of Parasequence Set 2A at I-70 showing Parasequences 2a, 2b, and 2c. A selected portion of a measured section at the I-70 roadcut showing Parasequences 2a, 2b, and 2c is shown in figure 7. The low proportion of shale present in Parasequences 2a and 2b, at I-70, is characteristic of wave reworked distal bar deposits in Parasequence Set 2A.Parasequence 2c occurs between the A1 and A2 *coal zones.*

Composition and Stratigraphic Positions of the Ferron Sub-A, A, and C Coal Zones

Coal zones have been defined by Garrison and van den Bergh (1996) as coal seams and their laterally equivalent carbonaceous shales and siltstones, carbonaceous rich mudstones and siltstones, paleosols, rooted horizons, and interlayered flood plain mudstones and siltstones. The sub-A *coal zone* caps Ferron Parasequence Set 1; the A *coal zone* caps Ferron Parasequence Set 2; the C *coal zone* caps Ferron Parasequence Set 3. At I-70, the delta plain facies association of Parasequence Set 3 overlies the A *coal zone* (fig. 3). At the I-70 road cut, Parasequence Set 3 is composed dominantly of the C *coal zone.*

The sub-A *coal zone* splits into two components near I-70, where they are designated the sub-A_3 and sub-A_4, which are 0.6 m and 0.3 m thick, respectively. The A *coal zone* splits into two components denoted A_1 and A_2; the A_1 *coal zone* disappears near I-70; the A_2 *coal zone* splits into two components near Corbula Gulch, denoted A_2 and A_3, and are well exposed at I-70. The A_2 and A_3 *coal zones* are 2.5 m and 0.6 m thick at I-70, respectively and are separated by a small mud-filled fluvial channel. The C *coal zone* splits into two components denoted C_1 and C_2; the C_2 *coal zone* pinches out at Blue Trail Canyon and is not present at I-70. A selected portion of a measured section from I-70 showing the nature and composition of the 6.3 m thick C_1 *coal zone* is shown in figure 15. The C *coal zone* is composed of 26% coal, 7% carbonaceous shale, 19% mudstone, 44% delta plain sandstones and siltstones, and 4% tonstein.

Within *coal zones,* coal seams themselves are rarely homogeneous and can generally be sub-divided into distinct lithological sections. A distinct lithologic subdivision of a coal seam that has a uniform character is call a ply or coal lithotype. A lithotype that can be correlated through a seam over large lateral distance is defined as a coal facies. Figure 16 shows the lithotype (i.e., coal brightness) profiles of the A_2 *coal zone* and the C_1 *coal zone* at I-70.

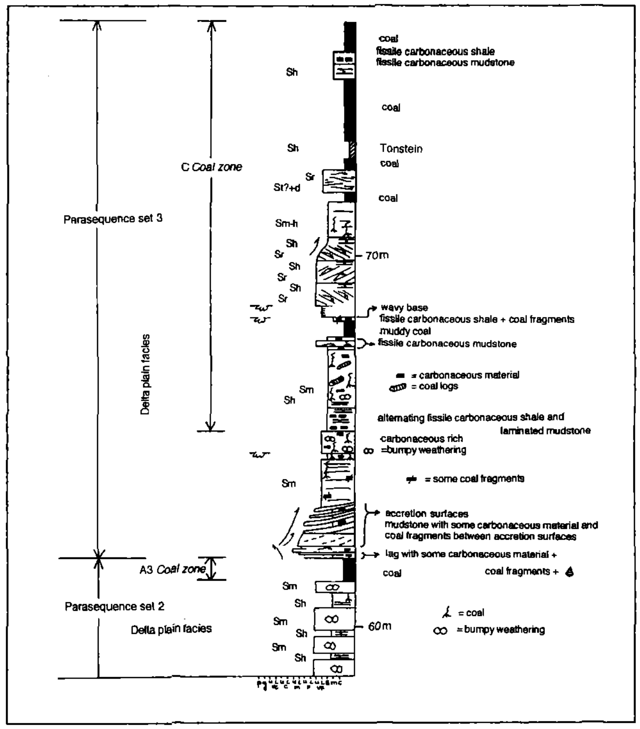


Figure 15. Measured section through the Upper Ferron C coal zone *at the I-70 roadcut. Symbols and nomenclature defined as in figure 5.*

In the Ferron Sandstone, *coal zones* frequently contain volcanic ash layers. These volcanic ash horizons are characterized as laterally continuous kaolinitic claystone partings called "tonsteins." Some whitish tonstein layers are almost completely kaolinized, while the other more grayish tonsteins are dominantly bentonitic and contain a full suite of volcanic minerals such as beta quartz, volcanic K-feldspars, Fe-oxide and Ti-oxide minerals, and zircons (fig. 14) (van den Bergh, 1995). The tonsteins associated with the Ferron Sandstone *coal zones* may represent time lines within the *coal zone* horizons. Splits in coal zones and multiple tonstein layers clearly indicate significant time represented by these *coal zone* deposits.

Tonsteins have been found in all major *coal zones* in the Ferron Sandstone (Garrison and van den Bergh, 1997). Many *coal zones* contain multiple tonstein layers. At I-70, the sub-A *coal zone* is devoid of tonstein layers, but further south in the Limestone Cliffs, it contains a very well-devel-

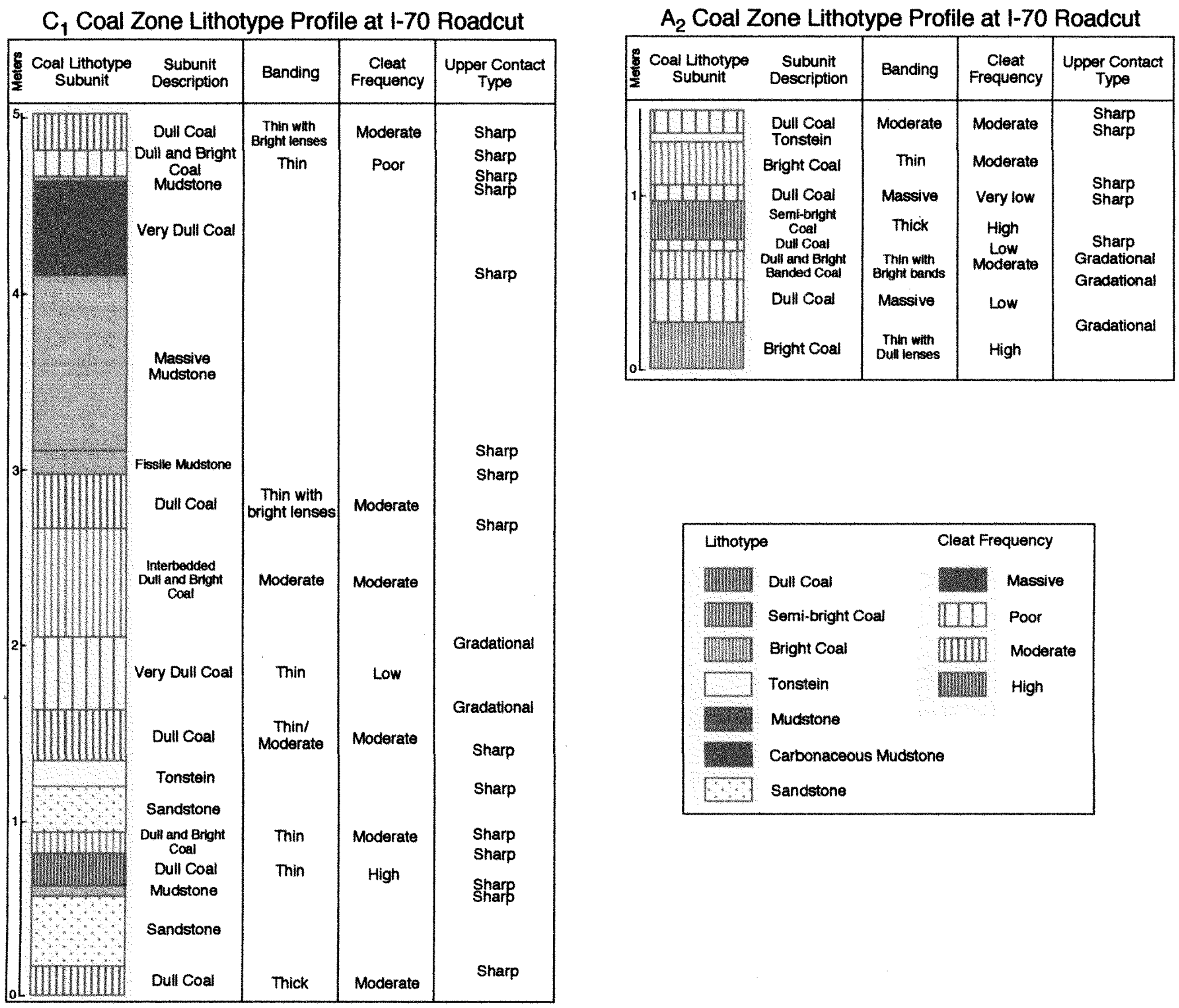


Figure 16. Lithotype profiles of the A_2 *and* C_1 coal zones *at the I-70 roadcut.*

oped tonstein. At I-70, the A_2 *coal zone* contain a 5 cm thick tonstein layer. The tonstein in the A_1 *coal zone* is not preserved at I-70, but it can be found just south of I-70 and can be traced to the Limestone Cliffs. North of I-70, the A_2 *coal zone* contains two tonsteins that can be traced northward to at least Bear Gulch. At I-70, the C *coal zone* contains a 23 m thick tonstein. North of I-70, the C *coal zone* contains at least two tonsteins. In some areas, north of I-70, the C *coal zone* contains up to four distinct tonsteins. Frequently these tonsteins show evidence of reworking. No tonsteins have been identified in the C *coal zone* south of Corbula Gulch. Tonsteins are generally preserved at, and seaward of the landward pinch-outs of the near-marine deltaic sands. As tonsteins are traced landward of near-marine pinch-outs, preservation potential decreased dramatically.

Key Concepts of Stop 1:

- The river-dominated, near-marine facies of Ferron Parasequences 1e, 1f, and 1g exhibit a vertical shoaling upward sedimentary profile and contain high proportions of shale. The vertical stacking pattern of Parasequence Set 1, indicates that each successively younger parasequence steps seaward (i.e., is progradational), relative to the underlying parasequence.
- The river-dominated, but wave-modified, near-marine facies of Ferron Parasequences 2a, 2b, and

2c, of Parasequence Set 2A, exhibit a vertical shoaling upward sedimentary profile and are extremely sand-rich. Parasequence Set 2A is a progradational (seaward-stepping) parasequence set.

- *Coal zones* are lithologically complex and are composed of coal seams, carbonaceous shales and siltstones, carbonaceous rich mudstones and siltstones, paleosols, rooted horizons, and interlayered flood plain mudstones and siltstones. *Coal zones* occur at the tops of parasequence sets. *Coal zones* frequently split into multiple zones.
- Coal facies are distinct, uniform, lithologic subdivisions of a coal seam that can be correlated through a seam over large lateral distance.
- *Coal zones* frequently contain altered volcanic ash layers called "tonsteins." Tonsteins tend to be preserved at and seaward of the landward pinch-outs of the delta front sands. As tonsteins are traced landward of near-marine pinch-outs, preservation potential decreases dramatically.

Stop 2: Quitchapah Creek Canyon

Lateral (Dip Section) Stacking and Architecture of the Near-Marine facies of Ferron River-Dominated Parasequence Set 1 and Wave-modified Parasequence Sets 2A and 2B

The canyon incised by Quitchapah Creek provides excellent 2-D, dip section, exposures of Upper Ferron Parasequence Sets 1, 2A, and 2B (fig.3). Ferron Parasequence Set 1 contains at least 12 river-dominated, fluvial-deltaic parasequences, that exhibit a seaward-stepping stacking pattern. In Quitchapah Creek Canyon, elements of 6 of these parasequence can be seen (Parasequences 1f–1k). In general, each successively younger parasequence steps seaward by an average of 2–5 km. The near-marine sandstones of Parasequence Set 1 extend at least 27 km in the dip direction.

Ferron Parasequences 1e, 1f, 1g, and 1i formed in response to the progradation of very small, river-dominated sub-delta lobes prograding in a northwesterly direction (310°–335° azimuth). Parasequences 1e, 1f, 1g, and 1i are approximately 2.9 km, 3.7 km, 2.5 km, and 3.2 km in strike width, respectively, and the maximum thicknesses are 22 m, 17 m, 10 m, and 13 m, respectively. Parasequence 1h and 1k appear to represent small delta lobes prograding in a northeasterly direction. Their dip lengths are approximately 2.5 km and 2.6 km and maximum thicknesses are 15 m and 6 m, respectively. Parasequence 1j, occurring with a split in the sub-A *coal zone,* is represented in the outcrop belt as a brackish water bay mudstone, to the south at I-70, and a small 2.92 km, 3 m thick delta front sandstone body occurs in Quitchapah Creek Canyon. Parasequence 1k can be seen pinching out into a split of the sub-A *coal zone.*

Parasequence Set 2A contains 4 river-dominated, wave-modified parasequences, that exhibit a seaward-stepping stacking pattern (Parasequences 2a–2d). All 4 can be seen in Quitchapah Creek Canyon. The near-marine sandstones of Parasequence Set 2A extend about 36 km in the dip direction. Parasequence 2e of Parasequence Set 2B is also exposed in Quitchapah Creek Canyon. The true extend of Parasequence 2e cannot be determined due to erosional truncation by fluvial channels in the overlying Parasequence Set. Parasequence 2e is hierarchically equivalent to a parasequence set and is placed in Parasequence Set 2B.

Parasequences 2a and 2b appear to represent large wave influenced, river-dominated delta lobes prograding seaward in a northeasterly direction. Parasequences 2a, 2b, 2c, and 2d all progrades northeast with azimuths of 025°, 045°, 025°, and 050°, respectively. The near-marine facies of Parasequences 2a, 2b, 2c, and 2d are approximately 18.0 km, 15.1 km, 11.4 km, and 24.0 km in dip length, respectively and maximum thicknesses are 31 m, 16 m, 10 m, and 19 m, respectively. The landward pinch-out of the near-marine facies of Parasequence 2b steps seaward 3.5 km, relative to the landward pinch-out of the near-marine facies of the immediately underlying Parasequences 2a. The landward pinch-out of near-marine facies of Parasequence 2c occurs almost 7.5 km seaward of the landward pinch-out of the underlying Parasequence 2b. The landward pinch-out of Parasequence 2d steps seaward almost 2.7 km from the pinch-out of Parasequence 2c. The landward pinch-out of Parasequence 2e steps seaward only about 0.5 km from the pinch-out of Parasequence 2d.

Although their compositions may vary laterally and they may split into multiple components, *coal zones* occur at the tops of parasequence sets. When they are not present at the tops of parasequence sets, it is due to the development of erosional unconformities associated with high-order sequence boundaries. This is well illustrated in Quitchapah Creek Canyon. In Quitchapah Creek Canyon, Parasequence Set 1 is capped by the sub-A (sub-A3 and sub-A4) *coal zone.* The sub-A3 and sub-A4 section of the sub-A *coal zone* extends some 8.5 km, from Blue Trail Canyon to North Quitchapah Creek. The total dip length for the sub-A *coal zone* is at least 27 km. In Quitchapah Creek Canyon, Parasequence Set 2 is capped by the A (A2 and A3) *coal zone.* The A *coal zone* extends over 40 km, from the Limestone Cliffs to north of Dry Wash. In Quitchapah Creek Canyon, the reddish coloring of the outcrop is due to a coal burn in the C *coal zone.* The C *coal zone* splits in the southern part of Quitchapah Creek Canyon and become one zone again in the northern part of Quitchapah Creek Canyon. The C *coal zone* extends over 34 km, from the Limestone Cliffs to just south of Dry Wash.

Key Concepts of Stop 2:

- The river-dominated, near-marine facies of Ferron Parasequences 1e, 1f, 1g, 1h, and 1i exhibit a down dip stacking pattern, within Parasequence Set 1, indicating that each successively younger parasequence steps seaward (i.e., is progradational), relative to the underlying parasequence.
- The river-dominated, but wave-modified, near-marine facies of Ferron Parasequences 2a, 2b, 2c and 2d, of Parasequence Set 2A, exhibit a progradational (seaward-stepping) down dip pattern.
- *Coal zones* are quite laterally extensive. The lateral dip section extend of the sub-A *coal zone* is over 27 km. The sub-A3 and sub-A4 section of the sub-A *coal zone* extends 8.5 km. The lateral dip section extends of the A and C *coal zones* are at least 40 km and 34 km, respectively.
- *Coal zone* compositions vary laterally and frequently they may split into multiple components. Within the Ferron clastic wedge, *coal zones* occur at the tops of parasequence sets. When they are not present at the tops of parasequence sets, it is due to the development of erosional unconformities associated with high-order sequence boundaries.

Stop 3: Bear Gulch

Depositional Sequence Stratigraphy and Sedimentology of the Near-Marine facies of Ferron Parasequence Sets 2A, 2B, 2C and Parasequence Sets 4A and 4B and the Nature of the Sequence Boundaries above Ferron 4th-order Sequences FS1 and FS2

The small north-south trending canyon of Bear Gulch exposes near-marine facies of Parasequence Sets 2A, 2B, 3, and 4A and non-marine facies associations of Parasequence Sets 4B, 5, and 6 (fig. 3). The sequence boundaries between FS1 and FS2 (i.e., SB1) and between FS2 and FS3 (i.e., SB2) are both well exposed in this canyon. Parasequences 1l and 1k, of Parasequence Set 1, pinch-out at the bottom of the southern end of the canyon of Bear Gulch.

The canyon exposes the seaward portions of parasequences 2a and 2b and more proximal portions of Parasequences 2c and 2d of Parasequence Set 2A. In this outcrop, the small back-stepped Parasequence 2e of Parasequence Set 2B can be seen sitting on a yellowish, highly bioturbated, transgressive lag deposit that overlies Parasequence 2d. This transgressive lag deposit can be traced over 5 km northward into Muddy Creek Canyon. Parasequence 2e has a very small mouth bar deposit and for much of its length, it has distal bar delta front facies lying stratigraphically above the mouth bar deposits of Parasequence 2d suggesting a slight back-stepping relative to Parasequence 2d. Parasequence 2e is almost completely scoured out by the fluvial channel belts of the overlying Parasequence Set 2C. This is best seen near the northwestern end of the canyon of Bear Gulch to Miller Canyon and on into Muddy Creek Canyon. In some areas, this surface represents over 25 m of erosion into Parasequence Set 2A and 2B. This erosional surface can be identified in outcrops from Coyote Basin to Muddy Creek Canyon, representing a distance of over 18 km. Based on the back-stepped nature of Parasequence Set 2B, lying immediately below this surface, and the regional extent of the erosional surface between Parasequence Sets 2B and 2C, this erosional surface has been interpreted to represent the sequence boundary between Ferron 4th-order Sequences FS1 and FS2. Parasequence Sets 1, 2A, and 2B have been assigned to Ferron 4th-order Sequence FS1 and Parasequences 2C, 3, and 4A have been assigned to Ferron 4th-order Sequence FS2.

In Bear Gulch, the upper part of Parasequence Set 2C, capped by the stacked A and C *coal zones*, is represented by a laterally restricted, flood tidal delta. This unit can be traced to the south of Bear Gulch only about 0.9 km and pinches out into the C *coal zone* on the western canyon wall of Bear Gulch. A correlative unit crops out again in Miller Canyon. These small flood tidal deltas crop out about 1 km landward of the associated shoreline near-marine facies, *sensu stricto*, of Parasequence 2g. This small near-marine unit rests on a thin, 30 cm thick, section of the A *coal zone*. The A *coal zone* pinches out 16 km northward of Bear Gulch, just north of Dry Wash. The flood tidal delta deposit of Parasequence Set 2C, exposed in Bear Gulch, is represented by a sand-rich middle to upper shoreface facies that is trough and herringbone cross-stratified and contains abundant *Ophiomorpha* burrows in the upper part and *Thallasinoides* burrows in the lower part.

Parasequence Set 4A is represented, in the outcrops of Bear Gulch, by the reworked stream mouth bar/upper shoreface and reworked proximal delta front/middle shoreface facies of Parasequence 4a. Parasequence 4a rests on the C *coal zone* and has a bioturbated base with sand-filled *Thallasinoides* burrows extending into the underlying C *coal zone*. Large wood fragments can also be seen in the base above the C *coal zone*. The lower part of Parasequence 4a is sand-rich, with horizontal to massive bedding, and is pervasively burrowed, containing *Thallasinoides* and *Teichichnus*, with occasional *Ophiomorpha* burrows. The upper part of Parasequence 4a is sand-rich, with trough cross-stratification, and contains pervasive *Ophiomorpha*. The upper surface of Parasequence 4a is scoured by the fluvial channel belts of Parasequence Set 4B (fig. 8). There is up to 20 m of erosion of Parasequence Set 4A by the fluvial facies of Parasequence Set 4B. In the non-marine part of the Parasequence Set 4A, south of Bear Gulch, Parasequence Set 4A is capped by a very laterally extensive rooted zone (designated the E Rooted Zone). This rooted zone can be traced from just north of Last Chance Creek northward to just south of Bear Gulch, where it is correlative with the erosional unconformity between Parasequence 4A and 4B cropping out from Bear Gulch to Miller Canyon to Muddy Creek (i.e. over 5 km). The paleoshoreline of the near-marine facies of Parasequence 4B shifts basinward some 7 km relative to the paleoshoreline of Parasequence 4A and is accompanied by at least 20 m of erosion. Northward in Miller Canyon, Parasequence 4A lies on a thick transgressive lag deposit, that is represented in Bear Gulch by only the *Thallasinoides* bioturbation of the upper part of the C *coal zone*. This lag can be traced 13 km north to Dry Wash. This change in shoreline position and baselevel and the development of an erosional unconformity indicate that the boundary between 4A and 4B is the sequence boundary between FS2 and FS3. Parasequence Sets 4B and 5A are assigned to Ferron 4th-order Sequence FS3.

Volcanic Ash Layers and Composition of the C Coal Zone

In Bear Gulch, the A and C *coal zones* are stacked into 5.9 m thick composite *coal zone* composed of 60% coal, 28% carbonaceous shale, 3% mudstone, and 9% tonstein. The coal lithotype profile is shown in figure 17. Based on tonstein regional correlations, the lower 3.7 m has been assigned to the A *coal zone*. The C *coal zone* is 2.2 m thick and is composed of 80% coal, 20% tonstein. A coal zone is composed of 42% coal, 45% carbonaceous shale, 10% mudstone and sandstone, and 3% tonstein. The composite A and C *coal zone*, in Bear Gulch, contains 5 tonsteins. The upper four tonsteins have been assigned to the C *coal zone* and the lower tonstein to the A *coal zone*. The uppermost tonstein in the C coal zone is a 5 cm thick impure tonstein, suggesting mixing of volcanic material with other terrigenous material. The thickest tonstein in the C *coal zone* is 30 cm thick. Below this thick tonstein is a tonstein doublet. The uppermost tonstein doublet is 3 cm thick and the lower is 5 cm thick. The thick, upper tonstein of the C *coal zone* can be traced over 13 km, from Miller Canyon southward (i.e., landward) to Corbula Gulch, south of Blue Trail Canyon, where it is 40 cm thick. There are no tonsteins preserved in the C *coal zone* further south than Corbula Gulch. Tonsteins correlative with the tonstein doublet can be traced as far south as Cowboy Mine Canyon and as far north as Miller Canyon. The tonstein in the A *coal zone* is 10 cm thick. This A *coal zone* tonstein can be correlated as far south as I-70 and as far north as Pictograph Point at the confluence of Muddy Creek and Rochester Creek.

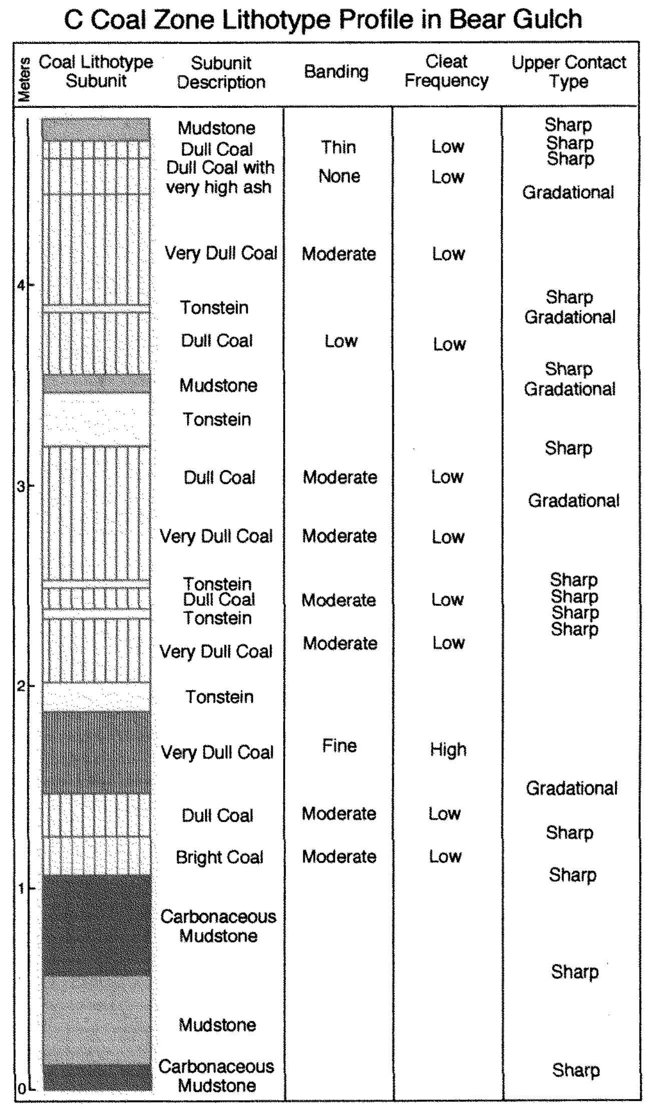


Figure 17. Lithotype profile of the A and C composite coal zone *at Bear Gulch.*

Coals such as those exposed within the A-C *coal zone* at Bear Gulch consist of microscopically identifiable organic substances formed from the initial plant materials and altered plant materials within the peat accumulation (i.e., cell wall material, spores, resins, cuticles, and fossil charcoals). These organic substances are called macerals. There are three basic maceral groups called vitrinite, liptinite, and inertinite. Vitrinites are generally derived from plant cell wall or woody material. Liptinites are derived from spores, cuticles, and resins. The inertinites represent fossil charcoal material and other oxidized, inert plant debris. The abundance and distribution of these macerals in coal seams is controlled by the original peat composition, as well as both pre-burial history. The maceral compositions have been compiled for coal seams from the Ferron Sandstone C and I *coal zones* (Sommer et al., 1991; Crowley et al., 1989). The Ferron C coal has a complex composition due to the presence of thick, laterally extensive altered volcanic ash layers (tonsteins) (Crowley et al., 1989). Sampling above and below tonsteins produced two distinct maceral compositions (figure 18). The C coal samples taken immediately below tonsteins (Group B) have a higher percentage of inertinite (range = 31–50% and mean = 38%) relative to vitrinite (range = 45–65% and mean = 57%), while samples take immediately above tonsteins (Group A) have a higher percentage of vitrinite (range = 72–89 and mean = 80%) relative to inertinite (range = 5.7–21.0 and mean = 14.6%). Liptinites remain fairly constant between the two groups, with means of 5.3% and 5.4%, respectively. Desmocollinite, telenite, and detrocollinite are the dominant vitrinite group macerals. Semifusinite, fusinite, and inertodetrinite are the dominant inertinite group macerals. Resinite, exsudatinite, and fluorinite are the dominate liptinite group macerals. Four samples taken from below tonsteins fall within Group A. Crowley et al., (1989) suggested that precursor peats formed in well drained environments until volcanic ash layers created impermeable zones and caused waters in the peat swamp to pond. Well drained, oxidizing initial conditions were favorable for the formation of degradofusinites, while poorly drained, more nutrient-rich conditions, following an ashfall, would be more conducive to the preservation of vitrinite.

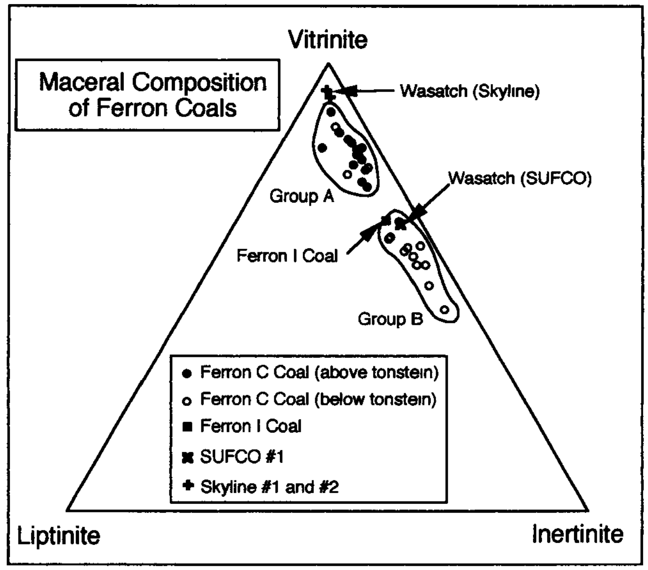


Figure 18. Ternary diagram showing the maceral composition of the Upper Ferron coal seams.

Key Concepts of Stop 3:

- The sequence boundary between Ferron 4th-order Sequences FS1 and FS2 is represented, in Bear Gulch, as an erosional unconformity between the near-marine facies of Parasequence Set 2B and fluvial channel belt facies of Parasequence Set 2C. This sequence boundary can be traced over 18 km and exhibits up to 25 m of erosional relief. The backstepped Parasequence 2e of Set 2B lies on a bioturbated transgressive lag deposit that can be traced over 3 km northward.
- The sequence boundaries between Ferron 4th-order Sequences FS2 and FS3 is represented, in Bear Gulch, as an erosional unconformity between the near-marine facies of Parasequence Set 4A and fluvial channel belt facies of Parasequence Set 4B. This sequence boundary can be traced over 5 km and exhibits up to 20 m of erosional relief.
- The A and C *coal zones* are stacked in Bear Gulch forming a thick composite zone containing 5 tonsteins. The C *coal zone* is 2.2 m thick and contains 4 tonsteins, the thickest of which is 30 cm thick. This thick tonstein can be traced over 13 km. The lower 3.7 m of the composite zone and the lowest tonstein has been assigned to the A *coal zone*.
- Volcanic ash deposits alter the local environments within peat accumulations. These lead to variations in, and the alteration of, coal composition and coal quality.

Stop 4: Miller Canyon

Nature of the C Coal Zone to the Transgressive Lag Deposits of Parasequence Set 3 and the Near-Marine Sandstones of Parasequence Set 4A

The outcrops of Miller Canyon offer a final opportunity to examine the composition of the C *coal zone* and evaluate the variations in the C *coal zone* over a substantial distance along the Ferron outcrop belt. We have examined the C *coal zone* at two previous localities, I-70 and Bear Gulch. From I-70 to Miller Canyon, a down dip distance of over an 8 km has been traversed.

In Miller Canyon, the A and C *coal zones* are stacked together into a composite 6.2 m thick *coal zone* which is composed of 44% coal, 38% carbonaceous shale, 16% mudstone, and 6% tonstein. This *coal zone* is correlative with the exposures in Bear Gulch, therefore the lower 5.0 m of the zone is assigned to the A *coal zone*. The coal lithotype profile for the *coal zone* is shown in figure 19. The C *coal*

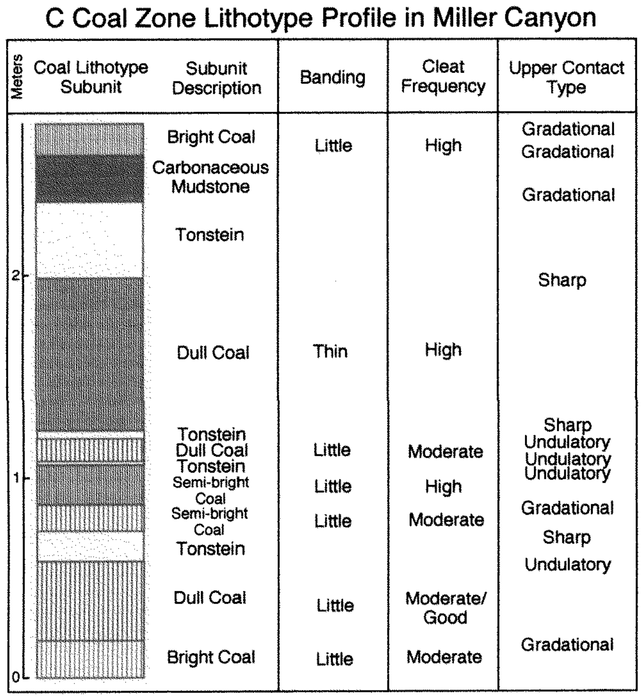


Figure 19. Lithotype profile of the A and C composite coal zone *in Miller Canyon.*

zone is composed of 76% coal and 24% tonstein. The A coal zone is composed of 35% coal, 42% carbonaceous shale, 20% mudstone, and 2% tonstein. The C *coal zone,* in Miller Canyon, contains three tonsteins. The thick tonstein seen in the C *coal zone* in Miller Canyon is the same tonstein examined in Bear Gulch and at the I-70 road cut. Recalling, at I-70 only a single tonstein was present, in Bear Gulch four tonsteins were present, and at this outcrop in Miller Canyon, only three tonsteins are present. About 4 km north of Miller Canyon, at Pictograph Point, where the C *coal zone* goes into the subsurface, the C coal tonsteins are still preserved. The lower tonstein in the composite A and C *coal zone* is assigned to the A *coal zone.*

The C *coal zone* is 6.3 m thick at I-70 and increases northward until it is 13.8 m thick in Quitchapah Creek Canyon and deceases again northward until it is 6.2 m thick in Miller Canyon. The percentage of the C *coal zone* that is coal varies from 26% at I-70 (1.6 m) to 40% in Quitchapah Creek Canyon (5.5 m) to 80% at Bear Gulch (1.8 m) to 76% in Miller Canyon (1.0 m). Figure 20 shows the lateral coal facies cross-section of the C coal from I-70 to Miller Canyon.

In Miller Canyon, prodelta deposits of Parasequence 4a of Parasequence Set 4A rests on a 2 m thick transgressive lag deposit. This lag deposit can be traced into Bear Gulch, where the reworked distal delta front facies lie on the feathered up-dip end of the transgressive lag, and as far north as Dry Wash, a distance of 13 km. In Miller Canyon, this lag is a fine to medium grained, poorly sorted, fining-upward deposit that reworks the upper part of the C *coal zone* and exhibits extreme bioturbation. Abundant *Ophiomorpha, Thalassinoides, and Teichichnus* are present at the top of the lag deposit. This deposit represents the lag developed during the sea-level transgression prior to the development of the back-stepped deltaic deposits of Parasequence 4a of Parasequence Set 4A. The shoreline shifted landward by over 7 km.

Key Concepts of Stop 4:

- The C *coal zone* contains 2 tonsteins, the thickest of which is 30 cm thick. The thick tonstein can be traced over 18 km within the C coal zone.
- The C coal has lithofacies and tonsteins that can be correlated over a distance of at least 20 km.
- Parasequence 4a rests on a 2 m thick transgressive lag deposit. This deposit reworks the upper part of the C *coal zone* and exhibits extreme bioturbation. This lag was developed during the sea-level transgression prior to the development of the back-stepped deltaic deposits of Parasequence Set 4A.

DAY 2 ROAD LOG

Int. Miles	Cum. Miles	
0.0	0.0	Leave parking lot of Holiday Inn in Price, Utah. Travel east on Utah Highways 6 and 191.
1.3	1.3	Exit 241. Junction with Utah Highway 10. Travel south on Utah Highway 10 through Huntington, Castle Dale, Ferron and Emery to Fremont Junction.
62.1	63.4	Fremont Junction. Junction of Utah Highway 10 with I-70. Proceed under overpass under I-70 and continue south on unpaved Sevier County Road.
2.0	65.4	Junction with Dog Valley Coal Mine Road. Continue east on unpaved County Road.
0.8	66.2	Jeep trail to east of the County Road leads to Scabby Canyon, Blue Trail Canyon, Corbula Gulch, and Rock Canyon.
0.6	66.8	U.S.G.S. drill hole WS-22 is located on the east side of the road. In 1977, eight drill holes were put down in Willow Springs Quadrangle to evaluate and classify the federally owned coal resources

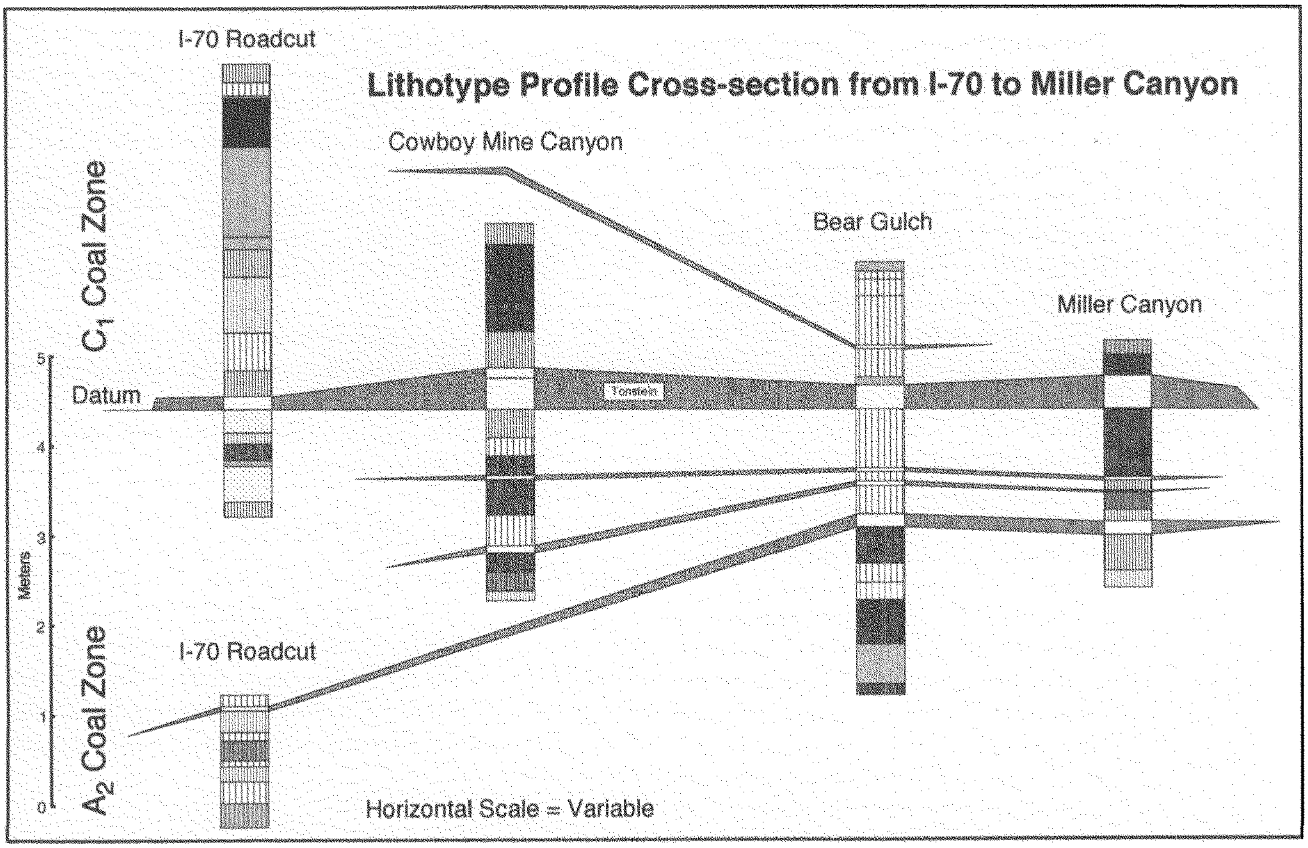


Figure 20. Lithotype profile cross-section of C coal zone *from I-70 to Miller Canyon.*

		and lands in the Emery Coal Field of the Upper Ferron Sandstone.
0.3	67.1	Jeep trail to the east of the County Road leads to Coyote Basin and Rock Canyon. A second jeep trail, up ahead a short distance, turns off the the west. U.S.G.S. drill hole WS-17 is located just north of this western jeep trail, about 0.5 miles west of the County Road.
0.6	67.7	Jeep trail to the east leads to the north canyon wall of Willow Springs Wash. Hills on the western skyline are formed of the Blue Gate Shale. Continue south on County Road.
0.2	67.9	Willow Spring Amphitheater. An outcrop of the Ferron Sandstone I *coal zone* can be seen on the south side of the County Road. Note the distributary channel belt of Ferron Parasequence Set 6 sitting on the I *coal zone.* Descend into Willow Springs Wash via County Road.
0.6	68.5	Willow Springs Wash. Note the small coal mine developed (and abandoned) in the Ferron A *coal zone.* Small mining shacks can be seen on both sides of the County Road and the mine loading chute can be seen down in bottom of Willow Springs Wash on the south side of the County Road, just ahead.
0.1	68.6	**STOP 5: Willow Springs Wash South Canyon Wall** (fig.1). Pull off on the south side of the County Road. Walk through Willow Springs Wash and climb up onto the south canyon wall.
0.0	68.6	Return to vehicles and proceed east along County Road on north side of Willow Springs Wash.
0.6	69.2	**STOP 6: Willow Springs Wash North Canyon Wall and The County Line Channel** (fig.1). Turn into dirt road on the north side of the County Road. Climb up to the base of the County Line Channel.

0.0	69.2	Return along County Road to the west to the Junction with I-70 and Utah Highway 10.
5.8	75.0	Fremont Junction. Junction of Utah Highway 10 with I-70. Proceed under overpass under I-70 and continue north on Utah Highway 10.
4.3	79.3	Junction with paved road, to the east, to Hidden Valley Mine. The mine, currently owned by Consol, has been reclaimed.
3.0	82.3	Sevier-Emery County Line. Enter Emery County.
1.0	83.3	Junction with road to Emery Coal Mine. Turn east onto Emery Coal Mine Road and proceed east toward Cowboy Mesa of the Molen Reef. Note the water pumping unit on the north side of the road. This unit is used by Consol to pump water from the Emery Mine Shafts 740 feet below. It is either used for irrigation or is held in holding ponds and then returned to Quitchapah Creek. This marks the northwestern extent of the underground Emery Mine.
1.3	84.6	Junction with paved County Road to Emery. Continue east on Emery Coal Mine Road.
0.9	85.5	**STOP 7: Emery Coal Mine (Consolidation Coal Company)** (fig.1). Stop in front of Mine Office. The Emery Mine of Consolidation Coal Company (Consol) is the largest mine in the Emery Coal Field.
0.0	85.5	Retrace route back to Utah Highway 10.
2.2	87.7	Junction of Emery Coal Mine Road with Utah Highway 10. Turn north onto Utah Highway 10 and proceed north through the Castle Valley to Price via Castle Dale, Ferron and Emery.
27.2	114.9	100 East Street in Castle Dale. Proceed north on Utah Highway 10 to Price via Huntington.
20.3	135.2	Emery-Carbon County Line. Enter Carbon County.
0.8	136.0	Junction with Utah Highway 122 to the west. Continue north on Utah Highway 10.
1.2	137.2	Junction with Stake Farm Road on east. Continue north on Utah Highway 10.
0.2	137.4	**STOP 8: Drunkards Wash Coalbed Methane Field (River Gas of Utah and Texaco)** (fig.1). Pull off to the west of Utah Highway 10 onto dirt road leading up to pump jack of the Utah 17-103 Coalbed Methane well. These pump jacks are used to pump produced salt water to the surface, along with the produced gas. The water is then disposed of by pumping units that pump it back into the subsurface Navajo Sandstone.
0.0	137.4	Continue north on Utah Highway 10 to Price.
3.9	141.3	Junction with Utah Highways 6 and 191 in Price. Turn west onto Utah Highways 6 and 191 and continue northwest to Helper, Spanish Fork, and Salt Lake.
0.0	113.6	End of Road Log.

DAY 2 STOPS

Note: Since the focus of the Day 2 Field Trip Stops will be petroleum and coal exploration and production oriented, the Day 2 Field Trip Stops will be discussed using the English units of feet, miles, and acres, in order to be consistent with current energy industry practice in the United States. The units of conversion for some of these units are given below:

1 ft = 0.3048 meters	1 meter = 3 28 ft
1 mile = 1.609 km	1 km = 0.621 miles
1 acre = 43560 ft^2	1 acre = 4049 m^2 = 0.004 km^2
1 mi^2 = 640 acres	1 km^2 = 247 acres
40 acre well spacing = 1380 ft	40 acre well spacing = 421 meters

Stop 5: Willow Springs Wash South Canyon Wall

Fluvial and Distributary Channel Belt Geometry and Architecture as a Function of Depositional Parasequence Set Stacking Patterns

The north and south canyon walls in Willow Springs Wash contains a strike outcrop section that exposes almost the complete delta plain facies association of Ferron Sandstone Parasequence Sets 2A-8 (fig.3). The lowermost cliff-forming units are the deltaic facies of Parasequences 1b and 1c. The delta plain facies association of Parasequence 1d also crops out. This canyon offers a superb opportunity to examine the geometry and architectural systematics of the non-marine delta plain facies of the Ferron parasequence sets, as a function of depositional parasequence and parasequence set stacking patterns.

van den Bergh and Garrison (1996) have quantified the geometry and internal architecture of the fluvial channel belts exposed in the north and south canyon walls of Willow Springs Wash. They used the parasequence and parasequence set subdivisions of the Ferron Sandstone defined by Garrison and van den Bergh (1996; 1997) and classified the channel belts according to their stratigraphic position within the 3rd-order parasequence set stacking pattern, originally outlined by Gardner. The channels belts in Willow Springs Wash exhibit differences in geometry and internal and external architecture that can be correlated with 3rd-order depositional parasequence set stacking patterns, which can be related to sediment supply and accommodation space systematics (fig. 10).

The channel belts of 3rd-order Ferron Sequence seaward-stepping parasequence sets formed in river-dominated deltas, when the available sediment supply exceeded the available accommodation space. These are generally laterally restricted and multi-storied with channel filling elements (i.e., macroforms and/or barforms) that are generally stacked vertically within the channel belt boundaries. Thicknesses from 10–15 feet and 40–45 feet and widths from 300–700 feet and 1200–1400 feet are most common. Width/thickness aspect ratios range from 7.8–52.9 and average about 29.5. Channel belts bifurcate as they approach the paleoshoreline and become narrower, averaging 638 feet in width, with lower aspect ratios, averaging about 16.6.

The channel belts of 3rd-order Ferron Sequence aggradational parasequence sets that formed in more storm-dominated deltas, when the sediment supply was balanced with rate of development of accommodation space, are generally quite laterally extensive and multi-storied with channel filling elements generally stacked en echelon laterally within the channel belt boundaries. Their thicknesses range from 25–35 feet and 55–60 feet. Widths from 1250–1900 feet are most common. Aspect ratios range from 31.9–97.4 and average about 57.2. Channel belts closer to the paleoshoreline have aspect ratios averaging about 12.0.

The channel belts of 3rd-order Ferron Sequence backstepping parasequence sets, formed in wave-dominated deltas, when the available sediment supply was less than the available accommodation space. These channel belts are laterally extensive and sheet-like, with channel filling elements generally stacked vertically within the channel belt boundaries. They range in thickness from 9–27 feet and 749–2652 feet in width, with vertically stacked elements. Aspect ratios of 65–90 and 185–195 are most common.

There is not much evidence to suggest that local preserved sand body thickness (i.e., channel fill elements) changes significantly as a function of distance to the paleoshoreline. Data suggest that preserved channel fill elements do become thinner downstream, but the data are scattered. Therefore, the data would tend to indicate that the preserved thickness of channel fill elements is controlled by local sedimentation rates, which decrease slightly down stream. The modelling of Heller and Paola (1996) suggests that such a scenario would result in channel stacking patterns (i.e., thickness and interconnectedness) that are a function of the relationship of avulsion frequency and sedimentation rate, but changes in stacking patterns downstream (i.e., along the dip direction of the alluvial/delta plain) are driven mainly by the rate of change of subsidence along the basin. Based on the modelling of Heller and Paola (1996), it appears that the driving force behind the development of different channel belt architectural styles can be attributed to changes in rate of sediment supply, with the relative rise in sea level being effectively constant and with regional avulsion frequency being also relatively constant.

The ratio of net sand thickness to gross stratigraphic thickness (net/gross), calculated for intervals within the Willow Spring Wash section, also vary as a function of 3rd-order deltaic stacking pattern. The overall Ferron Sandstone net/gross ratio, in Willow Springs Wash, ranges from 0.22 to 0.47, averaging 0.31. The net/gross ratios calculated for the seaward-stepping, aggradational, and landward-stepping intervals are 0.22±0.08 (range = 0.09–0.33), 0.43±0.18 (range = 0.14–0.65), and 0.32±0.9 (range = 0.23–0.45), respectively. The aggradational interval has the largest net/gross ratios, reflecting the aggrading and lateral stacking of the channel belts. The seaward-stepping interval has the lowest net/gross reflecting the wide spacing of confined channel belts, in the river-dominated systems.

The probability of inter-well connectivity (i.e., the probability that two wells, at a specified well spacing, will penetrated the same lithologic unit), at typical 40 acre and 80 acre well spacings is also a strong function of position within the overall stacking pattern of the 3rd-order deltaic parasequence sets. In the seaward-stepping parasequence sets, the average width is 742±412 feet. The probability of a channel belt extending between two wells spaced 40 acres apart is only about 10%, and there is very little probability at a 80 acre spacing. In the aggradational parasequence sets, the average width is 2045±1101 feet. The probability of a channel belt extending between two wells spaced 40 acres apart is about 75%, and the probability at a 80 acre spacing is only about 22%. In the landward-stepping parasequence sets, the average width is 1499±711 feet. The probability of a channel belt extending between two wells spaced 40 acres apart is about 50%, and the probability at a 80 acre spacing is less than 10%.

Key Concepts of Stop 5:

- The channels belts in Willow Springs Wash exhibit differences in geometry and internal and external architecture that can be correlated with 3rd-order depositional parasequence set stacking patterns, which are related to sediment supply and accommodation space systematics.
- Width/thickness aspect ratios for channel belts within 3rd-order seaward-stepping parasequence sets range from 7.8–52.9 and average about 29.5.

- Width/thickness aspect ratios for channel belts within 3rd-order aggradational parasequence sets range from 31.9–97.4 and average about 57.2.
- Aspect ratios of 65–90 and 185–195 are most common for channel belts within 3rd-order landward-stepping parasequence sets.
- Net/gross ratios, calculated for intervals within the Ferron Sandstone non-marine section, also vary as a function of 3rd-order deltaic stacking pattern.
- The probability of inter-well connectivity, at typical 40 acre and 80 acre well spacings, is also a strong function of position within the overall stacking pattern of the 3rd-order deltaic parasequence sets.

Stop 6: Willow Springs Wash North Canyon Wall and The County Line Channel

Internal Channel Belt Sedimentology and Architecture as a Function of Depositional Parasequence Set Stacking Patterns

The channel belts in Willow Springs Wash exhibit differences in internal sedimentology and architecture that can be correlated with 3rd-order depositional parasequence set stacking patterns, which can be related to sediment supply and accommodation space systematics. The channel belts of seaward-stepping parasequence sets are generally laterally restricted and multi-storied with channel filling elements (i.e., macroforms and/or barforms) generally stacked vertically within the channel belt boundaries. The channel belts of aggradational parasequence sets are generally quite laterally extensive and multi-storied with channel filling elements generally stacked en echelon laterally within the channel belt boundaries. The channel belts of landward-stepping parasequence sets are laterally extensive and sheet-like with channel filling elements generally stacked vertically within the channel belt boundaries.

The type channel belts for each of these architectural styles crop out in the north canyon wall. The County Line Channel, a Parasequence 1d (Parasequence Set 1) distributary channel belt, is excellently exposed in the lower cliffs of the north canyon wall of Willow Springs Wash (fig. 21). The Kokopelli Channel Belt, a Parasequence Set 4B channel belt, crops out mid-wall up the north canyon wall above the County Line Channel. The Caprock Channel, a Parasequence Set 7 channel belt caps the north canyon wall of Willow Springs Wash. This stop will focus on the internal sedimentology and architecture of the County Line Channel (fig. 22).

The County Line Channel, a Parasequence 1d distributary channel belt, trending 040°, is excellently exposed on the north canyon wall of Willow Springs Wash. It has a meander wavelength of about 3 miles and a meander amplitude of only 0.6 miles. The County Line Channel bifurcates just south of Indian Canyon, resulting in a smaller channel belt, exposed further west in Willow Spring Wash. This smaller distributary, the Coal Miner's Channel, generally trending 360° north and has a meander wavelength of about 2 miles and an amplitude of only 0.2 miles. The County Line Channel feeds a mouth bar complex near the mouths of Coyote Basin and Rock Canyon. The County Line Channel is a 1243 feet wide and 60 feet thick distributary channel belt, with an aspect ratio of 20.7. It incises through the Sub-A1 *coal zone* into Parasequence 1c. The Coal Miner's Channel is 354 feet wide and 16.1 feet thick, resulting in an aspect ratio of 22.0. This smaller channel branch does not cut through the Sub-A1 *coal zone.*

The external geometry of the County Line Channel suggests that there are at least three stages in the development of the distributary channel belt morphology. Each stage preserves from 14–33 feet of sand and each stage becomes progressively wider and less confined than the previous stage. The lower five elements represent scour and fill elements deposited within a narrow 332 feet wide, confined channel. The preserved thickness of this first phase of the channel belt is approximately 33 feet, resulting in a width/thickness aspect ratio of 10.0. The second phase of channel development is recorded by the next seven higher channel fill elements, reflecting both cut and fill characteristics and lateral accretion structures. These channel fill elements were deposited in a much wider, yet confined channel 1120 feet wide. The preserved thickness of this second phase of the channel belt is approximately 22 feet, resulting in a width/thickness aspect ratio of 50.9. The final phase of the channel belt is dominated by lateral accretionary bedforms and bedsets, which interfinger with the laterally equivalent delta-plain facies associations. This channel fill event has well-developed levees and overbank facies. The preserved width and thickness of this phase are 1243 feet and 13.6 feet, respectively, resulting in of a width/thickness aspect ratio of 91.4.

The County Line Channel is composed of fourteen channel fill elements. The lower 5 elements are associated with the narrow, confined first stage of the channel belt development and represent major scour and fill events. The bounding surfaces of these channel fill elements are frequently delineated by thick clay pebble lag deposits. These channel fill elements are generally medium-lower to medium-upper grained sandstones that fine upward to medium-lower to fine-upper grained sandstones. They generally have large trough cross beds (i.e., >0.5 feet thick) near their bases, which change upward into faint large troughs and massive sandstones. The trough cross-beds decrease in

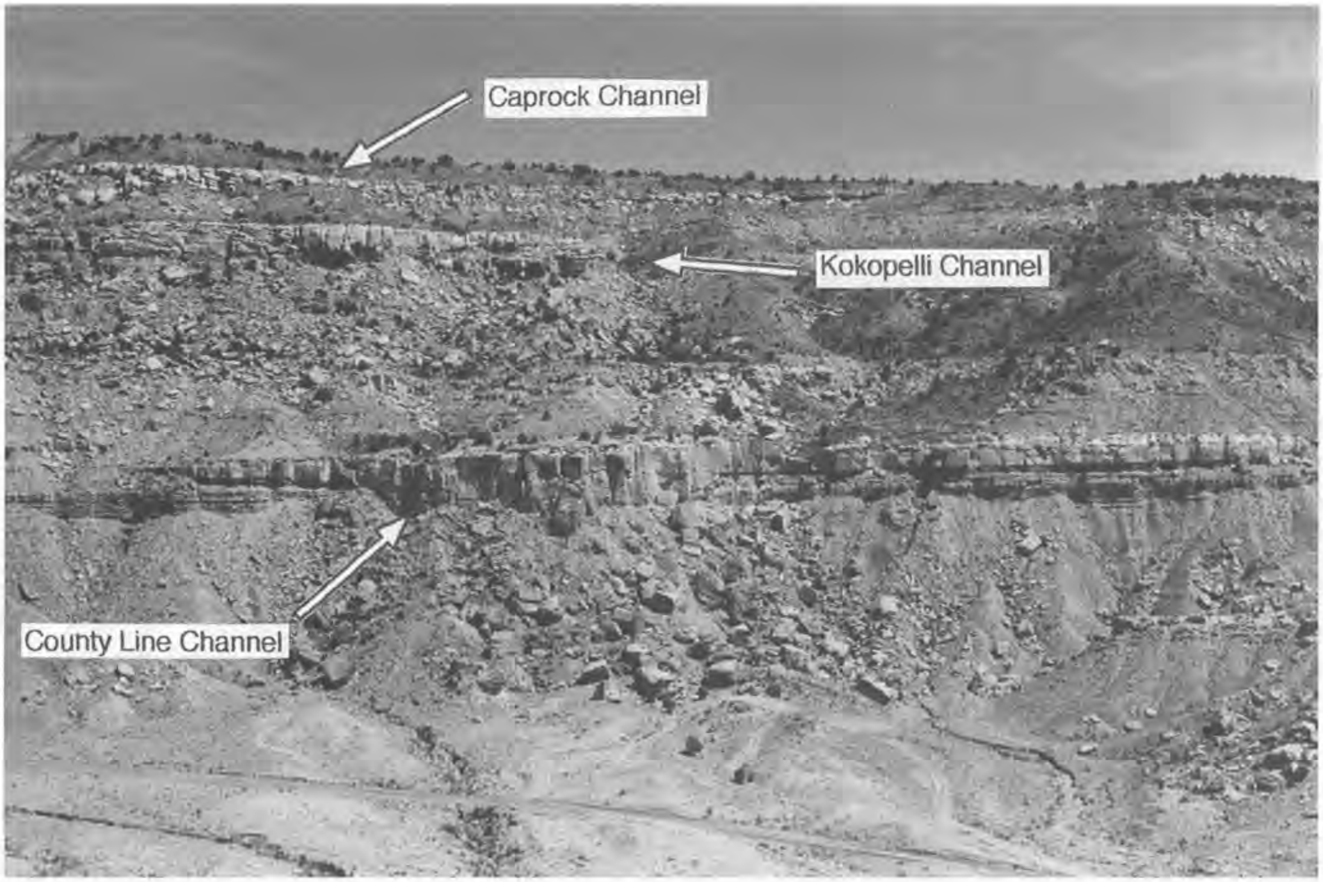


Figure 21. Photograph showing the County Line Channel in Willow Springs Wash. The channel belt is 1243 feet wide and 60 feet thick.

size upward (to < 0.3 feet thick). Occasionally, trough cross-beds near bounding surfaces are contorted. There are 7 channel fill elements in the second stage of the development of the County Line Channel. These channel fill elements are dominated by lateral accretion surfaces and bedforms. The bounding surfaces between these channel fill elements are frequently defined by bedding surfaces between major bedform domains or barforms. These channel fill elements are generally medium-lower to fine-upper grained and exhibit a general overall fining upward trend. These channel fill elements contain faint large trough cross-beds to massive, structureless sandstones that are transitional into smaller trough cross-beds and planar and wedge tabular cross-stratified beds that suggest a westward lateral migration. The upper two channel fill elements represent the final final phase of the development and preservation of the County Line Channel, and interfinger with delta-plain facies associations. These two channel fill elements are generally medium-lower to fine-upper sandstones. They exhibit large scale planar tabular cross-beds near the central portion of the channel, but exhibit small scale planar tabular cross-beds, ripple cross-stratification, and climbing ripple cross-stratification near the top and laterally towards the channel margins.

The changes in the geometry and architecture of the County Line Channel are most easily explained as simple consequences of channel belt evolution as a result of normal delta progradation. The narrow confined first stage of channel fill (i.e., aspect ratio of 10) probably represents the channel belt at a position close to the paleoshoreline. The wider second stage of channel fill may represent the channel belt cross-section, some 1.4 miles from the paleoshoreline, after the delta front deposits prograded seaward about 0.8 miles (Garrison and van den Bergh, 1997). This change in position of the cross-section relative to the paleoshoreline is consistent with the change in width/thickness aspect ratio (i.e., 50.9), although the overall preserved channel belt aspect ratio was only 24.3. During the third stage of channel fill, the channel fill deposits had an aspect ratio of 91.4, although the overall preserved channel belt aspect ratio was only 20.7. The final channel fill and abandonment is probably a normal abandonment phase of the second stage.

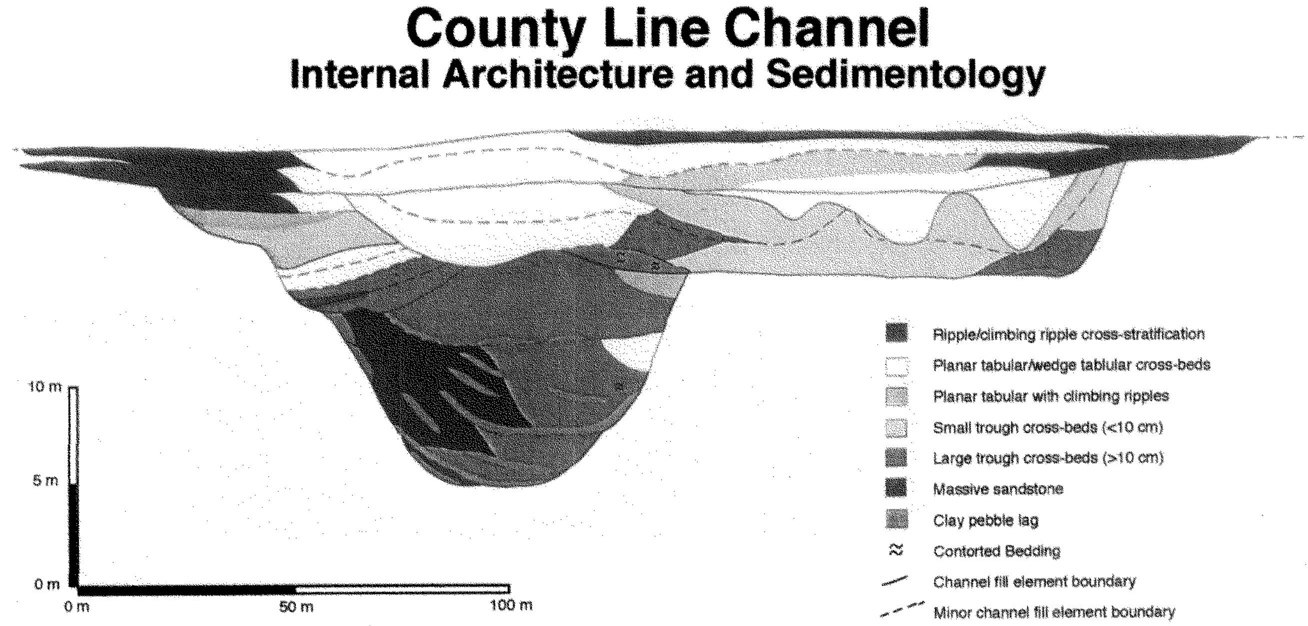


Figure 22. Schematic diagram showing the internal architecture and sedimentology of the County Line Channel.

Key Concepts of Stop 6:

- The channels belts in Willow Springs Wash exhibit differences in sedimentology and internal architecture that can be correlated with 3rd-order depositional parasequence set stacking patterns.
- The external geometry of the County Line Channel suggests that there are at least three stages in the development of the distributary channel belt morphology.
- The County Line Channel is composed of fourteen channel fill elements. The lower five channel fill elements represent major scour and fill events (1st stage). The overlying seven channel fill elements are dominated by lateral accretion sedimentary surfaces, structures, and bedforms (2nd stage). The upper two channel fill elements interfinger with the lateral delta-plain facies associations and represent the final stage of channel fill and abandonment.

Stop 7: Emery Coal Mine

The Emery Coal Field

The Emery Coal Field was originally defined from the surface exposures of coal in the Upper Cretaceous Ferron Sandstone Member of the Mancos Shale (Lupton, 1916) (i.e., Upper Ferron Sandstone). The surface exposures cover an area 25 miles long, from north to south and 2 to 10 miles from east to west along the Sevier-Emery County border (fig. 23). This area lies about 45 miles southwest of Price, Utah, the nearest rail loadout. The field, as originally defined, is bounded on the east by an erosional escarpment and on the west by a fault zone (Doelling, 1972). Recently published drilling data show that similar thick coal beds also are present in the subsurface extending northward all the way to Price (Bunnell and Hollberg, 1992; Tabet et al., 1995) (i.e., Lower Ferron Sandstone). Thus, the northern boundary of the Emery Coal Field actually extends northeastward beyond Price.

The coal of the Emery Coal Field, in the south, contains 13 coal seams, seven of which exceed 4 feet in thickness. Lupton (1916) gave the beds letter designations from A to M in ascending order of occurrence. Beds I and J are the most important, and the separation between them is minimal in many areas, resulting in a single seam up to 25 feet thick. The total net thickness of coal in the Ferron Sandstone reaches a maximum of nearly 60 feet in the southern part of the coal field, and is commonly 20 to 30 feet along the whole coal trend running northward past Price (Tabet et al., 1995).

The structure and stratigraphy of the coal field are favorable for mining. The coal beds strike northeasterly and dip to the west from 2° to 12°; most dips fall in the 4° to 7° range. Faulting is minor and presents little difficulty in mining or gas extraction. The overburden over 76 percent of the resources identified in the northern end of the field is less than 1,000 feet; very thin overburden in some areas creates surface mining possibilities (Doelling, 1972).

Original in-place resources for the southern part of the Emery Coal Field are estimated at 2.15 billion tons (Doelling and Smith, 1982) for all beds greater than 4 feet thick and under less than 3,000 feet of cover. Demonstrated resources make up 1.43 billion tons of the total, with the remainder falling in the hypothetical resource category. Cumulative coal production for the whole field through 1990 was 9.5 million tons (Jahanbani, 1996). Assuming a 40% recovery rate for both past and future underground mining, the Emery Coal Field's remaining recoverable coal resources are estimated to be 822 million tons. The use of surface mining to recover coal from areas with less than 100 feet of overburden would increase the recoverable resources in those areas.

Compositions of Upper Ferron Coals from the Emery Coal Field

Average proximate and ultimate compositional analyses for Upper Ferron Coals from the Emery Coal Field are summarized in Table 1 (Affolter et al., 1979; Hatch et al., 1979; Bunnell and Hollberg, 1991; Sommer et al., 1991). All analyses are reported in weight percent. Recent works indicate that the Upper Ferron coals are high volatile Bituminous B rank coals (Sommer et al., 1991; Tabet et al., 1995), although earlier studies by Doelling (1972) suggested high volatile Bituminous C rank coals. Vitrinite reflectance data from wells penetrating deep Ferron coals under the Wasatch Plateau indicate the coals gradually increase in rank to the west to high-volatile B bituminous (Tabet et al., 1995).

The most notable differences in the compositions of the Upper Ferron coals is their ash and sulfur contents. The ash content of the Ferron Coals ranges from 9.5% in the I Coal at the Emery Mine, to 29.4% in the J coal (Table 1). BTU content varies with ash content, ranging from 12690 BTU/lb, in the I coal, to 9480 BTU/lb, in the J coal. The sulfur content ranges from 0.6% in the I coal, up to 4.1% in the J coal (Table 1). With the exception of the I coal, the higher *coal zones* in the Upper Ferron Sandstone (i.e., the G, J, and the M) all have high ash and sulfur contents. The stratigraphically lower C coal also has a slightly higher ash and sulfur content than either the A and the I coals.

Figure 24 shows a ternary plot of the sulfur types for the Ferron coals. The A and I coals have a high weight percentage of organic sulfur, with pyritic sulfur being lowest; the G, J, and M are high in pyritic sulfur; the C coal appears to be intermediate between these two groups. Pyritic sulfur can be introduced after deposition. However, it is often early diagenetic and suggests continuing reducing conditions. Organic sulfur is generally introduced during deposition. The coals with the highest ash, total sulfur, and pyritic sulfur contents belong to transgressive phases of either the 3rd- or 4th-order depositional sequences; the coals with the lowest ash and sulfur contents belong to parasequence sets that are either strongly aggradational or strongly progradational. Peterson et al., (1996) noted that coals formed from peats influenced by marine waters, generally have high sulfur contents. Such conditions are likely to occur during marine transgressions. These observations are consistent with the stratigraphic positions of the high sulfur Ferron coals.

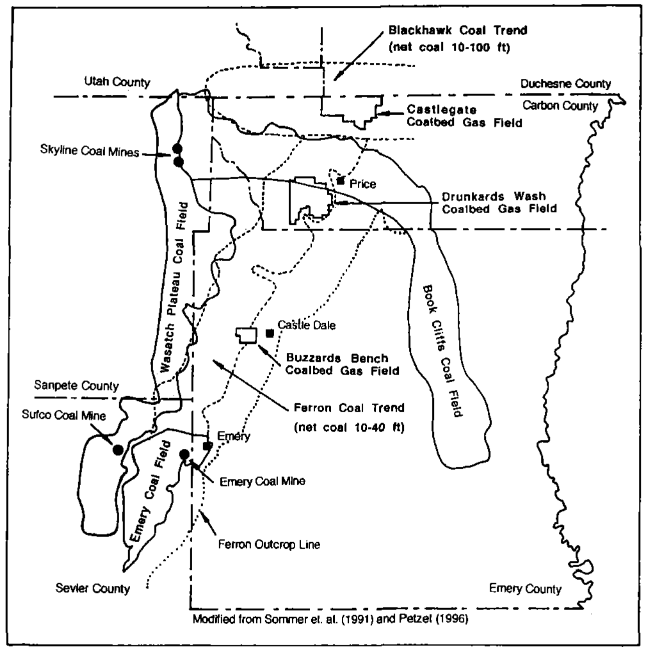


Figure 23. Location map for Emery, Bookcliffs, and Wasatch Coal Fields and the Ferron Coalbed Methane Play.

Coal Mining at the Emery Mine

The Emery Mine, now operated by Consolidation Coal Company (Consol), produced coal from the Upper Ferron I *coal zone*. This was the largest and longest producing mine in the Emery Coal Field. The Browning Mine, the original underground mine in the canyon, was opened in 1910. The old Browning Mine has its portal about 200 m southeast of the current Emery Mine portal. The Browning Mine was abandoned when a major coal burn to the south was encountered. The portal was moved northwest and the current Emery Mine opened in 1945. In 1975, Consolidation Coal Company began operating the underground Emery Coal Mine. By the early 1980s, Consol employed up to 200 people, and was producing over 430,000 tons of coal per year. Total coal production exceeded 18 million tons. The mine extends about 1.4 miles underground to the northwest and reaches a depth of 740 feet. There are over 5 miles of conveyor belts. The main market for the Ferron I Coal from

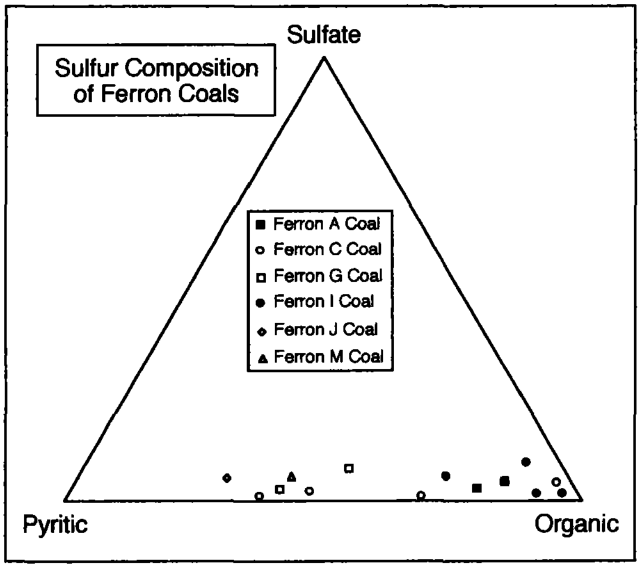


Figure 24. Ternary diagram showing composition of sulfur within the Upper Ferron coal seams.

the Emery Mine was the power plants scattered up the Castle Valley. In 1990, Consol ceased operations in the Emery Mine and by 1991, the mine was classified as inactive. In 1994, a small amount of coal was shipped from the stockpile. In 1995, Consol sealed the portals and limited maintenance to pumping water from the mine to prevent flooding. In 1996, the last coal from the Emery mine stockpile was shipped. The lack of railroad access and the high costs of trucking coal to the Castle Valley power plants contributed to the eventual closing of the Emery Mine.

At the Emery Mine, coal was produced from a 22 ft thick seam of coal within the Upper Ferron I *coal zone*. To the northwest the coal seam splits into two 10 ft thick seams. The I coal seam at the Emery Mine is low in ash (9.5%), with a BTU content of 12690 BTU/lb (dry-basis) (see Table 1). The sulfur content of the I coal seam is low (0.6%) and is dominantly organic sulfur, with only minor pyritic sulfur. The Emery Mine contains a moderate amount of free methane gas, and is considered by mining standards to be "gas-rich."

Key Concepts of Stop 7:

- The underground Emery Coal Mine of Consolidation Coal Company was the largest and most productive of the coal mines in the Emery Coal Field. It produced over 430,000 tons of coal per year from the Ferron I *coal zone*.
- At the mine, Ferron I coal seam is 22 feet thick and is the highest quality and thickest coal seam in the Emery Coal Field, containing only 9.5% ash and producing 12690 BTU/lb.
- The Upper Ferron coals have ash contents that range from 9.5%, in the I Coal at the Emery Mine, to 29.4% in the J Coal. The sulfur content ranges from 0.6%, in the I coal, up to 4.1%, in the J coal

Stop 8: Drunkards Wash Coalbed Methane Field

Generation, Retention, and Production of Methane from Coal: Implications for the Ferron Coalbed Methane Play

Coal forms a unique hydrocarbon reservoir in that the hydraulic pressure typically maintains the gas in place rather than in a sealed porous reservoir like that found in conventional hydrocarbon reservoirs. Coal bed gas (CBG) is also unusual in that the coal itself is the source of the gas it stores. This gas is methane-rich and has a biogenic or thermogenic origin. Biogenic gas generation is restricted to shallow depth but this generation can occur both during early diagenesis and burial or late diagenesis and exhumation. Thermogenic gas generation typically caused by burial heating increases with coal rank. A coal of high volatile Bituminous B (hvBb) rank typically produces about 960 standard cubic feet/ ton (SCF/ton) of methane (Choate et al., 1986).

Free gas is expulsed from coal when the internally generated gas volume exceeds sorption capacity. The sorption capacity can also be filled by externally generated gas that migrates into the coal. Internally generated or migrating gas in excess of the sorption capacity continues through the coal and is not retained unless trapped. Thus, if a coal exists within a conventional gas trap, it is possible for the coal to retain gas above its apparent sorption capacity and become supersaturated with gas.

Coal maceral composition and ash content are also important internal coal bed controls on CBG content. There are three maceral groups found in coal. The Vitrinite group is formed from woody plant debris, the liptinite group is from waxy, resinous and oily components and the inertinite is from fossil charcoal as well as other altered and oxidized plants materials. Increasing vitrinite content enhances gas storage capacity and cleat (i.e., fractures in coal) permeability. Increasing liptinite content enhances gas generation but reduces storage capacity. Increasing inertinite content enhances matrix permeability but decreases gas generation but reduces storage capacity. Ash (mineral matter) has little storage capacity, reduces gas content in direct proportion to its abundance, and inhibits cleat formation.

Although coal porosity is high, matrix permeability is low, making cleat permeability an important control in commercial production. The capacity to hold and generate gas can

Table 1. Analyses of Ferron coals (all analyses reported air dried).

	U. Ferron A Coal	U. Ferron C Coal	U. Ferron G Coal	U. Ferron I Coal	U. Ferron J Coal	U. Ferron M Coal	L. Ferron Core	Ferron Henry Mts	Wasatch Skyline	Wasatch SUFCO
Volatile (wt%)	41.2	40.4	40.5	41.7	36.8	41.8	36.0	36.2	52.7	43.9
Fixed Carbon (wt%)	48.0	46.7	42.4	48.8	33.8	44.4	47.3	49.5	39.2	46.3
Ash (wt%)	10.9	12.9	17.2	9.5	29.4	13.8	17.1	14.3	8.1	9.9
H (wt%)	5.2	5.0	4.7	5.1	4.3	4.8	5.0	4.8	5.3	4.7
C (wt%)	71.0	68.1	63.8	71.6	52.9	66.0	68.2	65.7	72.8	71.7
N (wt%)	1.4	1.2	1.2	1.4	1.2	1.3	1.2	1.3	1.4	1.3
O (wt%)	10.9	11.2	10.0	12.5	8.3	10.6	7.9	11.8	12.0	12.1
S (wt%)	0.8	1.6	3.1	0.6	4.1	3.6	1.7	2.2	0.5	0.3
Sulfate S (wt%)	0.03	0.03	0.15	0.03	0.20	0.20	n.a.	n.a.	n.a.	n.a.
Pyritic S (wt%)	0.14	0.66	1.59	0.08	2.68	1.92	n.a.	n.a.	n.a.	n.a.
Organic S (wt%)	0.66	0.88	1.40	0.59	1.18	1.49	n.a.	n.a.	n.a.	n.a.
Btu/lb	12650	12150	11320	12690	9480	11810	12690	11550	12690	12440

be predicted using coal rank but coal seam permeability must be assessed in the field. In particular finding areas of enhanced production or high methane content are important to commercial production. Zones of high methane content formed by coal facies, partial exhumation and conventional gas traps are likely in the Ferron CBG Fairway.

Exploration for CBG generally ranges from 150 m to 2 km depth because: (1) at shallow depths, low hydraulic head causes the coal to retain little methane; and, (2) beyond 2 km, coal cleat is closed making commercial production difficult. The depth of burial in the Ferron CBG Fairway to the east of the Wasatch Plateau and west of the outcrop belt is generally ideal for CBG production.

Coalbed Methane Resources of the Ferron Sandstone Coalbed Methane Play

The Ferron Sandstone Coalbed Methane Play is a 6–10 mile wide by 80 mile long fairway (Tripp, 1989; Tabet et al., 1995) (fig. 23). The methane is produced from coal beds in the Lower Ferron Sandstone (Vernal Delta). The coals occur at attractive drilling depths ranging from under 1,000 feet to over 7,000 feet. Some gas desorption data have been collected from shallow coals of the Upper Ferron Sandstone, at the southern end of the coal field (Doelling et al., 1979), but these few, near-outcrop samples yielded only 0–16 standard ft3/ton (SCF/ton) methane. Only one gas content measurement for deep Ferron Sandstone coals has been released by companies currently exploring for gas. River Gas of Utah reports its initial core test well had in excess of 400 SCF/ton methane in a 36.7 foot thick coal interval (Lyle, 1991). If the entire Ferron coal play contains similar gas contents, then in-place gas resources for the play could be as high as 9 TCF.

River Gas of Utah, Texaco, and Anadarko have been active in exploring and producing the coalbed methane from the Ferron play. The Ferron Sandstone CBM Play currently contains over 100 producing coalbed methane wells. In 1995, almost 4% of Utah's total gas production came from wells in the Ferron Sandstone CBM Play (Petzet, 1996). Cumulative production from the Ferron CBM play through October 1996 is approximately 30 BCF. Currently two fields are producing from the Ferron Sandstone CBM Play: the Drunkards Wash Field south of Price, Utah, operated by River Gas of Utah, and the Buzzards Bench Field at Orangeville, Utah, operated by Texaco.

Drunkards Wash Coalbed Methane Field

The Drunkards Wash Coalbed Methane Field is the largest field in the Ferron Sandstone CBM Play; it covers 120,000 acres and contains 89 producing wells on an 160 acre spacing (Lamarre and Burns, 1996). The wells have a classic coalbed methane negative decline curve with increasing gas rates as the reservoir pressure declines due to the production of water (Lamarre and Burns, 1996). These wells produce 43.7 MMCFD, averaging 491 MCFD/well. As of mid-1996, thirty of these wells had been producing for over 38 months and have an average of 692 MCFD/well (Lamarre and Burns, 1996). The daily water production is 16,500 bbl, averaging 185 BWPD/well. In 1995, the field produced 11 BCF of methane and 5.7 million bbl water. All wells are cased and hydraulically stimulated and most have pumping units to handle the large volume of produced salt water.

Salt water produced with the methane gas is disposed of by pumping units that pump the water into the subsurface Navajo Sandstone at a depth of 5500–6000 feet.

The typical depth for these wells is 1800–3400 feet. The total coal thickness within the field ranges from 4–48 ft, but averaging 24 ft (Lamarre and Burns, 1996). The coal occurs in from 3 to 6 distinct seams. The coal is high volatile Bituminous B (hvBb) coal. The hvBb rank of the Ferron coal is within the window of thermogenic gas generation, which typically produces about 960 SCF/ton of methane (Choate et al., 1986). This volume is gas is far more than the reported 440 SCF/ton of methane present in the Lower Ferron coals in the Drunkards Wash Field (Burns and Lamarre, 1996). The hvBb rank also suggests a sorption capacity of only 200 SCF/ton at their present burial depth of about 2,000 ft (Kim, 1977), suggesting the Ferron coals are supersaturated with gas. This amount of gas is higher than the coal rank and depth would suggest. The gas appears to be a combination of thermogenic and secondary biogenic gas (Lamarre and Burns, 1996). Canister desorption data and measured sorption isotherms suggest the coal is supersaturated with respect to gas at the initial measured reservoir pressures of 765 psi (Burns and Lamarre, 1996). Further, when wells are initially completed in these Ferron coals, gas can flow without stimulation, a signature of supersaturation. The excess gas in these marginally mature coals seems to come from Ferron coals themselves and perhaps other source rocks buried deeper in to the west. After generation, the gas apparently migrated into the conventional gas trap formed by the updip pinchout of coalbeds into the mudrocks at the Drunkards Wash field.

Key Concepts of Stop 8:

- The Ferron Sandstone Coalbed Methane Play is a 6–10 mile wide by 80 mile long fairway that has been estimated to contain as much as 9 TCF gas. Cumulative production from the Ferron CBM play, through October 1996 is approximately 30 BCF.
- The Drunkards Wash Coalbed Methane Field is the largest field in the Ferron Sandstone CBM Play; it contains 89 producing wells (1995). In 1995, the field produced 11 BCF of methane and 5.7 million bbl water.
- Salt water produced with the methane gas is disposed of by pumping units that pump the water into the subsurface Navajo Sandstone at a depth of 5500–6000 feet.

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