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GEOLOGICAL AND PETROPHYSICAL CHARACTERIZATION OF THE FERRON SANDSTONE FOR 3-D SIMULATION OF A FLUVIAL-DELTAIC RESERVOIR

Annual Report for the Period
October 1, 1994 to September 30, 1995

By
Thomas C. Chidsey, Jr.
M. Lee Allison

May 1996

Performed Under Contract No. DE-AC22-93BC14896

Utah Geological Survey
Salt Lake City, Utah

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Prepared for
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ABSTRACT

The objective of the Ferron Sandstone project is to develop a comprehensive, interdisciplinary, quantitative characterization of a fluvial-deltaic reservoir to allow realistic inter-well and reservoir-scale models to be developed for improved oil-field development in similar reservoirs world-wide. Quantitative geological and petrophysical information on the Cretaceous Ferron Sandstone in east-central Utah was collected. Both new and existing data is being integrated into a three-dimensional model of spatial variations in porosity, storativity, and tensorial rock permeability at a scale appropriate for inter-well to regional-scale reservoir simulation. Simulation results could improve reservoir management through proper infill and extension drilling strategies, reduction of economic risks, increased recovery from existing oil fields, and more reliable reserve calculations. Transfer of the project results to the petroleum industry is an integral component of the project. This report covers research activities for fiscal year 1994-95, the second year of the project. Most work consisted of developing field methods and collecting large quantities of existing and new data. We also continued to develop preliminary regional and case-study area interpretations.

The project is divided into four tasks: (1) regional stratigraphic analysis, (2) case studies, (3) reservoirs models, and (4) field-scale evaluation of exploration strategies. The primary objective of the regional stratigraphic analysis is to provide a more detailed interpretation of the stratigraphy and gross reservoir characteristics of the Ferron Sandstone as exposed in outcrop. The primary objective of the case-studies work is to develop a detailed geological and petrophysical characterization, at well-sweep scale or smaller, of the primary reservoir lithofacies typically found in a fluvial-dominated deltaic reservoir. Work on tasks 3 and 4, reservoir models and field-scale evaluation of exploration strategies, consisted of developing and testing modeling methods. The bulk of the work on these tasks will be conducted primarily during the last year of the project, and will incorporate the data and results of the regional stratigraphic analysis and case-studies tasks.

Regionally, the Ferron Sandstone consists of up to seven delta-front sandstone bodies or parasequence sets. Our work focuses on two parasequence sets (Kf-1 and Kf-2) in the lower part of the Ferron. The Kf-1 represents a river-dominated delta deposit which changes from proximal to distal. The Kf-2 contains more and cleaner sand, indicating a more wave-influenced environment of deposition.

During fiscal year 1994-95, photographs of the Ferron Sandstone outcrop belt within the study area were digitized and assembled into photomosaics. Lithofacies, measured sections, vertical and horizontal scales, and other data were plotted on the photomosaics in the field for both the regional and case-study analyses. Published and unpublished maps, measured sections, well logs, core descriptions, reports, and other data were collected, compiled, interpreted, and entered into a database developed by the Utah Geological Survey. Strip logs were generated from this database.

Field work continued in the two case-study areas: Ivie Creek and Willow Springs Wash in the central and southern parts respectively of the study area. Sixteen sections were measured and described with emphasis on major reservoir lithofacies. Sections were correlated to develop preliminary interpretations of the stratigraphy and lithofacies. Over 100 paleocurrent

measurements were taken at these and other localities. Lithologic and paleocurrent data were entered into the database from which stratigraphic sections, rose diagrams, and statistical presentations were produced. Six core holes were drilled and logged in the Ivie Creek case-study area. The Kf-1 and Kf-2 parasequence sets were cored in four holes. Fourteen gamma-ray traverses were done (corresponding to petrophysical and permeability transects), each consisting of 200 to 400 measurements from the Kf-1 and Kf-2. Surface core plugging of the Ferron Sandstone was done along 18 vertical or near-vertical traverses. In all, 285 plugs were taken from various lithofacies in both the Kf-1 and Kf-2 sandstones. Petrophysical and thin section analysis was conducted on core plugs collected in 1994.

A total of 15 permeability transects were made on the outcrop at the Ivie Creek case-study area and evaluated along with the data from seven 1994 permeability transects. The transects span the proximal, middle, and distal portions of the delta-front rocks of the Kf-1 and representative sections of the Kf-2. Transect locations were chosen to encompass the majority of the lithofacies present in the delta-front sequence. Data from these transects are being used to determine the statistical structure of the spatially variable permeability field within the delta front, to investigate how geological processes control the spatial distribution of permeability, and to evaluate permeability measurement techniques.

A methodology was established and tested for using a numerical modeling approach to explore the influence of reservoir architecture and permeability structure on oil production. Detailed architectural and permeability models will be based on the high-resolution field work which was performed in our outcrop-based studies of the Ferron Sandstone. Although our methodology is tested in a two-dimensional mode, this approach is readily extended to a three-dimension mode. The homogenization code for one-, two-, and three-dimensional problems was completed and extensively tested.

Technology transfer during the second project year consisted of booth displays for various professional conventions, technical presentations, and numerous publications.

EXECUTIVE SUMMARY

Understanding reservoir heterogeneity is the key to increasing oil recovery from existing fields in the United States. Fluvial-deltaic reservoirs have the largest developed oil reserves, and due to the high degree of reservoir heterogeneity, the largest amount of untapped and unrecovered oil within developed reservoirs. Reservoir heterogeneity is dramatically exposed in the fluvial-deltaic Ferron Sandstone Member of the Cretaceous Mancos Shale in east-central Utah.

The Utah Geological Survey (UGS) leads a multidisciplinary team to develop a comprehensive and quantitative characterization of the Ferron Sandstone as an example of a fluvial-deltaic reservoir which will allow realistic interwell and reservoir-scale modeling. These models may be used for improved oil-field development in similar reservoirs world-wide. The Ferron Sandstone project team consists of the UGS (prime contractor), University of Utah, Brigham Young University, Utah State University, Amoco Production Company, Mobil Exploration and Producing Company, and several geologic contractors. This research is performed under the Geoscience/Engineering Reservoir Characterization Program of the U.S. Department of Energy, Pittsburgh Energy Technology Center. This report covers research activities for fiscal year 1994-95, the second year of the project. Most work consisted of collecting and interpreting large quantities of existing and new data, and developing and testing methods for reservoir modeling. We also developed preliminary regional and case-study area interpretations.

The project is divided into four tasks: (1) regional stratigraphic analysis, (2) case studies, (3) development of reservoirs models, and (4) field-scale evaluation of exploration strategies. The primary objective of the regional stratigraphic analysis is to provide a more detailed interpretation of the sequence stratigraphy and gross reservoir characteristics of the Ferron Sandstone as exposed in outcrop. This regional study includes determining the dimensions and depositional environment of important sandstone reservoir bodies and the nature of contacts with adjacent rocks. The primary objective of the case-studies work is to develop a detailed geological and petrophysical characterization of some of the primary reservoir lithofacies typically found in a fluvial-dominated deltaic reservoir. The bulk of the work on tasks 3 and 4, reservoir models and field-scale evaluation of exploration strategies, will be conducted primarily during the last year of the project, and will incorporate the data and results of the regional stratigraphic analysis and case-studies tasks.

Regionally, the Ferron Sandstone consists of up to seven delta-front sandstone bodies or parasequence sets. The focus of our work is two parasequence sets in the lower part of the Ferron designated as the Kf-1 and Kf-2. The Kf-1 represents a river-dominated delta deposit which changes from proximal to distal. The Kf-2 contains more and cleaner sand, indicating a more wave-influenced environment of deposition. Recognizable sequences within the sets have been designated with lower-case letters (for example, Kf-1a). In some cases, the divisions may lack transgressive surfaces, yet are recognizable by changes in sedimentary styles.

During fiscal year 1994-95, photographs of the Ferron Sandstone outcrop belt within the study area were digitized and assembled into photomosaics. Lithofacies, measured sections, vertical and horizontal scales, and other data were plotted on the photomosaics in the field for both the regional and case-study analyses. Published and unpublished maps, measured sections,

well logs, core descriptions, reports, and other data were collected, compiled, interpreted, and entered into a database developed by the Utah Geological Survey. Strip logs were generated from this database. Base maps were created by digitizing the seven quadrangles within the study area. These base maps will be used for preparing lithofacies, paleogeographic, and other maps.

Field work continued in the two case-study areas: Ivie Creek and Willow Springs Wash in the central and southern parts respectively of the study area. The Ferron Sandstone in the Ivie Creek case-study area consists of two regional-scale parasequence sets, the Kf-1 and Kf-2. The Ivie Creek case-study area was selected since it contains abrupt facies changes in the Kf-1 delta-front sandstones. The basal unit is a thick, sandy parasequence composed of clinoform units which pinch out to the west. This basal unit is overlain by a thin, silty parasequence which extends farther to the west. Reservoir modeling will be conducted on data collected from and geological interpretations of both the Kf-1 and Kf-2 parasequence sets in the Ivie Creek case-study area. The modeling effort will concentrate on: (1) variations in fluid flow between the parasequence types, (2) the amount of communication between each parasequence set, and (3) the effects the various bounding surfaces within parasequences would have on fluid flow in these units.

The Willow Springs Wash area is the largest of the study areas and was selected for the excellent three-dimensional aspect of exposures in the Willow Springs Wash and Indian Canyon areas. The focus of the work in the Willow Springs Wash case-study area will be parasequences of the Kf-1 delta-front. No reservoir simulations will be conducted on data collected from the Willow Springs Wash area. However, the architectural elements interpreted from the outcrops will be incorporated into the overall reservoir model for the Ferron Sandstone.

Sixteen sections were measured and described in the Ivie Creek and Willow Springs Wash case-study areas with emphasis on major reservoir lithofacies. Sections were correlated to develop preliminary interpretations of the stratigraphy and lithofacies. Over 100 paleocurrent measurements were made at these and other localities. Lithologic and paleocurrent data were entered into the UGS database from which stratigraphic sections, rose diagrams, and statistical presentations were produced. In the Ivie Creek case-study area, a laser theodolite and a tape measure were used to position and scale information about lithofacies and polygons (modeling units based on lithology, permeability, grain size, and sedimentary structures) on photomosaics.

Six core holes were drilled and logged in the Ivie Creek case-study area. The Kf-1 and Kf-2 parasequence sets were cored in four holes. A total of 586 feet (179 m) of core was recovered from the Kf-1 and Kf-2 parasequence sets. Fourteen gamma-ray traverses were undertaken (corresponding to petrophysical and permeability transects), each consisting of 200 to 400 measurements from the Kf-1 and Kf-2. The gamma-ray profiles are being used for correlation and quantitative determination of sand/shale percentage. Core plugging of the Ferron Sandstone outcrop was done along 18 vertical or near-vertical traverses. In all, 285 plugs were taken from various lithofacies in both the Kf-1 and Kf-2 sandstones. Petrophysical and thin section analysis were conducted on core plugs collected in 1994. In thin section the samples are quartz-rich sandstones with a complex diagenetic history.

Spatial variations in lithofacies, stratigraphic thickness, sedimentary structures, and permeability data are being quantified through geostatistical analysis. The net footage and relative percentage of each sedimentary structure, biologic structure, average megascopic grain size, and sandstone/shale ratio were calculated for various facies in the Ivie Creek case-study area.

A total of 15 permeability transects were made on the outcrop at the Ivie Creek case-study area and evaluated along with the data from seven 1994 permeability transects. The transects span the proximal, middle, and distal portions of the delta-front rocks of the Kf-1 and representative sections of the Kf-2. Measured stratigraphic sections were tied to the permeability transects. Transect locations were chosen to encompass the majority of the lithofacies present in the delta-front sequence. Data from these transects are being used to determine the statistical structure of the spatially variable permeability field within the delta front, to investigate how geological processes control the spatial distribution of permeability and to evaluate permeability measurement techniques.

A 2-mile by 2-mile (3.2-km by 3.2-km) block within the Ivie Creek case-study area was selected as the site from which detailed, three-dimensional geological and petrophysical models will be developed as input to a series of reservoir simulations. Data needed for these models was be obtained by geological mapping, outcrop gamma-ray logging, petrophysical measurements on core plugs, and mini-permeameter testing of slabbed core from three Ivie Creek core holes. The simulation study area encompasses both river-dominated and wave-modified sedimentary facies of the Kf-1 and Kf-2 parasequence sets. In addition, a well-defined distributary channel cuts through the upper Kf-2 parasequence set.

We anticipate simulating fluid flow through at least three rock volumes at two different scales. We will begin at the interwell scale with a very detailed model of the Kf-1a clinoform features. At the larger, reservoir scale we will simulate the dynamic interaction between Kf-1, Kf-2, and the associated distributary channel. A scaling-up procedure will be used to homogenize and transfer petrophysical information from the very detailed interwell-scale models to the reservoir scale.

A methodology was established and tested for using a numerical modeling approach to explore the influence of reservoir architecture and permeability structure on oil production. Although our methodology is tested in a two-dimensional mode, this approach is readily extended to a three-dimension mode. The homogenization code for one-, two-, and three-dimensional problems was completed and tested extensively.

Technology transfer during the second project year consisted of displaying project materials at the UGS booth during the national and regional conventions of the American Association of Petroleum Geologists and the regional meeting of the Society of Petroleum Engineers. Seventeen technical and nontechnical project presentations were made to various professional organizations, government officials, and members of the media. Project team members published seventeen abstracts, open-file reports, trade journal articles, or newsletters detailing project progress and results.

ACKNOWLEDGEMENTS

This research is performed under the Geoscience/Engineering Reservoir Characterization Program of the U.S. Department of Energy (DOE), Pittsburgh Energy Technology Center, contract number DE-AC22-93BC14896. The Contracting Officer's Representative is Robert Lemmon of the DOE Bartlesville Project Office.

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1. INTRODUCTION

1.1 Project Purpose

Nationwide, fluvial-deltaic reservoirs have the largest developed oil reserves, and due to the high degree of reservoir heterogeneity, the largest amount of untapped and unrecovered oil within developed reservoirs. The purpose of this multi-year project is to use the Ferron Sandstone to develop a comprehensive, interdisciplinary, and quantitative characterization of an outcrop analogue to fluvial-deltaic reservoir which will allow realistic inter-well and reservoir-scale modeling to be used for improved oil-field development in actual reservoirs world-wide. The fluvial-deltaic Ferron Sandstone Member of the Cretaceous Mancos Shale in east-central Utah (figure 1.1) is a perfect analog since its reservoir heterogeneity is dramatically exposed in outcrop. The results may benefit industry by: (1) **increasing recoverable reserves** by identifying untapped compartments created by reservoir heterogeneity, (2) **reducing development costs** by more efficiently siting infill drilling locations, (3) **increasing deliverability** by exploiting the reservoir along optimal fluid-flow paths, (4) **enhancing the application of new technologies**, such as horizontal drilling, by identifying optimal drilling directions to maximize fluid-flow, and (5) **identifying reservoir trends** for field extension drilling.

The geological and petrophysical properties of the Ferron Sandstone are being quantitatively determined by a multidisciplinary team. To evaluate the Ferron Sandstone as a model for fluvial-deltaic reservoirs, the UGS, University of Utah, Brigham Young University, Utah State University, Amoco Production Company, Mobil Exploration/Producing Technical Center, The ARIES Group, and geologic consultant Paul B. Anderson entered into a cooperative agreement with the U.S. Department of Energy as part of its Geoscience/Engineering Reservoir Characterization program.

Both new and existing data is being integrated into a three-dimensional representation of spatial variations in porosity, storativity, and tensorial rock permeability at a scale appropriate for inter-well to regional-scale reservoir simulation. The project is divided into four tasks: (1) regional stratigraphic analysis, (2) case studies, (3) development of reservoirs models, and (4) field-scale evaluation of exploration strategies. Transfer of the project results to the petroleum industry is an integral component of the project.

This report is organized into five sections: Introduction, Regional Stratigraphy, Case Studies, Stochastic Modeling and Fluid-Flow Simulation, and Technology Transfer. It is a progress report of on-going research and is not intended as a final report. Whenever possible, preliminary conclusions have been drawn based on available data and field observations.

1.2 Background

The Ferron Sandstone Member of the Cretaceous Mancos Shale is well exposed along the west flank of the San Rafael uplift of east-central Utah (figure 1.1). The Ferron Sandstone is a fluvial-deltaic deposit with excellent exposures of a variety of delta facies along the margins of a rapidly subsiding basin (figure 1.2a). The Ferron Sandstone is an analogue for many of the highly productive reservoirs in the Alaskan North Slope, Gulf Coast, and Rocky Mountain regions.

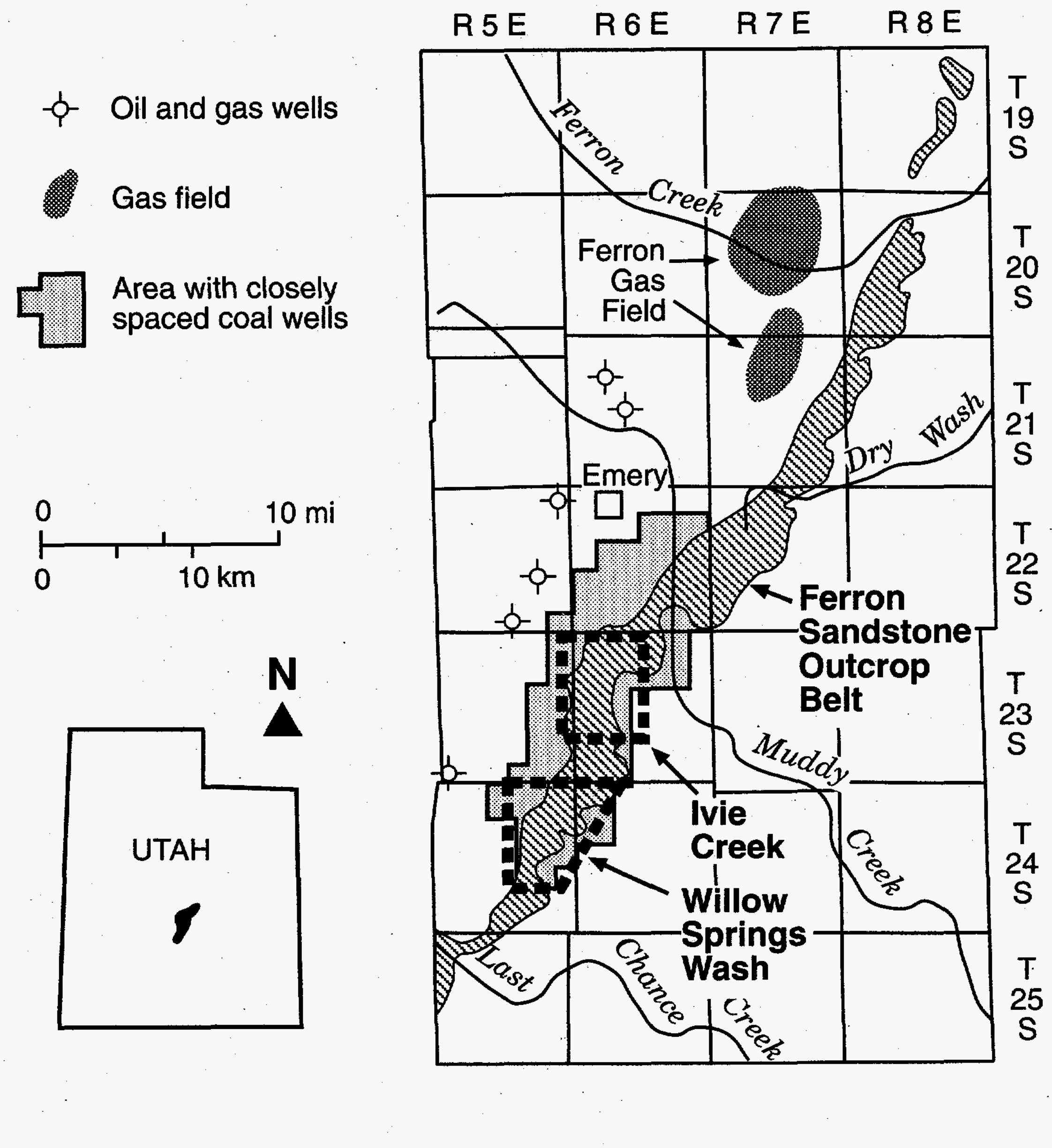
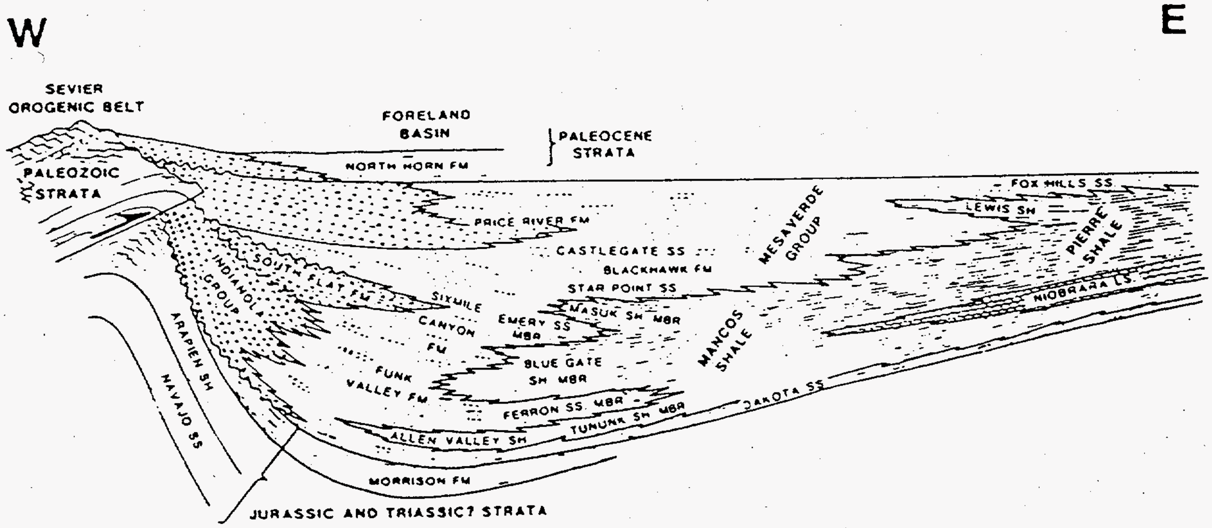
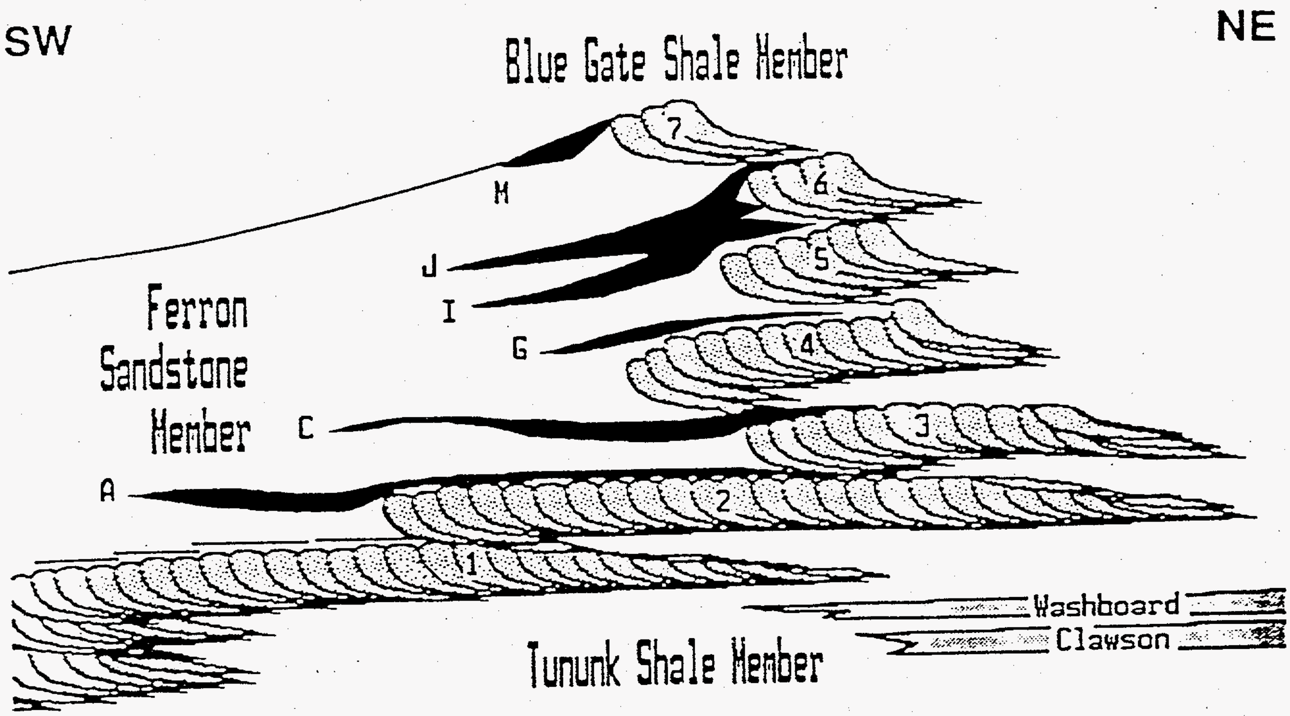


Figure 1.1. Location map of the Ferron Sandstone project area (outcrop belt is cross-hatched) showing detailed case-study areas (outlined by heavy dashed lines).



(A)



(B)

Figure 1.2. Ferron Sandstone stratigraphy: (A) cross section of the Cretaceous foreland basin across Utah (from Ryer, 1981a), and (B) diagrammatic cross section of the Ferron Sandstone and adjacent members of the Mancos Shale showing the numbering and stacking of the deltaic parasequence sets (from Ryer, 1991). Coal horizons (black) are designated by letters.

The Ferron Sandstone is an eastward-thinning clastic wedge deposited during Upper Cretaceous time. The Ferron and equivalent portions of the Frontier Formation in northern Utah and Wyoming record a pronounced and widespread regression of the Cretaceous Western Interior seaway. In the study area, these deposits accumulated on a deltaic shoreline in a rapidly subsiding portion of the Cretaceous foreland basin. The Ferron consists of a series of stacked, transgressive-regressive cycles (parasequence sets) which are well displayed in outcrop. Seven parasequence sets, numbered 1 through 7 in ascending order have been mapped (figure 1.2b). These various parasequence sets define a hierarchical pattern of seaward-stepping, vertically-stacked, and landward-stepping depositional geometries. This architecture indicates an initial strong supply of sediment relative to available space where sediment could accumulate, followed by near-balance and then a relative decrease in sediment supply. Each parasequence set contains in outcrop all, or portions of each of the complex lithofacies that make up a typical fluvial-dominated deltaic deposit. Such lithofacies include meander channels, distributary channels, tidal channels, mouth-bar complexes, wave-modified strandlines, bar-finger sandstones, prodelta and delta-front deposits, transgressive sandstones, as well as bayfill, lagoonal, and floodplain deposits.

The excellent exposures and accessibility of the three-tiered, hierarchical stacking pattern and associated complex lithofacies of the seven parasequence sets make the Ferron Sandstone of Utah the best analogue for petroleum reservoirs in fluvial-dominated deltas throughout the world. The Ferron Sandstone is a good analogue for the Triassic Ivishak Formation (the principal reservoir at Prudhoe Bay field, Alaska) and for the Tertiary Wilcox and Frio Formations of south Texas. The Ferron Sandstone is also an excellent model for and is correlative to, the Cretaceous Frontier Formation which produces petroleum throughout Wyoming. The Ferron lithofacies are also a good analogue for the Tertiary Green River and Wasatch Formations, the major oil and gas producing reservoirs in the Uinta Basin, Utah. In addition to its value as a reservoir analogue, sands and coalbeds of the Ferron Sandstone produce gas north of the study area in the Wasatch Plateau and along the west-northwest flank of the San Rafael uplift, (currently the most active gas play in Utah).

This project is motivated by the need to deal with complex reservoir heterogeneities on an interwell to field scale. These scales are difficult to resolve in reservoir exploration and development activities. Standard industry approaches to field development rely on generic depositional models constrained primarily by data obtained in petrophysical (logging and coring) evaluations of exploration and development wells. The quantity, quality, and distribution of these data are typically insufficient to adequately model the reservoir. Work on the Ferron Sandstone is predicated on the assumption that detailed outcrop mapping of petrophysical and geological properties of this analogue reservoir will provide an unusually comprehensive database and reservoir simulation. Simulation results can be used to guide exploration and development strategies in reservoirs found in similar depositional environments.

1.3 Approach

The primary approach of the study is to quantitatively determine geological and petrophysical properties of the Ferron Sandstone. This information should help to improve reserve estimates in fluvial-dominated deltaic reservoir systems and aid in designing more efficient production strategies. To reach this goal, existing and new data have been collected for integration into a three-dimensional representation of spatial variations in porosity, storativity, and tensorial character of rock permeability at a scale appropriate for interwell to regional scale reservoir simulation.

During the 1994-95 project year (the second year of the project), regional facies mapping was conducted to refine current models for the architecture, geometry, and distribution of lithofacies in the Ferron Sandstone (table 1.1). Case-study areas provided more detailed mapping and analysis of specific facies important to reservoir production (figure 1.1). Extensive vertical and lateral outcrops offered excellent opportunity for investigation. The existing database was augmented with additional detailed mapping of the three-dimensional geologic structure and determination of petrophysical properties of various lithofacies (tables 1.1 and 1.2) at case-study locations within the Ferron Sandstone outcrop belt to serve as reservoir analogues. Determining permeability anisotropy within each facies was an important consideration and was accomplished by: (1) mapping lithofacies (clay content variations/sandstone to shale ratios) and sedimentary structures (orientations/dips of sediment fabrics/structures), (2) collecting core plugs (in addition to those collected during the 1994 field season) for oriented permeability determinations in the laboratory, (3) producing additional gamma-ray profiles from outcrops, and (4) using a unique magnetic susceptibility technique to assess anisotropy in pore geometry (table 1.2). Mini-permeameter data collected on outcrop during the 1994 field season were augmented by additional vertical and horizontal mini-permeameter traverses. Core hole permits were obtained from State and Federal regulatory agencies. Five core holes were drilled near the outcrop to develop a three-dimensional view of the lithofacies/permeability network.

Information collected is being used to identify flow units within each case-study area at the scale of a single production well. Numerical simulations of reservoir response were used to assess the scale at which flow units must be defined within each lithofacies. Appropriate scales were established from which three-dimensional gridded databases are being developed that contain the best estimates of the three-dimensional distributions of both scalar (porosity and storativity) and tensorial (permeability) petrophysical properties of flow units found within the various lithofacies of the Ferron Sandstone. Architectural heterogeneities (such as texture and diagenesis) were examined in thin sections and are being compared to flow units. Standard geostatistical approaches are being used to extrapolate between the detailed study areas and other observation points.

Reservoir modeling at the field scale will be performed to evaluate how a detailed understanding of the geological and petrophysical structure of the Ferron Sandstone will enhance exploration and development strategies in similar reservoir systems. Numerical simulations of reservoir response to multiple-well production strategies will be used to quantitatively assess the effectiveness of both standard and modified strategies.

1.4 References

Ryer, T.A., 1981, Deltaic coals of Ferron Sandstone Member of Mancos Shale: predictive model for Cretaceous coal-bearing strata of Western Interior: American Association of Petroleum Geologists Bulletin, v. 65, no. 11, p. 2323-2340.

---1991, Stratigraphy, facies, and depositional history of the Ferron Sandstone in the canyon of Muddy Creek, east-central Utah: *in* Chidsey, T.C., Jr., editor, Geology of east-central Utah: Utah Geological Association Publication 19, p. 45-54.

Table 1.1. Characteristics of some sandstone facies within the Ferron Sandstone Member of the Mancos Shale.

Facies	Shape/Size	Features
meander/distributary channels		
a) multi-story (seaward stepping)	15-30 ft thick, W/T < 100	low bedform diversity, high interconnection
b) multi-lateral (landward stepping)	15-30 ft thick, W/T > 100	high bedform diversity, moderate interconnection
mouth-bar complex	≤ 10 ft thick	ball and pillow, bioturbated
wave-modified delta front	80-130 ft thick	storm-generated bedforms
tidal channels	elongate pods, 10 ft W x 100 ft L	erosional base, imbricate structure, bioturbated
transgressive lags	≤ 8 ft thick	erosional base, lags, bioturbated

(W = width, T = thickness, and L = length)

Table 1.2. Selected lithologic and petrophysical measurements to be made during field and laboratory studies of the Ferron Sandstone.

Measurement Type	Range	Precision
Outcrop		
outcrop gamma ray	0 to > 200 API	± 10 API
in-situ mini-permeameter	10.0 to 3,000 md	± 5 md
Well Logging		
density	1.0 to 3.0 g/cc	± 0.04 g/cc
sonic	50 to 200 units/ft	± 3 units/ft
neutron	0 to 100%	± 1%
resistivity	0.1 to 2,000 ohm-m	± 3%
gamma ray	0 to > 200 API	± 10 API
spectral gamma: K	0 to ≥ 10%	± 0.5%
spectral gamma: Th	0 to ≥ 100 ppm	± 10 ppm
spectral gamma: U	0 to ≥ 20%	± 15%
dipmeter	0 to ≥ 60°	± 1°
log-derived permeability	1.0 to 2,000 md	± 10 md
Core		
plug porosity, total	0 to ≥ 50%	± 0.5%
plug porosity, fracture	0 to ≥ 20%	± 0.5%
plug bulk density (dry)	1.5 to 3.0 g/cc	± 0.01 g/cc
plug bulk density (saturated)	1.5 to 3.0 g/cc	± 0.01 g/cc
plug grain density	2.0 to 3.0 g/cc	± 0.05 g/cc
plug compressional velocity	1.5 to ≥ 4.0 km/s	± 1.0 km/s
plug shear velocity	1.0 to ≥ 3.0 km/s	± 2.0 km/s
plug mineralogy	1 to 5 dominant minerals	± 5% each
plug natural gamma	0 to ≥ 200 API	± 20 API
plug permeability	0.1 to 3,000 md	± 30 md
continuous core gamma ray	0 to ≥ 200 API	± 20 API
continuous core mini-permeability	0.1 to 3,000 md	± 5 md
magnetic susceptibility	10^{-6} to 10^{-2} SI	± 5%
pore anisotropy: axes	not applicable	± 5%
pore anisotropy: magnitude	0 to 100%	± 2%

2. REGIONAL STRATIGRAPHY

The regional stratigraphy of the Ferron Sandstone has been described by Anderson (1991), Barton and Tyler (1991), Cotter (1971, 1975a, 1975b, 1976), Davis (1954), Gardner (1991), Hodder and Jewell (1979), and Ryer (1981a, 1981b, 1982a, 1982b, 1983, 1991). The primary objective of additional study of regional stratigraphy is to provide a more detailed interpretation of the stratigraphy of the Ferron Sandstone outcrop belt from Last Chance Creek to Ferron Creek (figure 1.1). This area is similar in scale to a moderate to large oil reservoir. The regional study includes determining the dimensions and depositional environment of each sandstone body, and the nature of the contacts with adjacent rocks or flow units. The regional study provides a basis for selecting prime outcrops for detailed case studies of the major reservoir types (mouth-bar complex, wave-modified and river-dominated delta front, distributary channel, and tidal channels). Toward the end of the project, the regional morphological framework will be incorporated into model simulations at the oil and gas field scale.

2.1 Surface Mapping/Interpretation of the Outcrop Belt

The main Ferron Sandstone cliff and its deeply incised canyons together provide a three-dimensional view of lithofacies variations and transitions. The Ferron Sandstone has excellent exposures along strike; numerous canyons that cut perpendicular to strike offer excellent exposures along the depositional dip direction. Most of the near-vertical outcrop belt within the study area was obliquely photographed during the 1994 field season. Outcrop images were digitized to develop a computer graphics database for interpretation and manipulation. Important bounding surfaces, geometries, and depositional environments are being mapped in the field on photomosaics to characterize the variability of fluvial-dominated deltaic reservoirs.

2.1.1 Methods

Reproducible black-and-white prints were generated from digitized oblique outcrop photographs using image-editing software and laser printers. Photomosaics were constructed from the images with distortions digitally removed. Scale of the photos was determined in the field by measuring between locatable points on the photograph and those same points on the ground. During field mapping, coverage of each photomosaic was plotted on a 7.5-minute topographic quadrangle map with the aid of aerial photos.

The photomosaics were annotated with parasequences, parasequence sets, and lithofacies. Parasequence sets generally correlate to the existing stratigraphy of the seven delta-front sandstones or genetic sequences. Parasequences names were based on case-study locations and were assigned an A-, B-, C-, D-type nomenclature, which allowed for adding parasequences identified later without disrupting the entire numbering system.

2.1.2 Results

The UGS combined digitized land-based and aerial photographs of the Ferron Sandstone outcrop belt into reproducible photomosaics using image-editing software. A total of 1,823 photos depict 80 miles (130 km) of Ferron Sandstone outcrop. Various field data (such as measured section and gamma-ray transect locations) were plotted on the photomosaics.

Parasequences, parasequence sets, lithofacies, vertical and horizontal scales, and other data were plotted on the photomosaics in the field for both the regional and case-study analyses (figure 2.1).

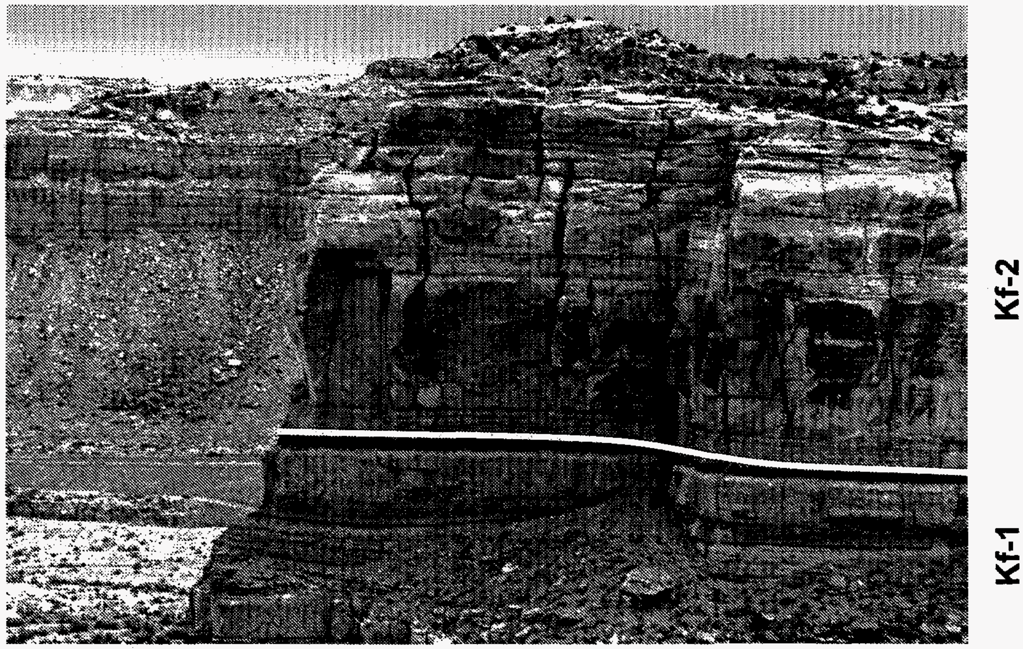


Figure 2.1. Digitized photomosaic, view to the south, of a typical Ferron Sandstone outcrop produced using image-editing software. Parasequence sets Kf-1 and Kf-2 are plotted on the photomosaics for regional and case-study analyses. Outcrop in photomosaic located in SW1/4SW1/4SW1/4 section 16, T. 23 S., R. 6 E., Salt Lake Base Line, Emery County, Utah.

2.2 Collection of Existing Surface and Subsurface Data

Existing geophysical and core logs from the study area were collected and interpreted to complement the lithofacies identification, depositional environment interpretation, and sandstone body geometries determined from the interpreted photomosaics. These data and other geologic information were compiled in the **INTEGRAL*gim** database developed by the UGS. This database is a geologic-information manager that links a diverse set of geologic data to records through a common, nongraphical user interface. **INTEGRAL*gim** contains much of the geologic data managed by the UGS and Utah Division of Oil, Gas and Mining (DOGM). The database includes petroleum, coal, mining, and stratigraphic data. These data were used to produce stratigraphic strip logs for correlation and lithofacies mapping.

2.2.1 Methods

Published and unpublished maps, measured sections, well logs, core descriptions, mini-permeameter data, reports, and other data were collected by the UGS. **INTEGRAL*gim** was modified for this study to link various geologic attributes of the Ferron Sandstone to point-source locations. Formats for lithologic, paleocurrent, and core descriptions have been developed to standardize data collection. The database is designed so that geologic information, such as types and percentages of lithologies and sedimentary structures, can be incorporated into statistical models and exported into software programs to produce strip logs and lithofacies maps, percentage of lithofacies maps, and reservoir maps showing percentage of texture/fabric.

The database also includes well, core, and outcrop locations, lithology, porosity, mini-permeameter values, core plug permeability data, unit tops, as well as other information. Assigned stratigraphic rank of the various units measured in the field is included in the database and the thicknesses of these units is calculated. The **INTEGRAL*gim** database, containing information from the Ferron Sandstone, will be available at the conclusion of the project.

Base maps were created by digitizing the seven quadrangles within the study area. These base maps will be used for preparing lithofacies, paleogeographic, and other maps.

2.2.2 Results

The UGS collected maps, published measured sections, well logs, core descriptions, and other data which pertain to the study area. This information was compiled into **INTEGRAL*gim**. The drill-hole data contained in the database will allow others who are making detailed surface measurements of Ferron rock units in the area to correlate those surface rock units into the subsurface. In addition, the drill-hole data can be used by coal and petroleum companies evaluating the Emery coal field, an area of current coalbed methane drilling activity.

Data were collected from wells that penetrate the Ferron Sandstone in the area from Last Chance Creek in the south to Ferron Creek in the north (figure 1.1). Well data from coal-company exploration wells; oil, gas, and stratigraphic test wells; and government test wells were entered into the database (table 2.1). First, a literature search was conducted and publicly available data were collected. Second, oil and gas geophysical well logs were copied from the UGS geophysical log library. Finally, unpublished data were requested from companies known to have drilled in the area. Lithologic data were transcribed from published or company core and cutting descriptions onto standard data entry forms before entry into the database. When available, geophysical well logs were interpreted and the lithologies were transcribed onto the data entry forms.

The Ferron Sandstone drill-hole data were extracted from **INTEGRAL*gim**. The database contains drill-hole data sorted by township, range, and section. It consists of header or well-location information and lithologic descriptions for each well. The header information includes county name, operator name, well name and number, API number, field or area name, cadastral location, meridian, surface elevation, and total depth or length of information recorded. Each record also includes latitude and longitude location (in decimal degrees) and quadrangle map names. The lithology data includes the depth below surface at which the top of each rock unit was penetrated by drilling, the unit name, and the unit description. Table 2.1 provides a list of the data sources and the number of data records from each information source in the database.

Stratigraphic data were transferred from the database to software which plotted a total of 489 strip logs and lithologic descriptions (figure 2.2). These strip logs are being used for

Table 2.1. Summary of drill-hole data entered into the Ferron Sandstone drill-hole database for the Ferron reservoir characterization study.

Data Source	No. of Wells w/ Lithologic Logs	No. of Wells w/ Geophysical Logs
Coal Company		
Consolidation Coal Co.	348	62
Western States Minerals Corp.	14	0
Hidden Valley Coal Co.	7	6
Rio Vista Oil LTD.	8	0
Marad Exploration Corp.	19	0
Government Agency/University		
U.S. Bureau of Land Management	7	2
University of Utah Research Institute	2	2
U.S. Geological Survey	35	15
Petroleum Company		
ARCO Exploration Co.	7	7
Other	42	42
Total	489	136

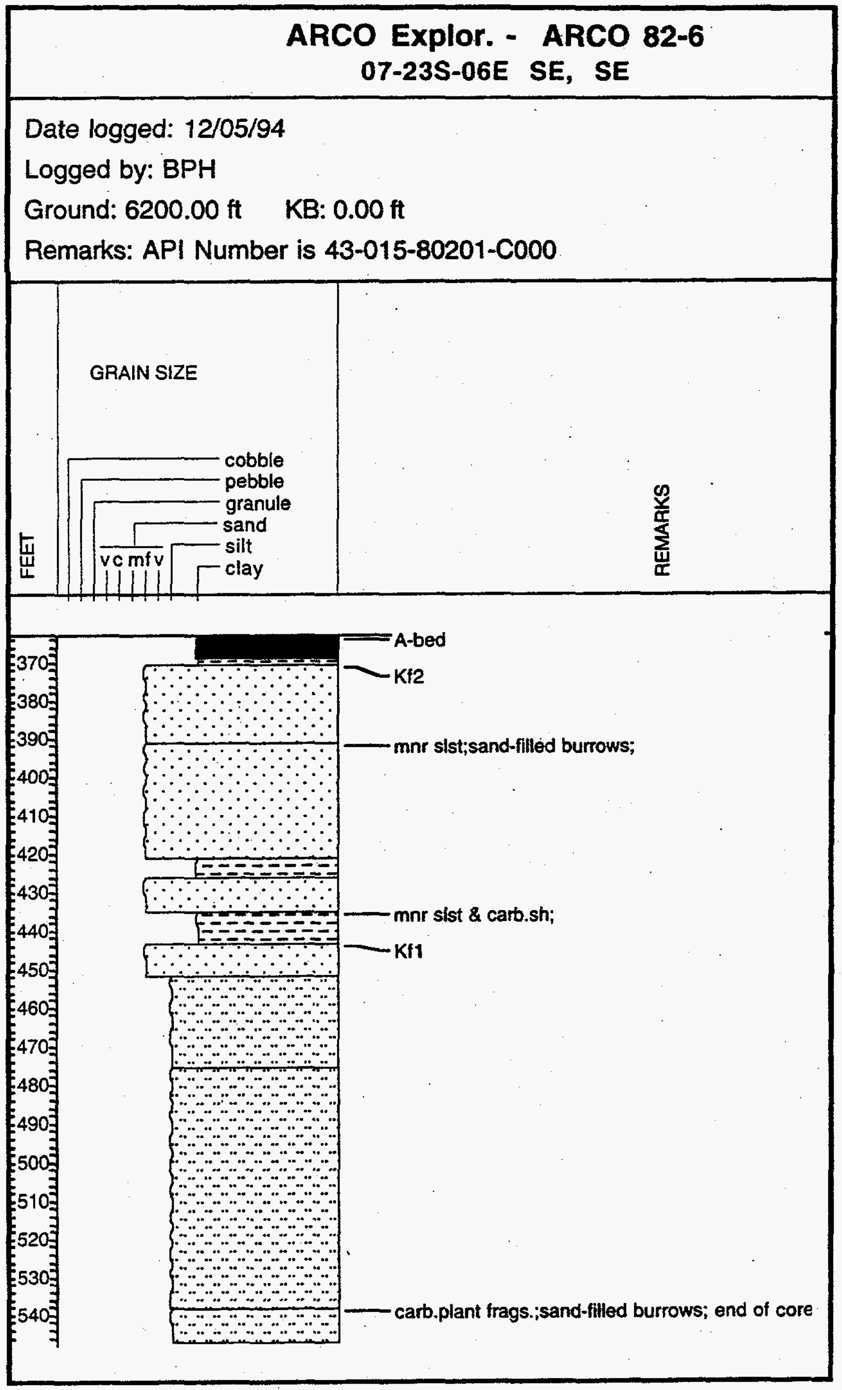


Figure 2.2. Typical strip log and lithologic description, from ARCO Exploration Company 82-6 well (section 7, T. 23 S., R. 6 E., Salt Lake Base Line, Emery County, Utah) for Ferron Sandstone regional stratigraphic interpretation.

regional correlation of parasequences and lithofacies mapping. The files used to plot the strip logs were archived for possible future use and manipulation.

All base maps were digitized for the seven 7.5 minute quadrangles encompassing the study area. These base maps show drill-hole locations (petroleum exploratory and development wells, and coal core holes), measured sections, coal outcrops, coal mined-out areas, drainages, and the top and base of the Ferron Sandstone. Digitized 7.5 minute base map files were converted to latitude/longitude coordinates from the existing 7.5 minute digitizer-inch coordinates. Rose diagrams of paleocurrents and other data are being plotted on the base maps for use in regional paleogeographic interpretation.

2.3 Preliminary Regional Stratigraphic Interpretations

The Ferron Sandstone was divided into parasequences and parasequence sets. Van Wagoner and others (1990) defined a parasequence as "a relatively conformable succession of genetically related beds or bedsets bounded by marine-flooding surfaces or their correlative surfaces." This definition is clear and precise. It is easy, using this definition, to draw diagrammatic cross sections distinguishing parasequences and the parasequence sets (grouping of parasequences that display a recognizable pattern of organization) that they represent (figure 2.3). In the Ferron Sandstone, distinguishing exactly what is and what is not a parasequence can be quite easy or extremely difficult. There are numerous clear-cut examples of easily defined bodies of sediment that most geologists would agree represent parasequences. However, there are also have many that fall into a "gray area" where they might represent parasequences or might represent something else.

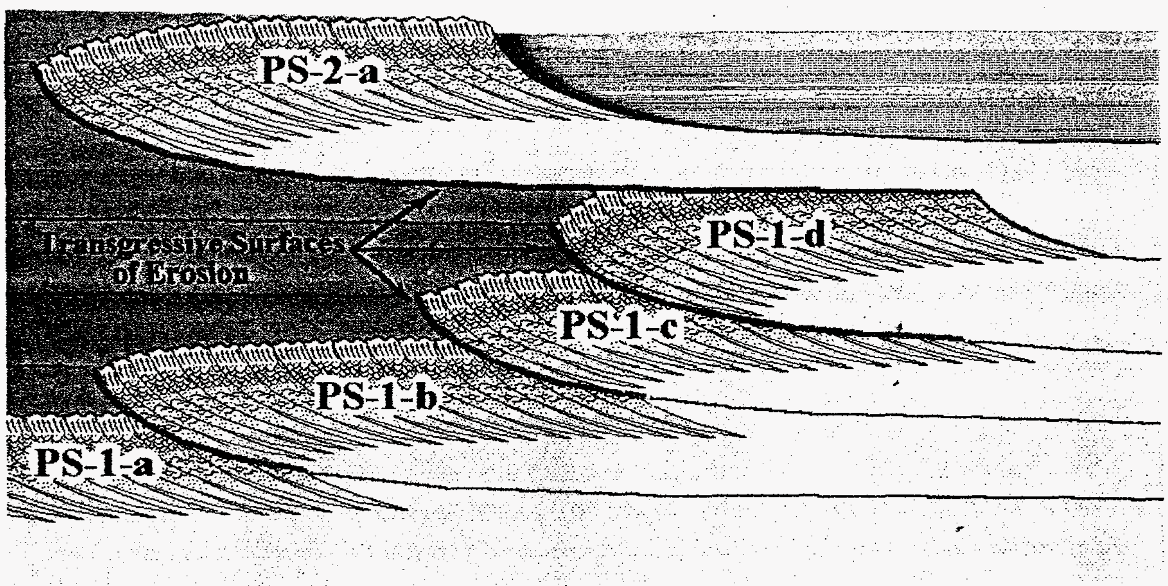


Figure 2.3. Parasequences and parasequence sets (PS-1 and PS-2) in a dip-oriented cross section. PS-1 comprises four parasequences designated *a* through *d*. The heavy weight lines indicate transgressive surfaces of erosion, which display evidence of truncation of previously-existing strata as a consequence of the landward shift of the shoreface profile. The lighter weight lines that extend from them are the correlative surfaces.

The key part of the definition is the required presence of a "marine-flooding surface" or what the project team prefers to call a "transgressive surface." Whether one regards the sea as "flooding" the land or "transgressing" the land, the evidence in the stratigraphic record is quite clear: shallow-marine facies overlie and intertongue with non-marine facies. The landward pinch-outs of shoreline sandstone bodies distinguished in the Ferron Sandstone, when fully preserved, overlie and in turn are overlain by nonmarine or, in some instances, brackish-water facies. Landward pinch-outs of shoreline sandstone bodies constitute indisputable evidence of a transgression followed by progradation. They are the means by which parasequences are recognized.

A major problem with the definition of a parasequence is the emphasized part of the phrase "marine-flooding surfaces ***or their correlative surfaces***." In a stratigraphic model, the concept of "correlative surfaces" makes sense, but on outcrops, it rarely does: how is a surface, generally, in practice, a bedding plane, that can be identified on an outcrop to be recognized as being correlative to a transgression that took place somewhere else? Except in rare instances, it cannot be done. This is a problem in the Ferron Sandstone project area. A parasequence includes not only a shoreline sandstone body, but nonmarine beds landward of it and offshore-marine mudstones seaward of it that are bounded by the correlative surfaces of the transgressive surfaces that bound the shoreline sandstone body. In practice, there are no means whereby one can identify the correlative surfaces. The approach used in this study is to focus on what actually defines a parasequence in practice - a shoreline sandstone body bounded by transgressive surfaces. In this study, the <> symbols are used to designate these bodies, such as the abbreviation <Kf-1-IC-a> should be read "the shoreline sandstone body of parasequence Kf-1-Indian Canyon-a."

To complicate matters, the designation of correlative surfaces in figure 2.3 is simplistic. The layout of the time lines represented by the transgressive surfaces and their correlative surfaces implies that marine transgressions occur, geologically speaking, instantaneously. In other words, the transgressive surface, the correlative surface that extends landward into nonmarine strata, and the correlative surface that extends seaward into offshore-marine strata are together assumed to represent a single time line. That clearly is not the case, and there are many examples in the Ferron Sandstone to prove it. Transgressions take time, and during those times, sediment accumulates both in coastal plain and offshore marine environments (figures 2.4 and 2.5). How does one identify the "correlative surface" of a stratigraphic surface that spans considerable time? It's a question that can't be answered: the time equivalent of a transgressive surface in a coastal plain environment is a volume of sediment, not a surface. Although the supply of sediment to offshore marine environments is greatly reduced during transgression (hence "condensed sections"), some undoubtedly occurs there during even the most rapid transgression. The same problem of identifying the correlative surface, therefore, exists in offshore-marine sections.

The practical implications of all this for the Ferron Sandstone project is quite simple: although there is appreciation for the theory behind correlative surfaces and one can speculate about where they might extend through outcrops, one cannot actually make use of them in the field. Only in a few cases can one, with any confidence, correlate into nonmarine and offshore-marine sections, and then only for short distances. Parasequences, for the Ferron project, equate to shoreline sandstone bodies.

A clear trend in how the term parasequence is being used is apparent in the literature of sequence stratigraphy. It is being applied increasingly to smaller and smaller scale units. For some geologists, any traceable, seaward-inclined bedding surface across which there is the slightest hint of facies change is designated a marine-flooding surface. The units that they bound are then called parasequences. What many geologists are doing, in practice, is defining

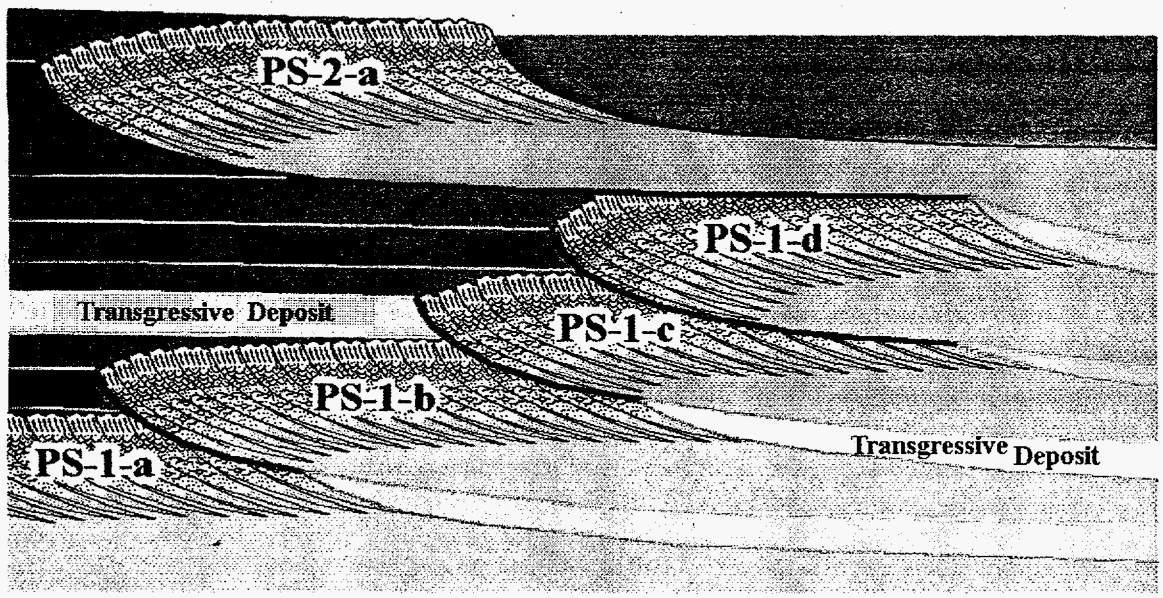


Figure 2.4. Transgressive surfaces diagram of the Ferron Sandstone. Transgressive surfaces are not time lines. Transgressions take time and during the spans of time they represent, sediment accumulates in coastal plain and offshore-marine environments. The transgressive phase deposits that accumulated during the transgression that preceded progradation of <PS-1-c> are highlighted here.

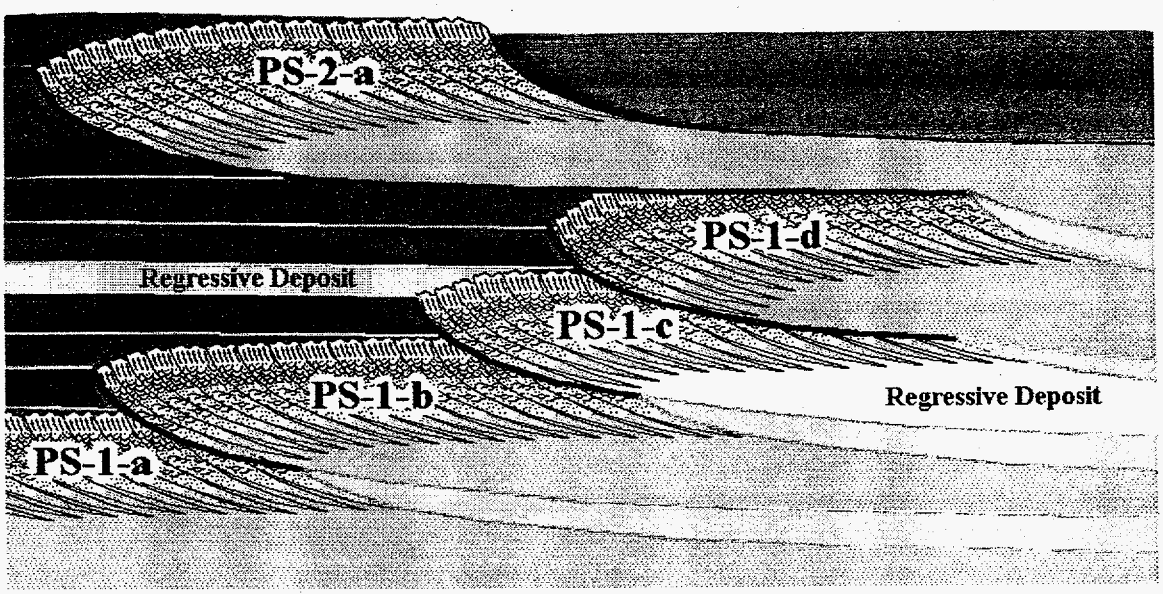


Figure 2.5. Regressive phase deposits diagram. The shoreline sandstone bodies are regressive phase deposits. <PS-1-c> and time-equivalent coastal plain and offshore-marine strata are highlighted here.

parasequence boundaries at the top and bottom of each end every upward-coarsening succession that can be distinguished. The assumptions are that if an upward-coarsening succession of shallow-marine strata is overlain by another such succession, deepening of water occurred at the boundary between the two. Deepening of water is the result of rising of sea level, and rising of sea level results in transgression. Therefore, such a boundary is a marine-flooding surface. This line of reasoning is often right, but not always. There are other processes that can lead to stacking of upward-coarsening successions. Wave energy levels incident on a coastline could change as a function of climatic change. Sediment supply and the ratio of coarse to fine material could change as a function of a number of processes. Most importantly, along deltaic coasts, progradation and abandonment of delta lobes can cause changes both in sediment supply and wave climate.

In order to qualify as a parasequence in our Ferron Sandstone study, a unit must be bounded by surfaces that one can demonstrate are transgressive surfaces, or that at least manifest most of the key characteristics of transgressive surfaces. The project team recognizes the importance of bedding surfaces that can be used to divide a shoreline sandstone body that defines a parasequence into units that represent distinct depositional episodes. Perhaps a quarter to a half of the parasequences that have been recognized can be divided into smaller-scale units, and these will be incorporated into stratigraphic scheme as it develops.

Figure 2.6 shows all of the Ferron parasequences that have been recognized, named, and placed in their relative positions. The parasequences are described in the Appendix. The abundance of parasequences in parasequence sets Kf-1 and Kf-2, as compared to the younger parasequence sets, is striking. This is the result of two factors. First, Kf-1 and Kf-2 prograded farther than did the later parasequence sets and so would be expected to be made up of more "building blocks." To draw a crude analogy: a longer tier of bricks has more bricks in it than does a short tier. The second factor hinges on the fact that the amount of relative sea-level rise that occurred during progradation was greater for the younger Ferron parasequence sets than it was for the older ones. This affected parasequence-level stratigraphy profoundly and requires some explanation. During progradation of parasequence sets Kf-1 and Kf-2, the supply of sediment was abundant compared to the creation of space in the basin to accommodate it. A relatively small amount of sediment was required to aggrade the coastal plain and a considerable proportion passed through the fluvial systems to reach the shoreline. Rapid supply of sediment at the river mouths promoted the building of river-dominated deltas, the deposits of which are conspicuously more abundant in Kf-1 and Kf-2 than they are in Kf-4 through Kf-7. It is highly probably that rises of relative sea level caused either by eustatic fluctuations or by pulses of basin subsidence continually affected the area and are the underlying mechanism for inducing parasequence-level transgressions and regressions. A delta is very much "at risk" should even a minor rise of relative sea level occur. Transgression of the coasts adjacent to a delta diminishes the river's already inefficient gradient, leading inevitably to avulsion of the river, abandonment of the delta, and rapid transgression across the delta plain. Many such transgressions are recognizable in Kf-1 and Kf-2.

In the case of parasequence sets Kf-4 through Kf-7 (KF-3 being something of an in-between case), the volume of sediment delivered to the area was much less than the increase in accommodation space. Accommodation space decreased through time, resulting in overall backstepping of the parasequence sets. As a consequence, an increasingly large volume of sediment was required to aggrade the coastal plain behind the shoreline; less and less came through the fluvial systems to nourish the shoreline. The lower sediment supply tipped the balance in favor of the process of wave reworking. Major delta lobes did not form, the sediment

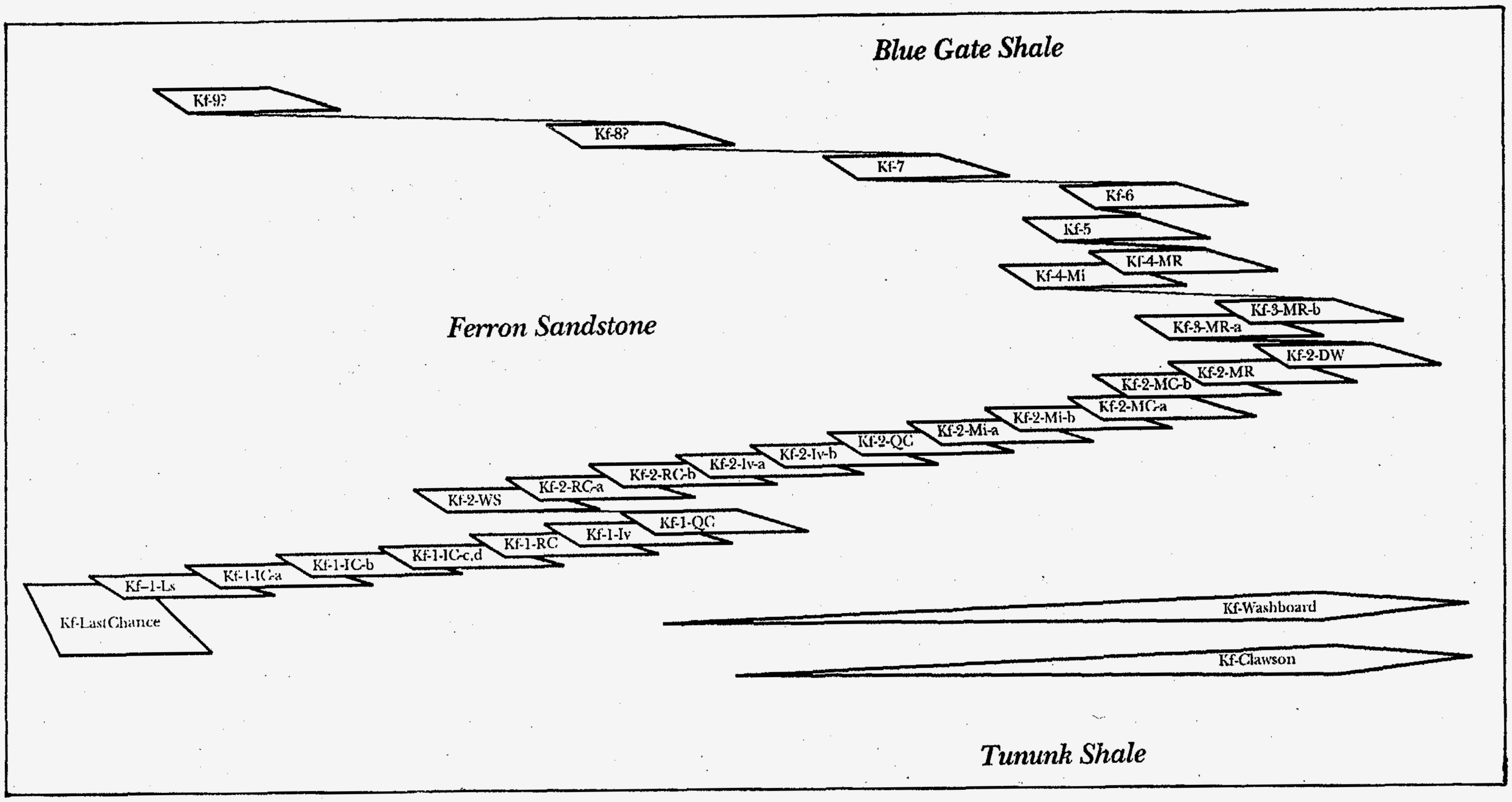


Figure 2.6. Diagram showing relative positions of Ferron parasequences and parasequence sets. The diagram has no scale. Landward is to the left, seaward to the right. The vertical axis is probably better equated to time than to rock section. Note that parasequence sets Kf-5, Kf-6, and Kf-7 are presently not divided into parasequences. Kf-8? and Kf-9? are shoreline sandstone units that have been recognized but not yet formally incorporated into the scheme.

was more evenly distributed along the coast. Minor rises of relative sea level had little effect on the shoreline. Transgressions probably did occur, but over very limited distances. It is likely that they simply haven't been recognized.

Another fact reflected in the Appendix is that the earliest, proximal part of each parasequence consists of deposits of wave-modified coasts. The relative sea level rises that brought about the parasequence-level transgressions caused reduction of sediment supply to the coasts. As the rise slowed and the balance shifted back to progradation, the supply of sediment to the coast increased. Initially, the supply was low, allowing extensive wave reworking. This also explains the pronounced seaward stratigraphic rise of many parasequences just seaward of their pinch-outs. The more distal parts of parasequences commonly contain deltaic deposits. At these times, the rates of rise of relative sea level were slower and the amounts of sediment delivered to the shorelines were correspondingly greater. The supply was great enough to allow progradation of recognizable deltas, particularly in the cases of parasequence sets Kf-1 and Kf-2.

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3. CASE STUDIES

The primary objective of the case studies is to develop a detailed geological and petrophysical characterization, at well-sweep scale or smaller, of the primary reservoir lithofacies typically found in a fluvial-dominated deltaic reservoir. Sedimentary structures, lithofacies, bounding surfaces, and permeabilities measured along closely spaced traverses (both vertical and horizontal) will be combined with data from core drilling to develop a three-dimensional view of the reservoirs within each case-study area. In developing the characterization, an evaluation will be conducted on how variations in sedimentary structures and lithofacies influence both compartmentalization and anisotropy of permeability.

A secondary objective of the case studies involves developing empirical relationships between mini-permeameter measurements made in the field and laboratory-determined permeabilities at both irreducible water saturation and residual oil saturation. The resulting transforms will be used to estimate the relative permeability values to be used as parameters in single-phase reservoir models.

Two case-study areas were selected in 1994 for the project: **Ivie Creek** and **Willow Springs Wash,** in the central and southern parts respectively of the project study area (figure 1.1). The Ivie Creek case-study area was selected since it contains abrupt facies changes in the lower Ferron delta-front sandstones or parasequence sets in outcrops north of Ivie Creek, east of the mouth of Ivie Creek Canyon. Access to the area is excellent because of the close proximity to Interstate 70 (I-70). Field trips to the this area, as part of technology transfer activities, will be easily conducted. Willow Springs Wash is the largest of the two case-study areas. It covers an area 3.5 miles (5.6 km) long and 4 miles (6.4 km) wide (figure 1.1). The site was selected because of the excellent three-dimensional exposures in the Willow Springs Wash and Indian Canyon areas.

The Ferron Sandstone in the Ivie Creek case-study area consists of two regional scale parasequence sets, the Kf-1 and Kf-2. Reservoir modeling will be conducted on data collected from and geological interpretations of both the Kf-1 and Kf-2 parasequence sets in the Ivie Creek case-study area. The modeling effort will concentrate on: (1) variations in fluid flow between the parasequence types, (2) the amount of communication between each parasequence set, and (3) the effects the various bounding surfaces within parasequences would have on fluid flow in these units. Recommendations will be made on how bounding surfaces can be identified from core and well-log data and, ultimately, how such features should be considered in field development and secondary or enhanced oil recovery programs.

The focus of the work in the Willow Springs Wash case-study area will be parasequences of the Kf-1 delta-front. No reservoir simulations will be conducted on data collected from the Willow Springs Wash area. However, the architectural elements interpreted from the outcrops will be incorporated into the overall reservoir model for the Ferron Sandstone.

3.1 Field Work and Field Data Analyses

Field work during the 1995 field season consisted of measuring stratigraphic sections, measuring paleocurrents, and scaling and interpreting photomosaics in Ivie Creek and Willow Springs Wash case-study areas. Closely spaced stratigraphic sections within a specific study site were measured in order to: (1) map variations in lithofacies, sedimentary structures (size, geometry, orientation/dip, and percent of sedimentary structures), and bedding types; and (2) characterize bounding surfaces both between and within sandstone bodies.

3.1.1 Methods

Description of the individual units in the measured sections includes the following information: (1) primary and secondary lithologies, composition, color, and grain size of the rocks; (2) size, shape, and degree of induration of the beds; (3) sedimentary structures, biologic structures (trace fossils), and fossils in the rocks; and (4) bounding surfaces and depositional environment of the unit. Sections were correlated to develop preliminary interpretations of the stratigraphy and lithofacies. Lithologic and paleocurrent data were entered into the UGS **INTEGRAL*gim** database using codes from field forms.

Stratigraphic data were transferred from the UGS database to software which drafted stratigraphic sections and core descriptions. This software generated graphic logs of stratigraphic sections at scales of 1 inch: 2.5 feet (2.5 cm: 0.8 m) and 1 inch: 10 feet (2.5 cm: 3 m) (figure 3.1). Logs at both scales contain attributes, such as lithologies, sedimentary structures, and parasequence designations. General comments, grain sorting, grain roundness, and degree of consolidation were also noted on the 1 inch: 2.5 feet (2.5 cm: 0.8 m) logs. All attributes will be used to define reservoir components in the statistical and reservoir-modeling parts of the project.

Paleocurrent measurements, grouped by parasequence and by lithologic units composing parasequences, were plotted as rose diagrams (figure 3.1). Measurements plotted according to parasequence give an overall indication of the direction of parasequence progradation. Measurements plotted according to units within a parasequence give direction of sediment transport of components of the parasequence (for example, distributary channels, mouth bars, or parts of the delta front). In addition, paleocurrent measurements from wave ripples were plotted separately from measurements taken from unidirectional current ripples and cross beds (figure 3.1). Wave-ripple measurements provide information on direction of waves impinging on and modifying the delta front. Unidirectional measurements provide information on depositional processes that delivered sediments to the deltaic parasequence and can be used in modeling fluid flow in reservoirs.

In the Ivie Creek case-study area, a laser theodolite and a tape measure were used to position and scale information about lithofacies and polygons (modeling units based on lithology, permeability, grain size, and sedimentary structures) on photomosaics. In the area of the Kf-1a parasequence, for which detailed reservoir models will be developed, dimensional data need to be determined at a high level of precision. To achieve this, a number of points were surveyed with a laser theodolite followed by reduction of the survey data to yield horizontal and vertical scales. These scales were plotted on the photomosaics and will be used to determine dimensions of lithofacies units and polygons. These survey data were reduced to develop x-y-z coordinates to be used in making the three-dimensional geologic model of the case-study area.

A less precise technique was developed to produce horizontal and vertical scales for photomosaics throughout the rest of the case-study area where reservoir modeling will be at a coarser scale. For this information, there is no need to precisely position lithofacies and polygons, and horizontal and vertical scales were produced using a 50-foot (15-m) nylon measuring tape. A 35-to 50-foot-(9-15-m-) interval (horizontal or vertical) was measured in the field and the endpoints were recorded on the photomosaics. Key features on the photomosaics were recorded on 7.5 minute topographic maps and will be used to generate x-y-z coordinates for the three-dimensional geologic model.

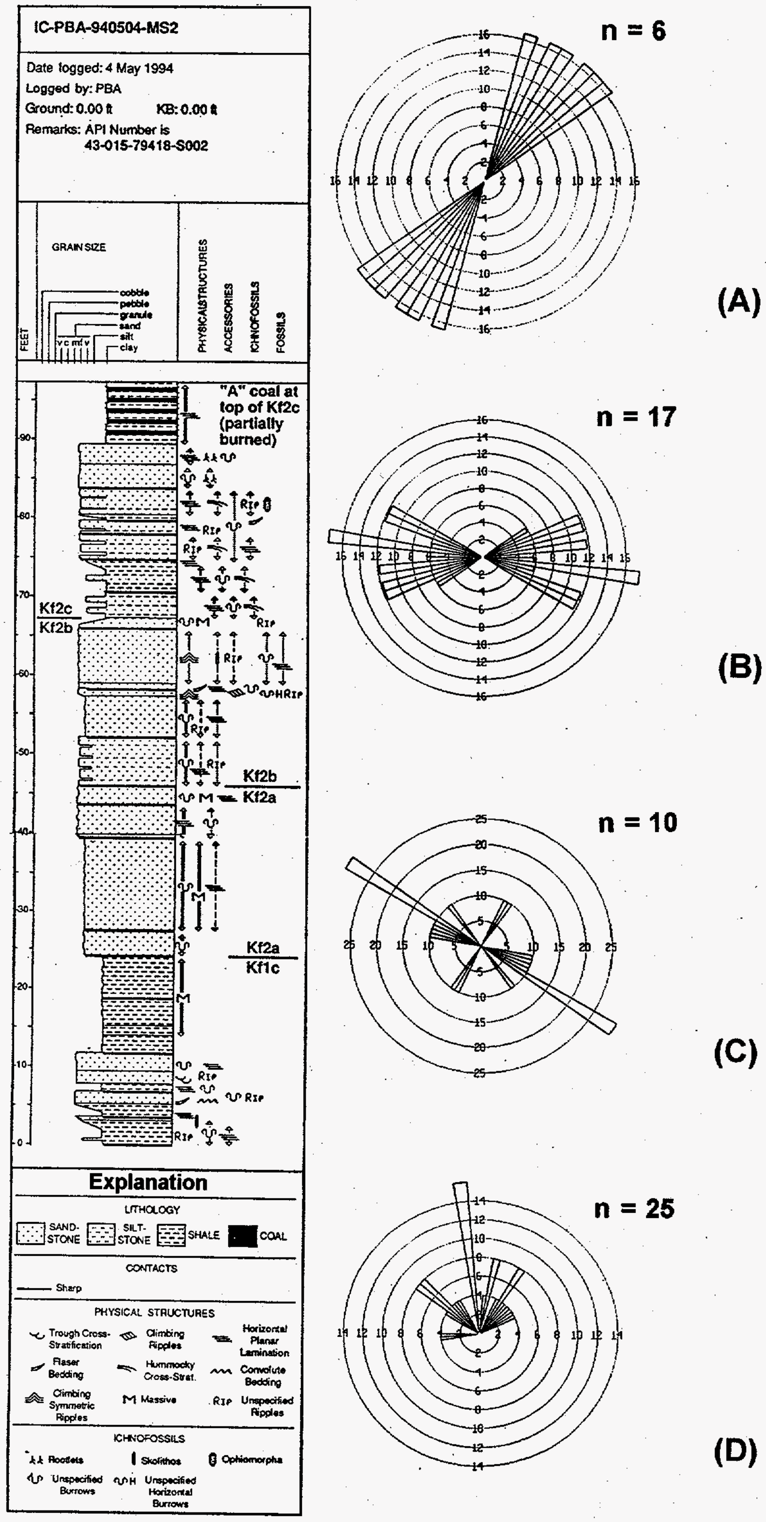


Figure 3.1. Stratigraphic section and rose diagrams from the Ivie Creek case-study area. On the left is a log of stratigraphic section IC-PBA-940504-MS2 from the Ivie Creek case-study area (originally at a scale of 1 inch: 2.5 feet [2.54 cm: 0.8 m]) showing lithologies, sedimentary structures, and parasequence designations. The outcrop and orientation of the transect where this section was measured is shown on figure 3.2. On the right, paleocurrent rose diagrams for several parasequences are displayed: (A) shows bidirectional data from Kf-2c, (B) shows bidirectional data from parasequence Kf-2b, (C) shows bidirectional data from parasequence Kf-1c, and (D) shows unidirectional data from parasequence Kf-1c.

3.1.2 Results

Sixteen sections were measured and described in the Ivie Creek (ten sections) and Willow Springs Wash (six sections) case-study areas in addition to the 33 sections made during the 1994 field season. Over 100 paleocurrent measurements were made at these and other localities. Lithologic and paleocurrent data are being entered into the UGS **INTEGRAL*gim** database for use in constructing statistical models, strip logs, and lithofacies maps.

1994 field data (measured stratigraphic sections and paleocurrent measurements) were edited and entered into the UGS database. Thirty graphic logs of stratigraphic sections and paleocurrents were generated. Field-interpreted photomosaics in the Ivie Creek case-study area were redrafted and acetate overlays added which show the interpretation of parasequences and deltaic subfacies (figure 3.2). The photomosaics will be the base for construction of scaled cross sections. In turn, the cross sections will form the base for construction of the three-dimensional model of the reservoir architecture.

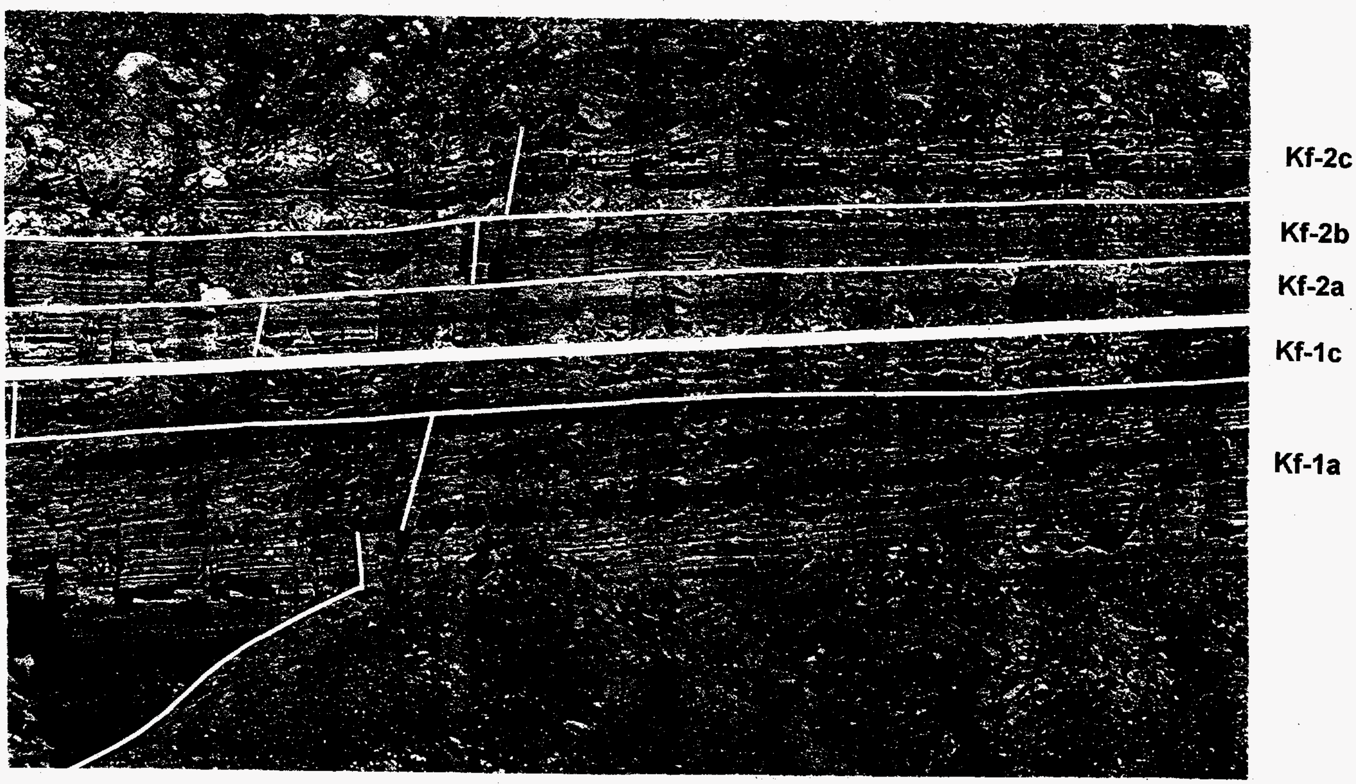


Figure 3.2. Photomosaic (oriented east-west) displaying Ferron parasequence sets in the Ivie Creek case-study area, view to the north. The heavy, white horizontal line is a parasequence set boundary and is underlain by parasequence set Kf-1 and overlain by parasequence set Kf-2. The thin, white horizontal lines are parasequence boundaries. Parasequence Kf-1b, normally present between parasequences Kf-1a and Kf-1c, is not present due to either post-depositional erosion or non-deposition. The marine sandstone of Kf-2c is overlain by nonmarine sandstone and shale. The thin, white vertical and steeply inclined lines mark the location of two measured stratigraphic sections. Section IC-PBA-940504-MS1 describes Kf-1a and section IC-PBA-940504-MS2 describes Kf-1c through Kf-2c. Outcrop in photomosaic located in SE1/4SE1/4NW1/4 section 16, T. 23 S., R. 6 E., Salt Lake Base Line, Emery County, Utah.

Clinoform boundaries were digitized for the Kf-1a parasequence identified on photomosaics. All scaling of the photomosaics was completed and elevation profiles were created using the Kf-1/Kf-2 boundary as a datum, and the data was input into a spreadsheet. General facies categories were assigned to units on the photomosaic panels based on geometry, sedimentary structures, and apparent shale content. Utilizing tie points on the panels that were identified in the field, the elevation profile picks were positioned on the 7.5 minute topographic maps.

3.1.3 Preliminary Interpretation of Reservoir Architecture

Parasequence designations in the stratigraphic sections have been standardized by combining facies descriptions and photomosaic interpretations. Locally, each parasequence set is divided into mappable, coarsening-upward, stratigraphic sequences (designated with letters a through e) which may or may not represent parasequences. In Ferron deltaic deposits, parasequences may be considered as primary reservoir building blocks because marine and/or delta-plain shales act as laterally extensive permeability barriers and commonly separate parasequences. Fluid-flow communication may occur between parasequences where shales are absent due to erosion or non-deposition. Porosity and permeability values, dependent on lithofacies distribution, vary laterally and vertically within a parasequence. Mouth-bar and proximal-delta-front lithofacies are high quality reservoirs; these lithofacies are related to spatial arrangement of parasequences making up the reservoir. Therefore, the initial stage in reservoir characterization must be an analysis of the architecture of parasequences and of lithofacies within parasequences.

In the Ivie Creek case-study area (figure 1.1), three possible parasequences are present within the Kf-1 parasequence set: the Kf-1a, Kf-1b, and Kf-1c (figure 3.3). Delta-front sandstones of a modified Gilbert delta make up the sand-rich lithofacies of the basal parasequence, the Kf-1a. This river-dominated deltaic deposit changes from proximal to distal (where the sandstone pinches out) east to west across the Ivie Creek area. Clinoforms (steeply inclined beds of sandstone that accumulated on the prograding delta) in the delta front dip 10°-15° and shale-out laterally within a mile (1.6 km) down depositional dip (figure 3.3). This lateral change in composition occurs within the case-study area and will be incorporated into the reservoir modeling. The core-hole sites were chosen to help characterize the sequence from proximal to beyond the pinch-out.

The overlying sand-rich lithofacies of the Kf-1b and Kf-1c parasequences also vary in thickness within the case-study area. In contrast to the Kf-1a, delta-front clinoforms of these parasequences dip less than 5°. Thinning of sand-rich lithofacies occurs in both up-depositional-dip and down-depositional-dip directions due to lateral lithofacies changes. The Kf-1b laps onto the more distal parts of the Kf-1a in the western part of the study area and represents the distal portion of another delta lobe, probably originating from the southwest. Kf-1b may be completely absent in some locations as a result of erosion and/or non-deposition (figure 3.4). It also includes a channel sandstone body, lenticular in cross section, deposited by a northwesterly flowing stream (figure 3.4).

The Kf-1c, the uppermost section of the Kf-1, is continuous across the entire Ivie Creek area and represents a wave-modified delta (figures 3.3 and 3.4). It is capped by unidirectional, trough-cross-bedded sandstone. The Kf-1c contains loading features near the mouth of Ivie Creek. It thickens to the north as the Kf-1a pinches out. Above the cross-bedded sandstone are

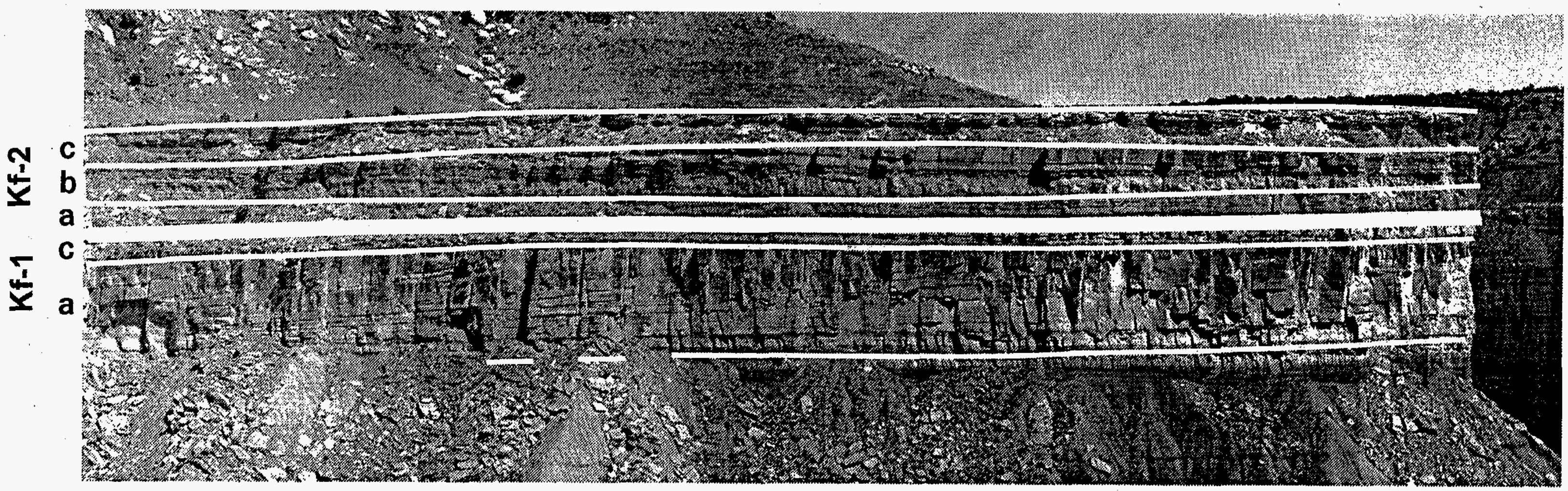


Figure 3.3. Photomosaic of Ferron parasequence sets, view to the north, of the Ivie Creek case-study area displaying contrasting delta-front architectural styles. The heavy, white, horizontal line is a parasequence-set boundary separating parasequence set Kf-1 and parasequence set Kf-2. The thin, white, horizontal lines are boundaries separating individual parasequences (designated with letters). Kf-1a has steeply inclined (10 to 15°) clinoforms representing fluvial-dominated deposition. Kf-2 has gently inclined (< 3°) clinoforms representing wave-modified deposition. Outcrop in photomosaic located in SW1/4NE1/4 section 16, T. 23 S., R. 6 E., Salt Lake Base Line, Emery County, Utah.

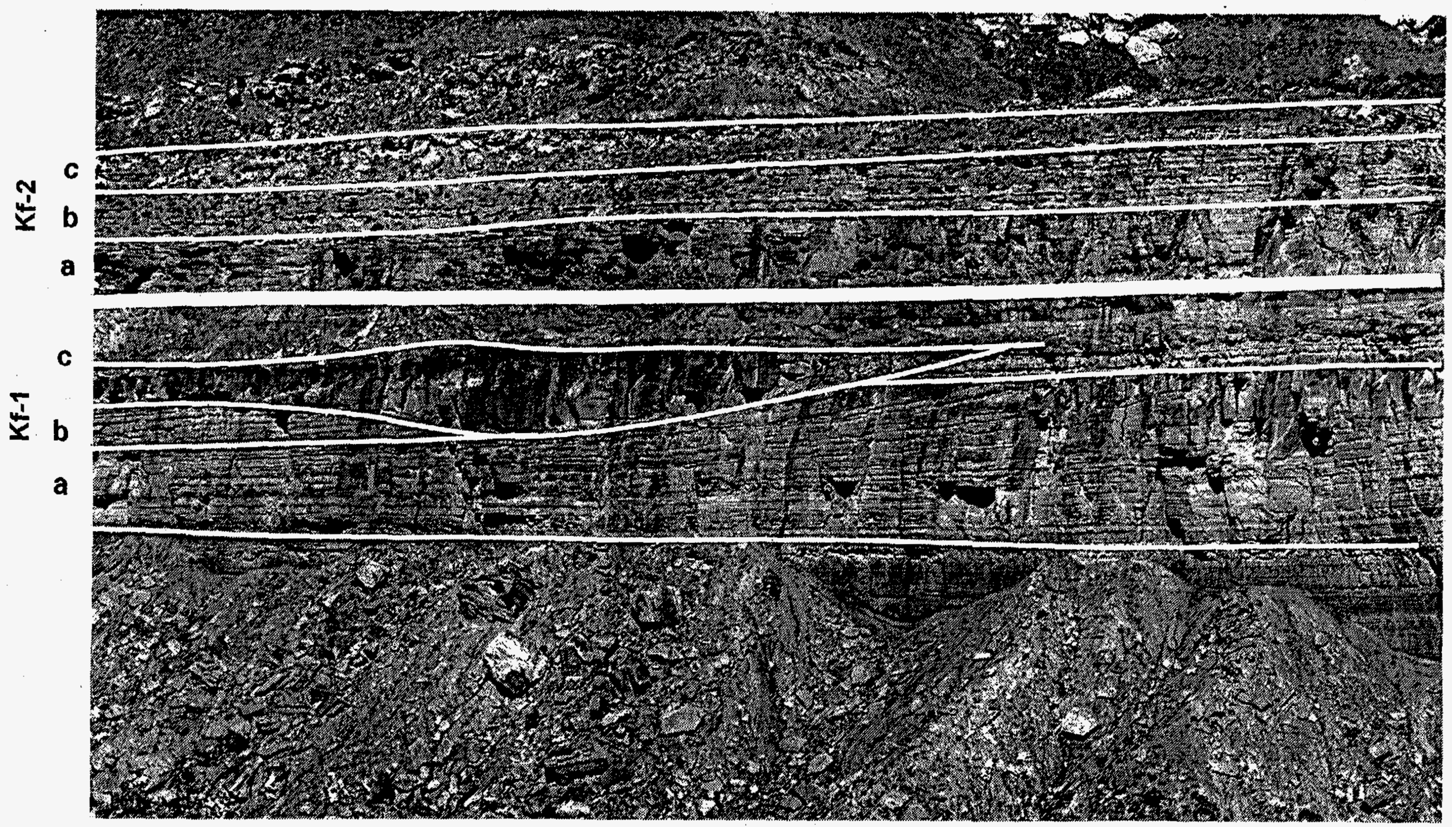


Figure 3.4. Photomosaic, view to the north, of Ferron parasequences in the Ivie Creek case-study area displaying Kf-1a clinoforms and a Kf-1c distributary channel. The Kf-1a contains more distal clinoforms than observed to east on figure 3.3. Kf-1b is absent to the right as a result of erosion and/or non-deposition. Outcrop in photomosaic located in SW1/4NE1/4SW1/4 section 16, T. 23 S., R. 6 E., Salt Lake Base Line, Emery County, Utah.

10 to 15 feet (3-6 m) of bay-fill deposits. These deposits consist of carbonaceous mudstone; thin, rippled-to-bioturbated sandstone and siltstone; fossiliferous mudstone to sandstone; oyster coquina; and ash-rich coal. The uppermost carbonaceous mudstone or ash-rich coal is the sub-A coal zone. A flooding surface has been identified at the top of the sub-A. The boundary with the overlying Kf-2 parasequence set is drawn at this flooding surface.

The Kf-2 parasequence set contains three possible parasequences: the Kf-2a, Kf-2b, and Kf-2c (figures 3.3, 3.4, 3.5, and 3.6). These parasequences show less lateral variation in lithofacies than the Kf-1 parasequences, possibly due to greater modification by wave processes. Within the case-study area, there is little lateral variation in thickness of sand-rich lithofacies, even when lateral change occurs from one depositional subfacies to another.

The lowest parasequence of the Kf-2 parasequence set is the Kf-2a. The Kf-2a begins as interbedded sand and shale in a prodelta to lower shoreface environment (figure 3.6). These deposits are thin, typically less than 10 feet (3 m) thick. They are overlain by a 0.5-to 1-foot- (0.2-0.3-m-) zone of highly carbonaceous to coaly sandstone which grades into 20 to 30 feet (6-9 m) of very-fine-grained, silty, and slightly carbonaceous sandstone. The unit is intensely bioturbated and was deposited in the middle-shoreface environment.

The Kf-2b consists of horizontally bedded, silty sandstone at the base and unidirectional, trough-cross-bedded sandstone toward the top. In a road cut along I-70 and in Ivie Creek Canyon, this unit displays trough sets which become horizontally bedded in a downdip direction. These deposits are interpreted as mouth-bar deposits (figure 3.5).

The Kf-2c is separated from the underlying Kf-2b by a siltstone to shale interval which varies in thickness across the Ivie Creek case-study area. Generally the entire unit fines from west to east. In the east, the Kf-2c is interpreted as a bay-fill deposit (although it is devoid of fossils). At the top of the sequence is a thin, medium-grained carbonaceous sandstone which may represent the migration of a beach (foreshore deposits) across the bay fill prior to capping by coastal-plain deposits and deposition of the overlying A coal.

In the Ivie Creek case-study area deposition of sandstones in the Kf-1 parasequence set was from the south to southeast, whereas the general coarsening of the Kf-2 parasequence set to the west suggests that this unit was deposited from west to east. The Kf-2 contains more and cleaner sand, indicating a more wave-modified environment of deposition. The Kf-1 is more heterolithic, indicating a river-dominated environment of deposition. Modeling of Kf-1 parasequences will aid understanding of reservoir production in fluvial-deltaic deposits that exhibit lateral changes over short distances. Modeling of Kf-2 parasequences will improve understanding of reservoir production in fluvial-deltaic deposits that exhibit gradual lateral changes over great distances.

The Ferron Sandstone in Indian Canyon of the Willow Springs Wash case-study area (figure 1.1) consists of excellent exposures of the Kf-1 parasequence set. The set is divided into five mappable stratigraphic sequences, Kf-1a through e; three are considered parasequences. The parasequences are displayed in a forward-stepping arrangement similar to many delta-front reservoirs. The transgressive (or "flooding") surfaces that separate the parasequences are overlain, at least in part, by mudstone units that may act as permeability barriers between sandstone bodies. Rocks in these sequences contain prodeltaic; lower, middle, and upper shoreface; foreshore; and fluvial-dominated delta-front deposits.

The Kf-1a through 1c represent non-deltaic coastal deposits; in contrast, the Kf-1d represents deposits from a subdelta of a river-dominated deltaic complex. Paleocurrent measurements on large-scale, trough-cross-stratification in the delta-front sandstone at the top of the Kf-1d indicate flow to the north. Several distributary channels cut the Kf-1d in this area.

Figure 3.5. Photomosaic, view to the southwest, of Ferron parasequences in the Ivie Creek case-study area displaying the mud-rich distal, delta-front deposits of the Kf-1 and stream-mouth-bar deposits of the Kf-2. The Kf-1 has now changed laterally from the sand-rich, proximal delta-front deposit observed in figure 3.4 a quarter of a mile to the northeast. The stream-mouth-bar deposits of the Kf-2b are broadly channelized. Outcrop in photomosaic located in SE1/4SE1/4 section 17, T. 23 S., R. 6 E., Salt Lake Base Line, Emery County, Utah.

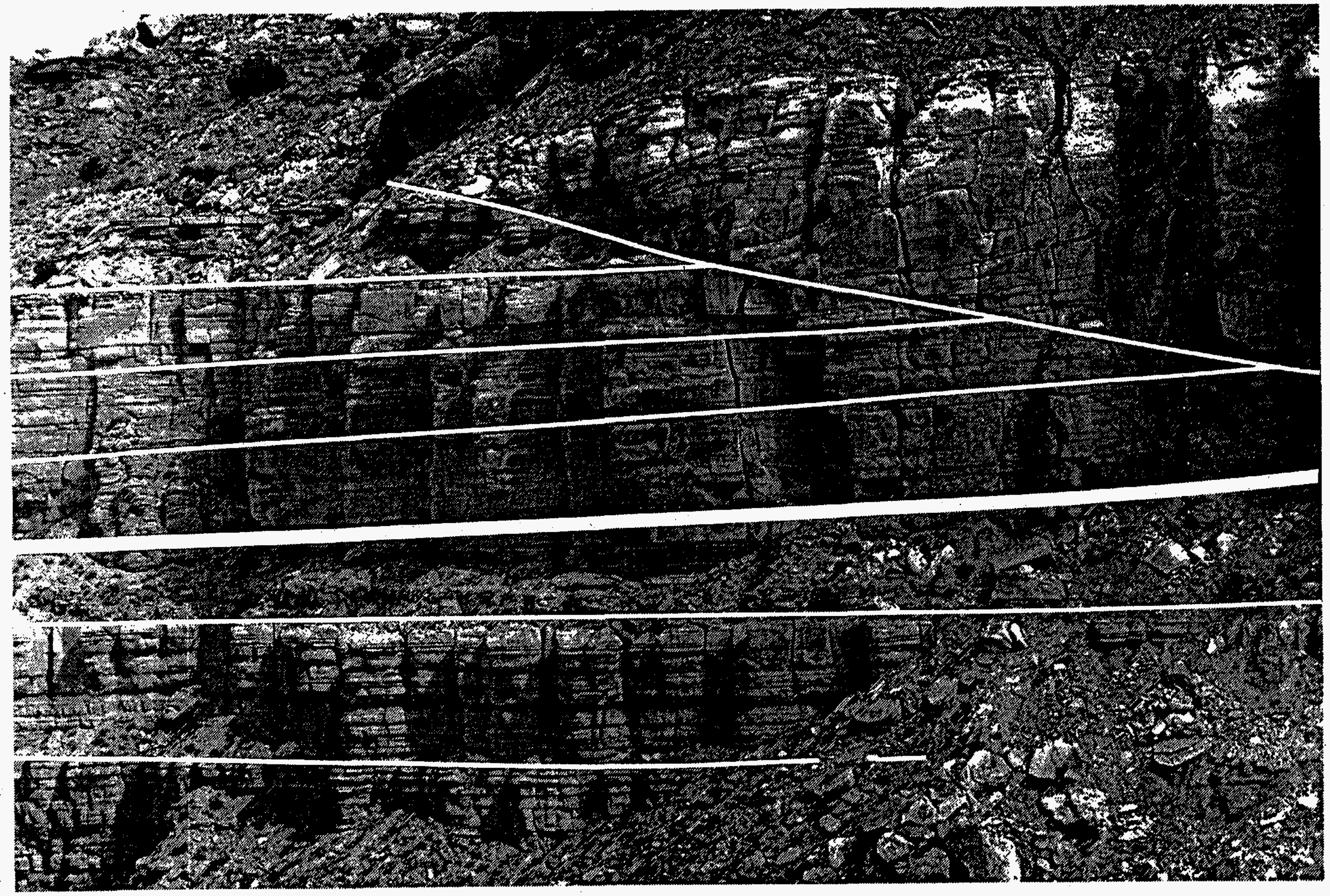


Figure 3.6. Photomosaic, view to the south, of the Ivie Creek case-study area showing both the Kf-1 and Kf-2 parasequence sets. A major distributary channel (upper right of photo) associated with the Kf-2c has cut down to the Kf-2a. Outcrop in photomosaic located in NW1/4NE1/4NW1/4 section 21, T. 23 S., R. 6 E., Salt Lake Base Line, Emery County, Utah.

Paleocurrent measurement taken from these channels indicate north to northeast flow. A bay-fill sequence caps the top of the Kf-1 parasequence set.

The Kf-2 parasequence set in Indian Canyon of the Willow Springs Wash case-study area is thin and consists of coastal-plain deposits containing little sandstone.

3.2 Core-Hole Program

Core holes in the Ivie Creek case-study area were permitted, drilled, logged, and plugged. Where hole conditions allowed, core holes were logged with sonic, density, neutron, focused resistivity, spectral gamma ray, and dipmeter tools. The spacing pattern of the core holes was similar to that typically used to develop an oil field. Stratigraphic logs from core-hole data will be used to prepare facies maps and to define "type" logs for the principal reservoir(s) in the case-study area. These data will also help provide a three-dimensional geometry of lithofacies which will be incorporated into the reservoir model. Cores and geophysical logs from these wells will also provide data for three-dimensional morphologic interpretation of individual lithofacies.

3.2.1 Methods

The core holes were located downdip 200 to 1,200 feet (60-265 m) from the Ferron outcrop. Surface right-of-ways from Utah School and Institutional Trust Lands Administration and the U.S. Bureau of Land Management (BLM) were obtained. A survey of current mineral-lease ownership showed no active coal lessees or other mineral-rights holders. Staking and permitting procedures were approved by the Utah Division of Oil, Gas and Mining (DOGM) (the oil and gas regulatory agency for Utah) and the BLM. Core-hole locations were surveyed using a global-positioning system. Permitting involved filing a DOGM "application to drill" (APD) which included: (1) an eight-point drilling program and a pre-site inspection, (2) clearance by the Utah Division of Wildlife Resources, (3) an on-site archeological inspection by Utah Division of State History, (4) a monitor-well construction permit (requires identification and notification of any significant encounter of water), and (5) a water-use permit (allows use of water from sources other than municipal sources) from the Utah Division of Water Rights, and an on-site surface inspection by the BLM.

A small, truck-mounted rotary drilling rig was used to drill and core the wells. A hand-dug, bermed pit was constructed to contain all drill cuttings and fluids at the sites. Water for drilling was trucked in to the locations; air and mist were used for circulation. Cuttings were described and tied to existing wells in the area to pick tops and core points. Three-inch (7.6-cm) cores were obtained with a 20-foot (6-m) split-core barrel. The wells were logged with slim-hole tools. The wells were plugged with a mixture of water and Enviroplug (swelling clay) and capped with 10 feet (3 m) of cuttings. After all equipment and trash were removed from the drill sites, the drill cuttings were raked out or buried and the areas reseeded as required by the BLM.

3.2.2 Results

Six core holes were drilled in the Ivie Creek case-study area (figure 3.7). These wells were located to evaluate the lithofacies and reservoir characteristics of the Kf-1 and Kf-2 parasequence sets. Core and geophysical logs from these wells will provide data for a three-dimensional morphologic interpretation of individual lithofacies and capture the various reservoir changes in the Kf-1 and Kf-2 parasequence sets over an area analogous in size to a small oil field. The Kf-1 represents a river-dominated delta deposit which changes from proximal to distal from east to west across the Ivie Creek area. The Kf-2 contains more and cleaner sand, indicating a more wave-modified environment of deposition.

The Ivie Creek Nos. 3, 5a, 9, and 9a (figure 3.7) were drilled and completed in November and December 1994. The total depths of the wells are 443, 320, 200, and 310 feet (135, 98, 61, and 95 m) respectively. Even though the wells were located down dip 200 to 1,200 feet (60-365 m) from the Ferron cliff face, the Ivie Creek Nos. 5a, 9, and 9a encountered drilling and coring problems due to coal burn and fracture zones in the targeted sections. The Ivie Creek No. 9 was abandoned before coring and logging operations could be completed. Geophysical logs run in the three other core holes include the gamma ray, caliper, formation density, and where the drill holes could hold water, sonic and dipmeter (figure 3.8). Continuous-core logging of the core recovered from the Ivie Creek Nos. 3, 5a, and 9a was conducted using the a computer-interfaced multisensor track which simultaneously recorded natural gamma, density (via gamma-ray attenuation), and magnetic susceptibility. These data are being used to determine porosity and clay content, the dominant controls on fluid flow (permeability) in the Ferron Sandstone and most oil-producing, fluvial-deltaic reservoirs.

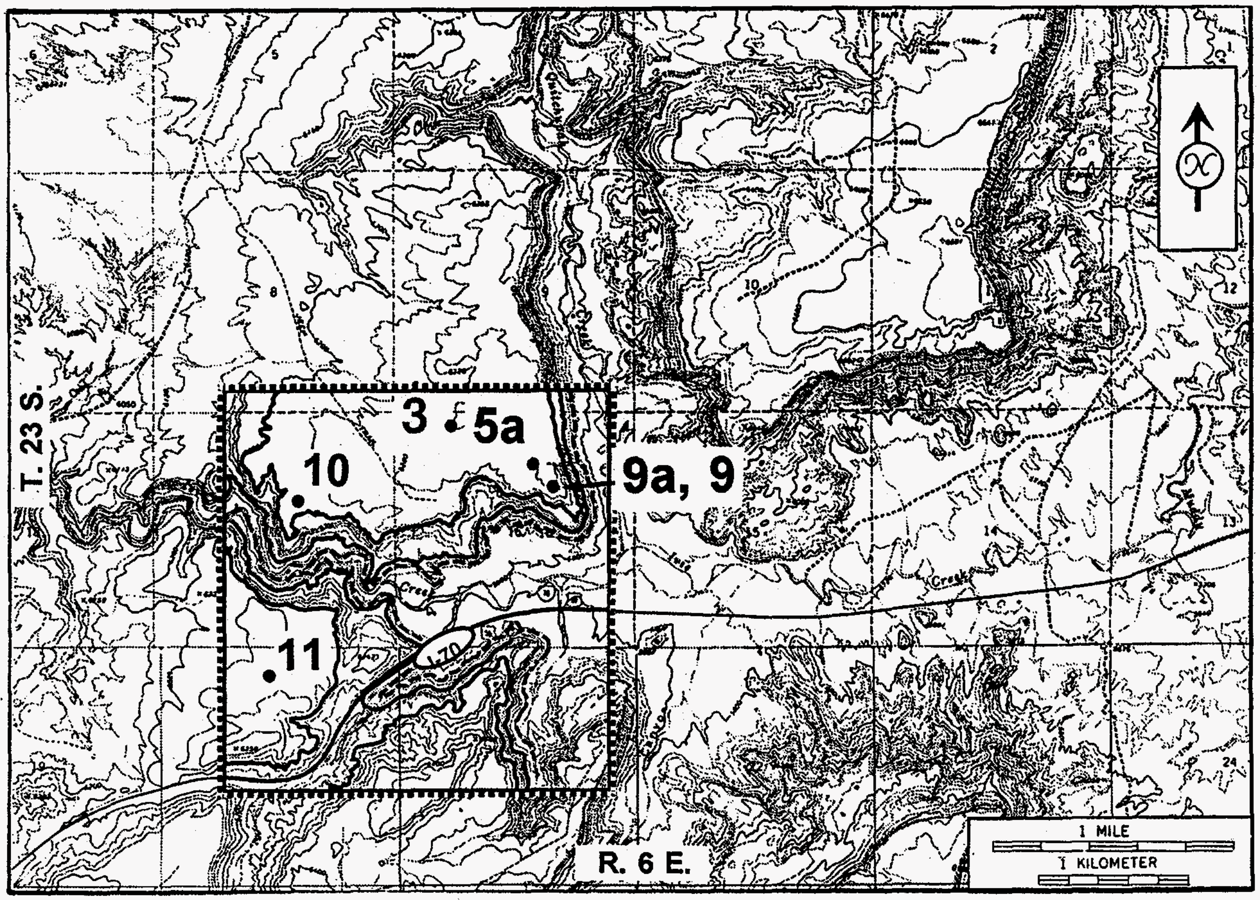


Figure 3.7. Locations of six core holes drilled in the Ivie Creek case-study area, sections 16, 17, and 20, T. 23 S., R. 6 E., Salt Lake Base Line, Emery County, Utah to evaluate the Kf-1 and Kf-2 parasequence sets. A 2-mile-by 2-mile-(3.2-by 3.2-km) detailed, block is outlined. Base map from U.S. Geological Survey Mesa Butte and Walker Flat 7.5' topographic maps; contour interval is 40 feet (12 m).

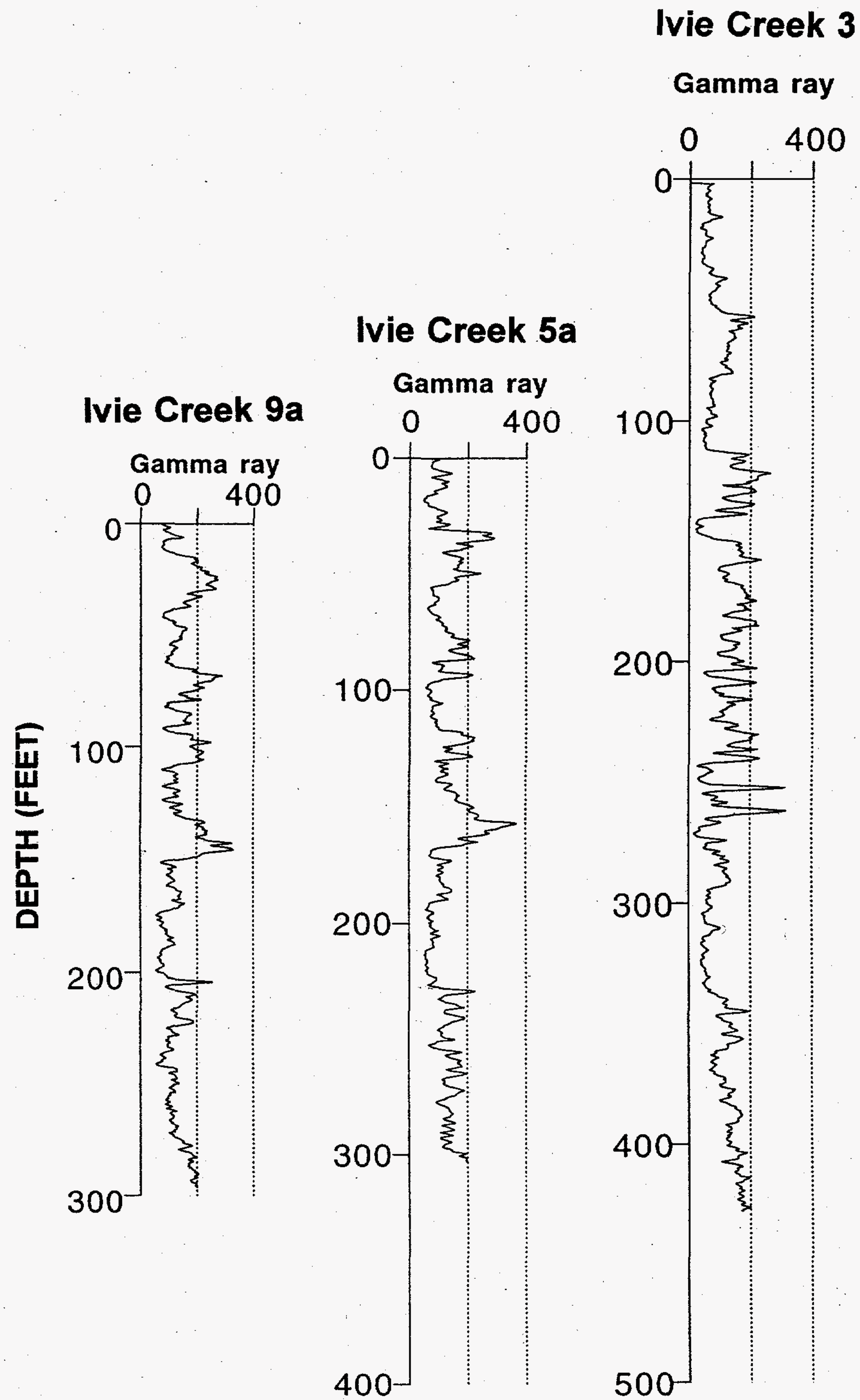


Figure 3.8. Gamma-ray logs, in API units, from the Ivie Creek Nos. 9a, 5a, and 3 core holes (locations shown on figure 3.7).

The Ivie Creek Nos. 10 and 11 (figure 3.7) were drilled and completed in September 1995. The total depths of the wells are 420 and 444 feet (128 and 135 m) respectively. These wells were located farther back from the outcrop to avoid the coal burn and fracture zones encountered during the 1994 drilling program. The Ivie Creek No. 10 was not cored. Geophysical logs run in the Ivie Creek Nos. 10 and 11 wells included the formation density, caliper, and gamma ray. Sonic, dipmeter, and dual-spaced neutron logs were recorded in the Ivie Creek No. 11 well; these logs could not be run in the Ivie Creek No. 10 well since it would not hold water due to a large fracture zone.

A total of 586 feet (179 m) of core was recovered from the Kf-1 and Kf-2 parasequence sets. The geophysical logs are available for public use in the UGS Library at our general office and the cores are stored at the UGS Sample Library where they can be examined by any interested party for a nominal fee.

3.3 Outcrop Gamma-Ray Measurements

Objectives for collecting outcrop gamma-ray measurements for the Ferron Sandstone in the Ivie Creek case-study area are: (1) to determine variations in clay-mineral content (or sand/shale ratios), (2) to permit detailed correlation among and between outcrop traverses and core-hole gamma-ray logs, and (3) to detect possible diagenetic changes associated with precipitation of uranium. Variations in the gamma-ray signal are related to clay content in shaly sandstones which, in turn, influences the compartmentalization of flow units.

3.3.1 Methods

Field measurements were taken using a portable 256-channel gamma-ray spectrometer capable of determining total natural gamma counts as well as concentrations of potassium, thorium, and uranium. The spectrometer was tested in the lab and field to determine its vertical resolution and replicability. Test measurements in the field were found to be unreliable in rough topography because gamma rays entered the sides of the detector. This problem was corrected by covering the sides with lead shielding.

Field measurements showed that the total gamma-ray count is not always a reliable indicator of clay content. Potassium and thorium co-vary, probably because they are present primarily in clays. Uranium, however, is not commonly correlated with potassium and thorium. This indicates that uranium is present in minerals other than clays. Consequently, for reliable determination of clay content, potassium and thorium must be measured rather than just total gamma rays. One-minute measurements were made, almost five times the duration needed for good total-gamma values but barely sufficient for reliable potassium, thorium, and uranium measurements. Gamma-ray measurements were run along the same transects as the mini-permeameter sampling and measured sections.

3.3.2 Results

All gamma-ray outcrop logging was done along 14 vertical or near-vertical (depending on access) transects which were also permeability and petrophysical transects. Each transect consisted of 200 to 400 measurements at 0.5 to 1.0 foot (0.15-0.3 m) intervals. All traverses included the entire Kf-1 parasequence set, and most also included all or part of the Kf-2 parasequence set. The gamma-ray profiles of the transects are being used for correlation (figure 3.9) and quantitative determination of sand/shale percentage.

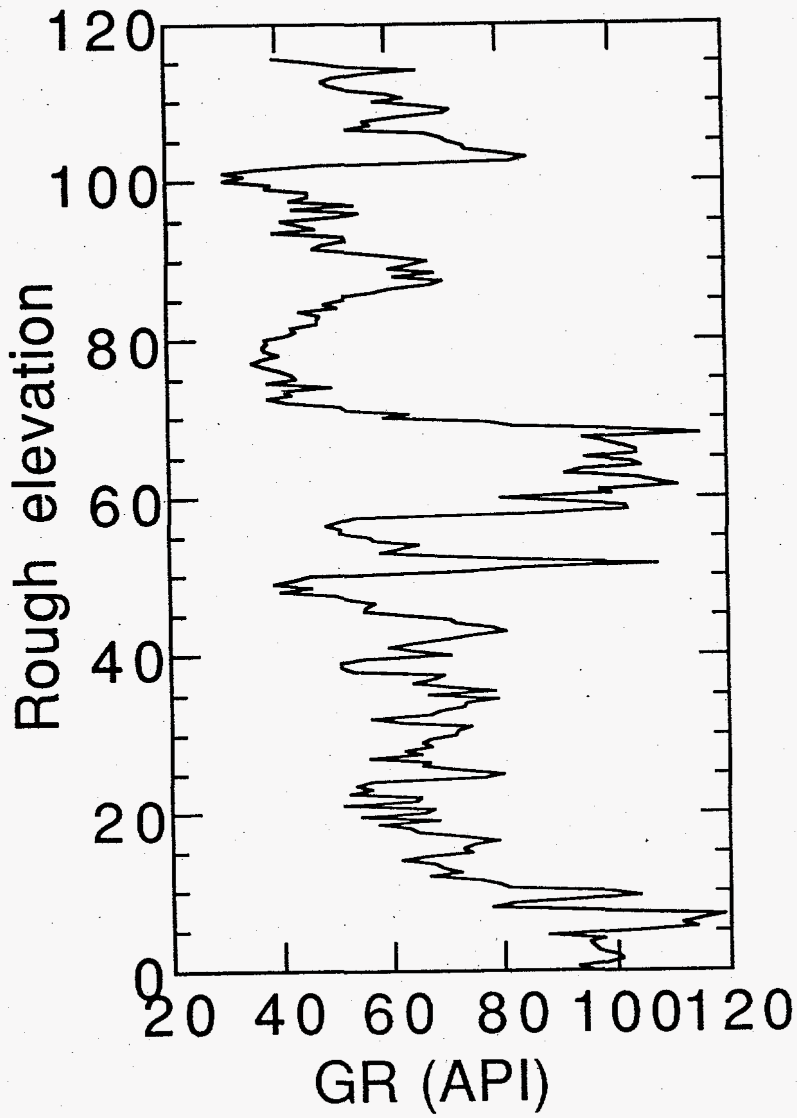


Figure 3.9. Typical gamma-ray profile from outcrop transect in the Ivie Creek case-study area. The X axis is of gamma ray intensity measured in API units; the Y axis is of elevation of the sample location above the start of the transect in feet.

3.4 Outcrop Core-Plug Sampling

The objective of core-plug sampling in the Ivie Creek case-study area was to characterize vertical and lateral variations of a number of petrophysical properties (velocity, density, porosity, permeability, and mineralogy) in various types of reservoir rocks and to determine the interrelations among these properties in the Kf-1 and Kf-2 parasequence sets.

3.4.1 Methods

The technique involved drilling 1- to 4-inch- (2.5-10-cm-) long core plugs, 1 inch (2.5 cm) in diameter, with a portable gas-powered drill and water-cooled diamond bit. The orientation of each sample was determined and the sedimentary structures of the bed photographed. All core-plugging was done along vertical or near-vertical (depending on access) traverses with one sample per "bed" and about 30 to 50 samples per transect.

One significant change from the 1994 sampling program was a greatly increased emphasis on sampling for anisotropy studies: rather than taking just one horizontal sample per site, a set of three samples (horizontal, vertical, and 45°) was taken. Anisotropy is a variable that needs to be considered in the fluid-flow modeling. It is also a much broader petrophysical concern because anisotropy can be caused by either mineral alignment (platy, subhorizontal clay minerals) or by microfractures (usually one set of vertical microfractures); both causes affect fluid flow.

3.4.2 Results

All core plugging was done along vertical or near-vertical (depending on access) traverses. A total of 208 horizontal samples were taken from 10 traverses and 77 three-dimensional sets from eight traverses. These traverses correspond to permeability transects, measured sections, and gamma-ray transects. Various lithofacies from both the Kf-1 and Kf-2 parasequence sets were sampled.

3.5 Mini-Permeameter Measurements

A large quantity of permeability data was collected and analyzed from outcrop exposures in the Ivie Creek case-study area. These data can be integrated into a complete reservoir characterization product that can assist in subsequent reservoir-simulation work. The core-hole drilling program make the Ivie Creek case-study area important as a reservoir analog. Five core holes were successfully drilled in close proximity to the cliff exposures extensively studied in both the 1994 and 1995 field seasons. These wells provide core and geophysical logs through the sedimentary sections of primary interest. Most importantly, the data from the cores and logs provide a sound basis for determining the detailed vertical variation in reservoir properties that cannot easily be determined in outcrop work.

Outcrop permeability testing, when combined with detailed geologic mapping, will improve understanding of the lateral variability in permeability for specific bedform types. Vertical permeability transects provide a coarse map of vertical permeability variations. These variations can be used, along with outcrop gamma-ray mapping, to match the lateral permeability transects and geological mapping. Additional detailed data was provided from the nearby core holes.

3.5.1 Methods

Twenty-two permeability transects, 18 vertical and four sub-horizontal (parallel to bedding), were made on the outcrop at the Ivie Creek case-study area (figure 3.10). Transect locations were jointly chosen by the geological and engineering teams to include the majority of the lithofacies present in the Kf-1 and Kf-2 parasequence sets. Data from these transects were used to determine the statistical structure of the spatially variable permeability field within the

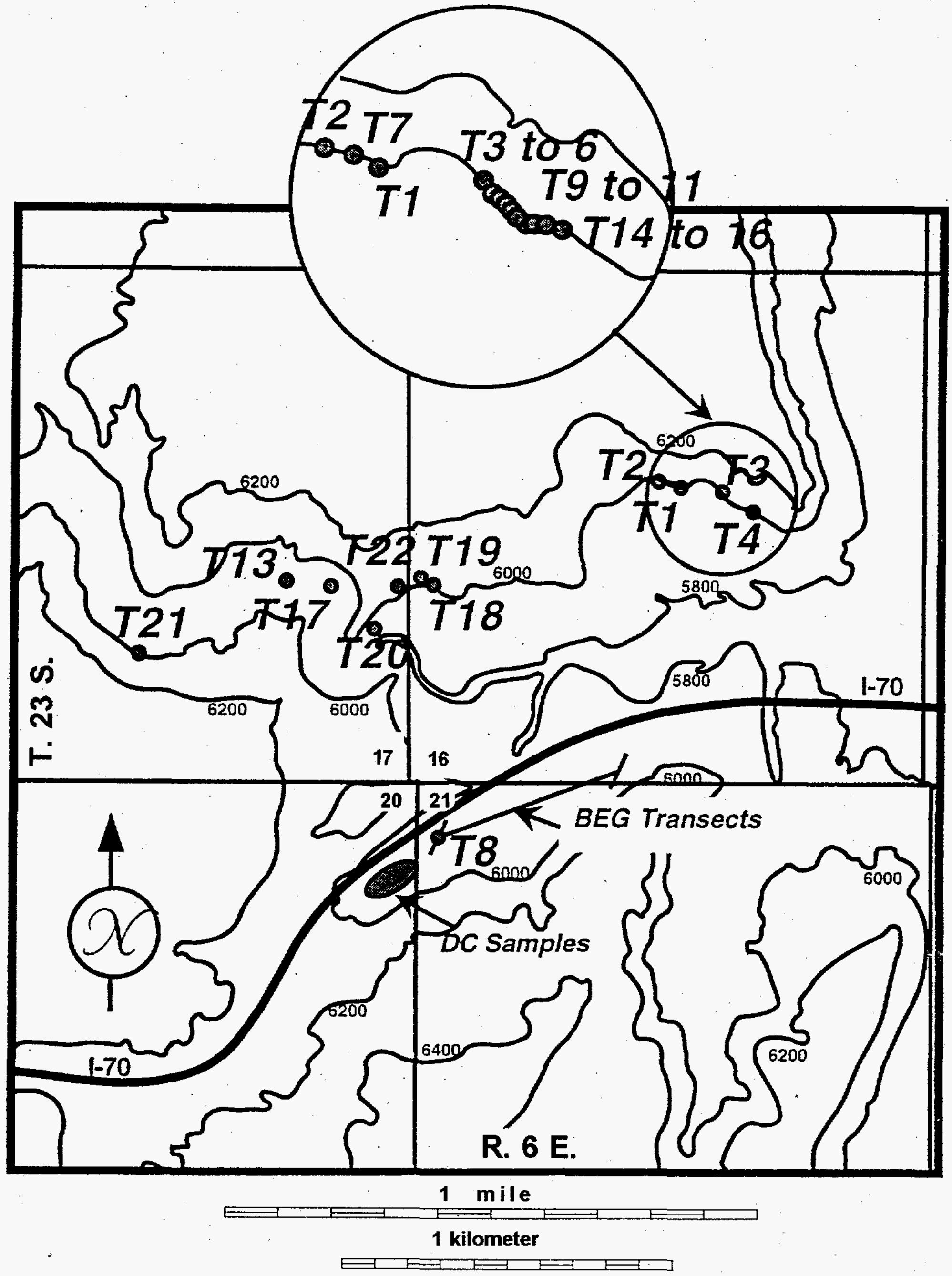


Figure 3.10. Location of 22 permeability transects (vertical and parallel to bedding) in the Ivie Creek case-study area, sections 16, 17, 20, and 21, T. 23 S., R. 6 E., Salt Lake Base Line, Emery County, Utah. BEG transects refers to the location of permeability transects conducted by the Texas Bureau of Economic Geology. The DC Samples was a series of plugs collected to study the influence of cross bedding and soft-sediment deformation structures on anisotropy.

delta fronts, to investigate how geological processes control the spatial distribution of permeability, and to evaluate permeability measurement techniques. Measured stratigraphic sections were tied to the permeability transects.

Measurement intervals (station spacing) on all of the vertical transects are 0.3 feet (0.1 m). Core plugs were collected at 3.0-foot (1-m) spacing along the horizontal transects. Core plugs roughly 0.75 inches (0.3 cm) in diameter and 1 to 3 inches (2.5-7.5 cm) long were drilled from the outcrop at each transect station (where possible) to ensure that permeability measurements could be made on fresh, unweathered rock surfaces. Drilling experience and examination of the core plugs indicate that chemical weathering extends into the rock less than 0.5 inches (1.3 cm). Whole plugs were typically recovered only from sandstone beds greater than 2 inches (5 cm) thick. Useful plugs could usually not be obtained from thinner sandstone beds or from thinly bedded sandstones, siltstones, and mudstones. Core-recovery rates range from 50 to nearly 100 percent. Where core plugs could not be recovered, small rock samples were taken, except where the outcrop was buried under colluvium.

Permeability was measured in the laboratory on the unweathered end of the core plugs after the unweathered end was trimmed flat with a rock saw. The thin disks trimmed from the plug ends were saved for possible future petrographic analysis. At those stations where a good hole was drilled but a broken core was recovered, permeability was measured in the hole. Prior to measuring field permeability in a core hole, the back of the hole was prepared using a screwdriver and a rock hammer to chip away rough spots, providing a flat surface for the mini-permeameter probe tip. The hole was rinsed out with water and allowed to dry for at least 24 hours prior to permeability testing. The hole was also "cleaned" by a blast of compressed gas immediately before testing.

An electronic miniprobe permeameter (EMP) supplied by the Mobil Exploration/Producing Technical Center was used to make laboratory permeability measurements on the trimmed, whole core plugs and to make field measurements in core holes. Each sample was washed then dried in an oven for two days in an effort to ensure that all moisture was removed from the samples prior to testing. This instrument has an accuracy of 1 to 12 percent and a precision of 1 to 3 percent on homogenous core plugs with permeabilities ranging from 1 to 4,500 millidarcies (md) (J.R. Garrison, Jr., Mobil, verbal communication, 1994). A rack was used to secure the probe in the laboratory; an expansion packer was used to secure the probe in a core hole in the field. In both cases, an air-actuated piston pushes the probe tip against the center of the sample, providing a air-tight coupling between the probe tip and the rock. A subset of these core plugs (220 plugs) was tested using Mobil's Hassler cell equipment. All test results were compiled in a spreadsheet and plotted in graphical form.

Permeability testing was also performed on 3-inch- (7.6-cm-) wide slabbed core from core holes using Mobil's stage-mounted, automated mini-permeameter. The distance between measurement points on the core ranged from 0.03 to 0.05 feet (0.9-1.5 cm) along the core. Core was selected for slabbing and testing after a series of reconnaissance mini-permeability tests were performed on segments of whole core.

3.5.2 Results

3.5.2.1 Results of 1994 Mini-Permeameter Data Collection. The first phase of mini-permeability analysis involved testing core plugs, and compiling and documenting the test results. A total of seven permeability transects, four vertical and three sub-horizontal (parallel to bedding), were made on the outcrop at the Ivie Creek case-study area during the 1994 field season (figure 3.10). The transects as a group span the proximal, middle, and distal portions of the delta-front rocks of the Kf-1 parasequence set. The four vertical transects are approximately 600 feet (200 m) apart and 100 to 200 feet (30-60 m) long. From west to east (distal to proximal), the transects are: T-2, T-1, T-3, and T-4. The three sub-horizontal, bed-parallel transects are approximately 50 feet (15 m) long. From west to east the transects are: T-7, T-6, and T-5. Station spacing on the bed-parallel transects is 0.5 feet (0.2 m).

Mini-permeameter testing in the laboratory was completed on 379 plugs from these transects. Core plugs obtained from the Kf-2 parasequence set in the field were also tested. These permeability data and related information were entered into spreadsheets for subsequent analysis. The results of mini-permeameter tests performed on core collected from vertical (T1, T2, T3, and T4) and horizontal (T5, T6, and T7) outcrop transects are shown on figures 3.11, 3.12, and 3.13. A large percentage of the rock tested apparently has a permeability lower than the resolution of the mini-permeameter (approximately 2 md). Overall, permeabilities in Kf-1 sandstones are relatively low; less than about 50 md. In Kf-2 sandstone (figure 3.13), permeabilities are locally much higher; in excess of 80 md. A clear increase in permeability within distinct bedforms of Kf-1 sandstones exists from distal to proximal transects (T2 to T1 to T3 to T4). Although permeability values are below instrument resolution in horizontal transects T6 and T7 (figure 3.12), results obtained from T5 suggest that there is a definite permeability structure that may correspond to mappable variations in lithology and grain size.

In performing the field and laboratory testing, we collected sufficient information to compare the results of *in-situ* testing (k-hole) to laboratory tests performed on core (k-plugs) collected from the holes tested in the field (figure 3.14). The *in-situ* tests produce generally larger permeability values. We suspect that this effect might result from differences in surface preparation; the core plugs are trimmed with a saw while testing surfaces in the *in-situ* holes are chipped to a roughly flat surface. Because *in-situ* testing requires a large field commitment (in time and field personnel) and appears to provide overestimates of rock permeability, we continued to emphasize the collection of core plugs during the 1995 field season for subsequent laboratory testing.

Outcrop core plug sampling of both the Kf-1 and Kf-2 parasequence sets in the Ivie Creek case-study area were obtained during the 1994 field season to characterize the vertical and lateral variations of petrophysical properties such as density, velocity, mineralogy, and porosity. These samples were also tested for permeability (figure 3.15). Figure 3.15 shows that at least 14 percent porosity is required to obtain measurable permeabilities with the mini-permeameter. Data shown in figure 3.15 are grouped to illustrate that grain-size variations appear not to influence the relationship between permeability and porosity.

3.5.2.2 Stage-Mounted Mini-Permeameter Data from Slabbed Core. Using Mobil's stage-mounted, automated mini-permeameter, detailed permeability data (1,939 measurements) were collected from approximately 110 feet (34 m) of slabbed core obtained from Ivie Creek Nos. 3, 5a, and 9a core holes (figure 3.7). These samples were tested for comparison to the other portions of the delta-front rocks. Figure 3.16 illustrates low permeabilities obtained from two core segments from the Ivie Creek No. 5a (Kf-2 sandstones) and 9a (Kf-1 sandstones) core holes.

The reconnaissance results are shown with the corresponding gamma-ray profiles in figure 3.17. Each hole is approximately "hung" on the gamma-ray peak that represents the approximate interface between the Kf-1 and Kf-2 parasequence sets. The plots are arranged in a proximal-to-distal pattern when viewed from left to right (figure 3.17). Sections of core with higher reconnaissance permeability values were submitted for detailed testing because they

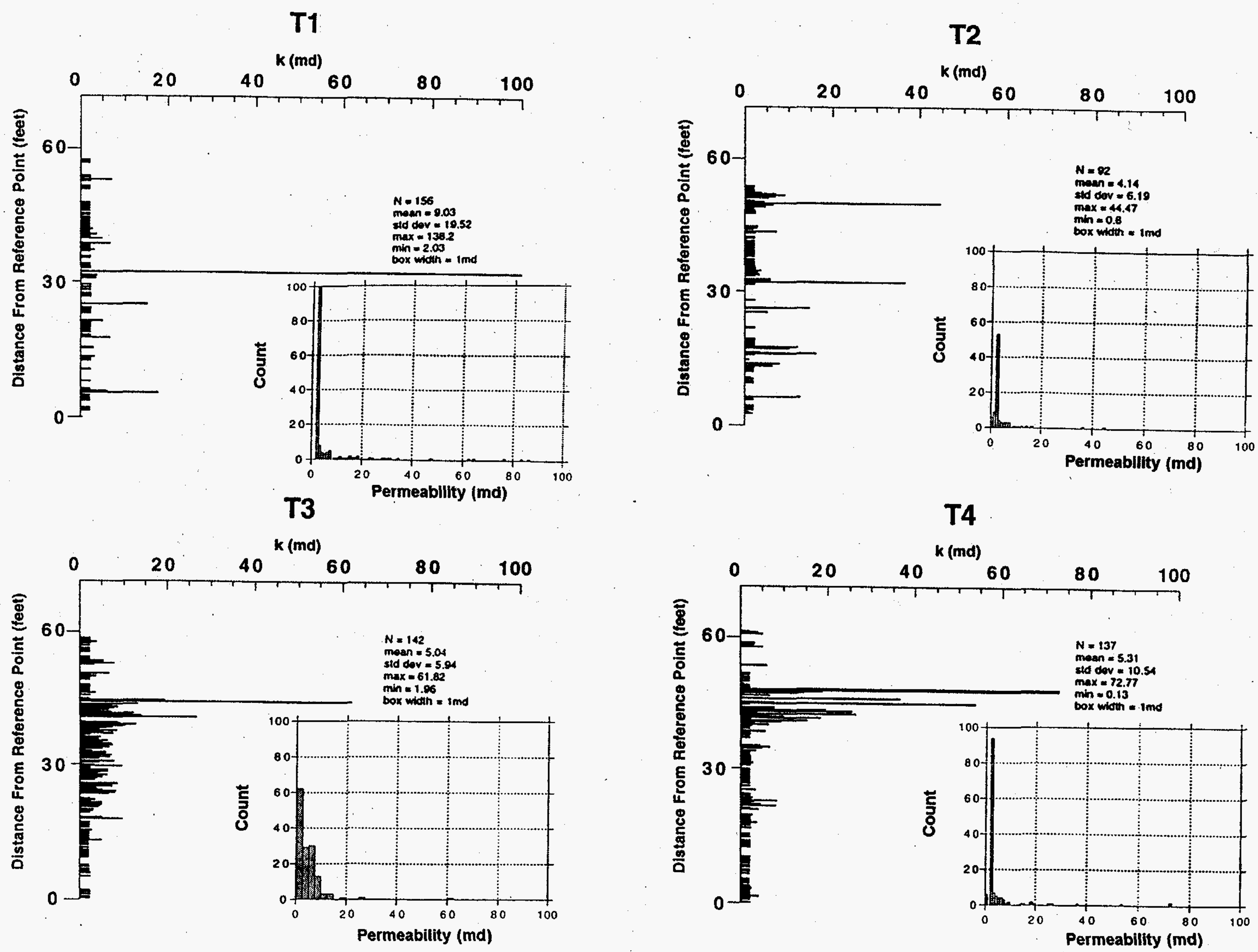


Figure 3.11. Permeability as a function of position and permeability histograms from mini-permeameter tests on core plugs collected from the Kf-1 sandstones along vertical transects T1, T2, T3, and T4 (locations shown on figure 3.10). Reference points do not necessarily coincide with a common geological feature but are end points of the transect.

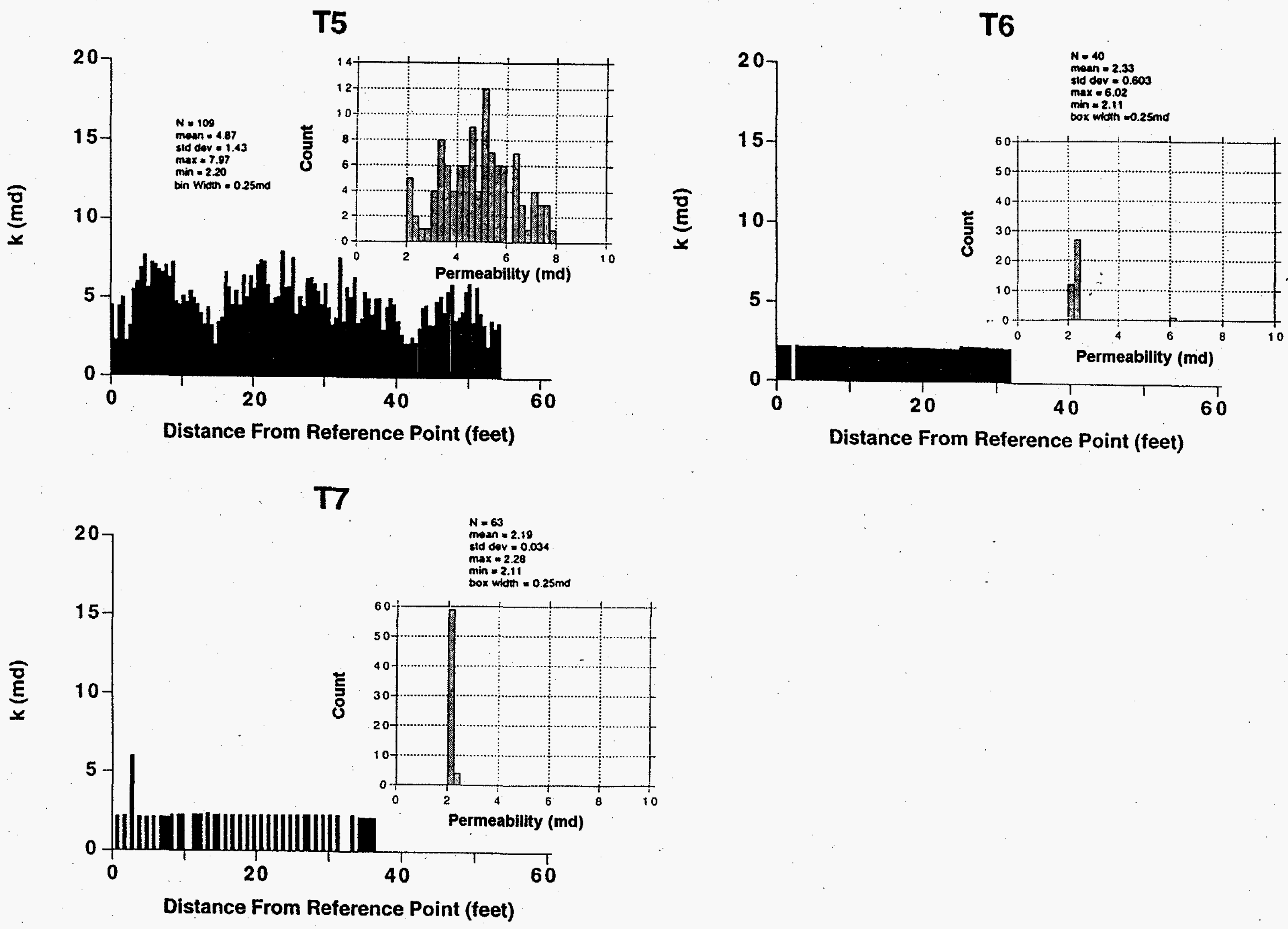


Figure 3.12. Permeability as a function of position and permeability histograms from mini-permeameter tests on core plugs collected from the Kf-1 sandstones along horizontal transects T5, T6, and T7 (locations shown on figure 3.10).

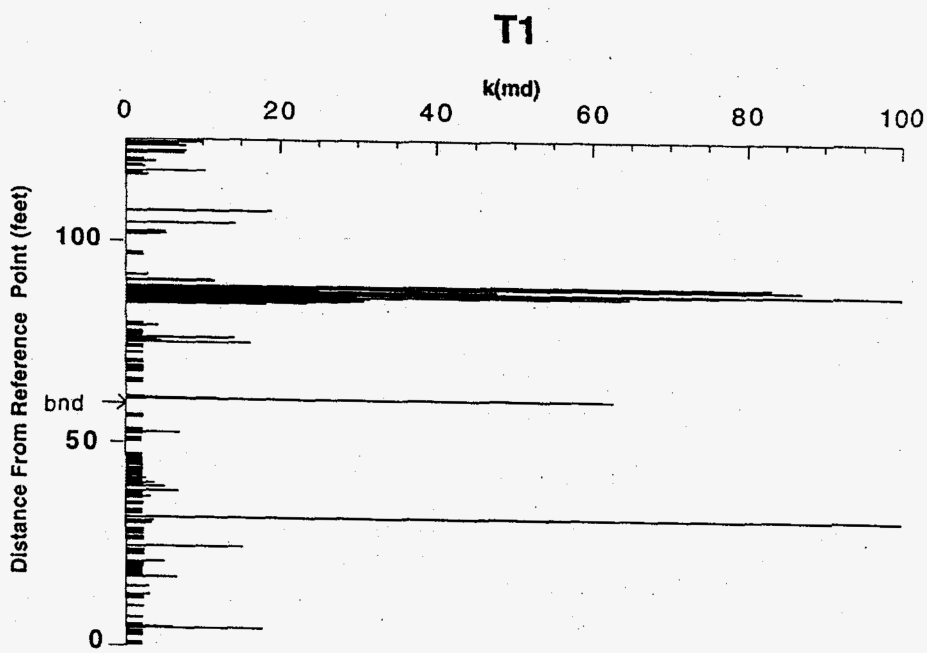


Figure 3.13. Permeability as a function of position from mini-permeameter tests on core plugs collected from Kf-1 and Kf-2 sandstones along vertical transect T1 (location shown on figure 3.10). Bnd = boundary between Kf-1 and Kf-2 parasequence sets.

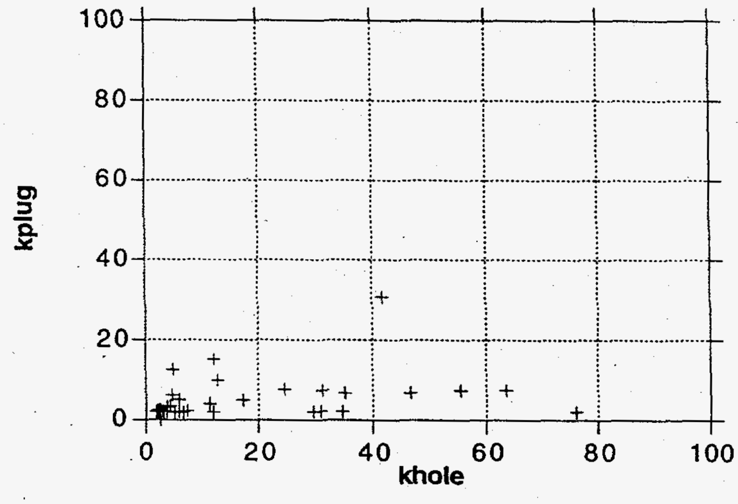


Figure 3.14. Comparison of results in millidarcies, of mini-permeameter tests on core plugs (kplug) collected from holes where *in-situ* tests (khole) were also conducted.

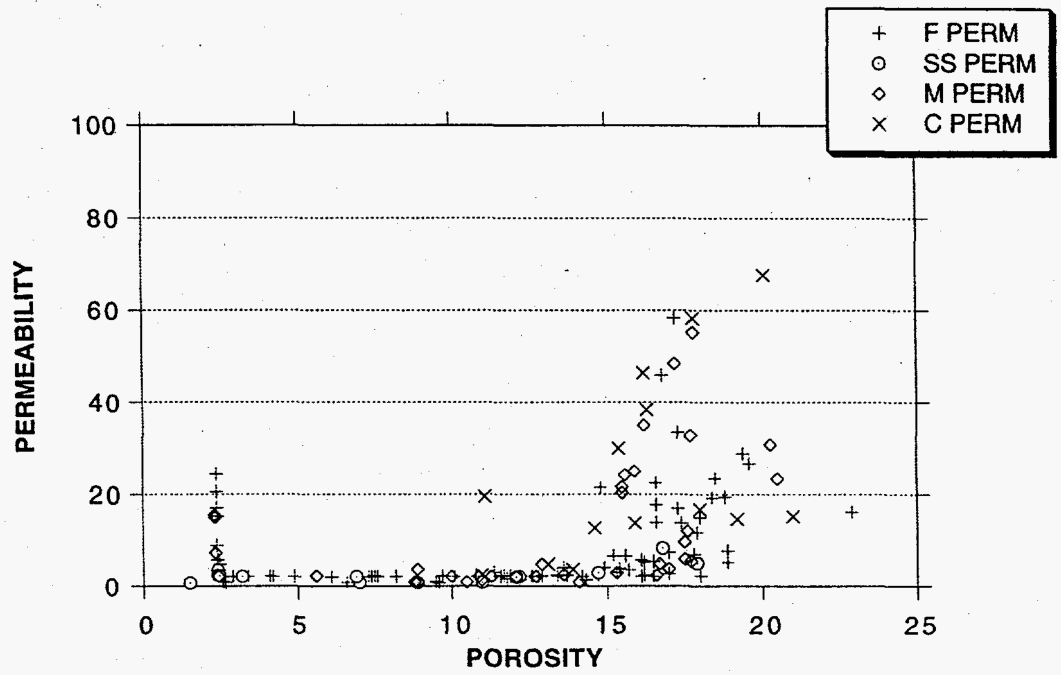
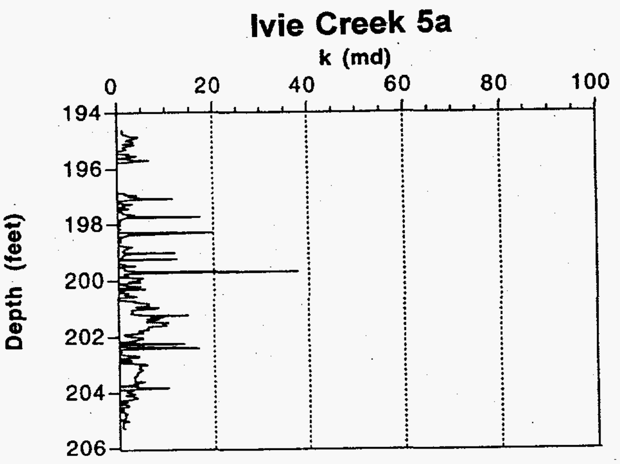


Figure 3.15. Comparison of permeability (in millidarcies) and porosity (in percent) values obtained from core plugs collected from outcrop; values grouped by grain size (F = fine grained, SS = silty/shaley, M = medium grained, and C = coarse grained).



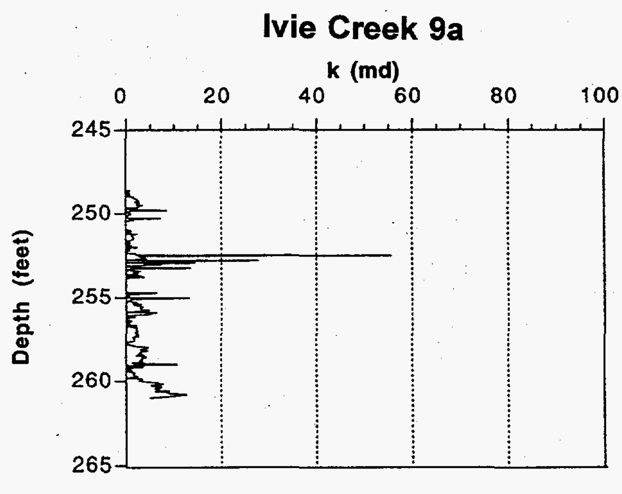


Figure 3.16. Detailed permeability measurements using a stage-mounted, automated mini-permeameter (0.05-foot [1.5-cm] spacing) on slabbed core obtained from the Ivie Creek Nos. 5a and 9a core holes.

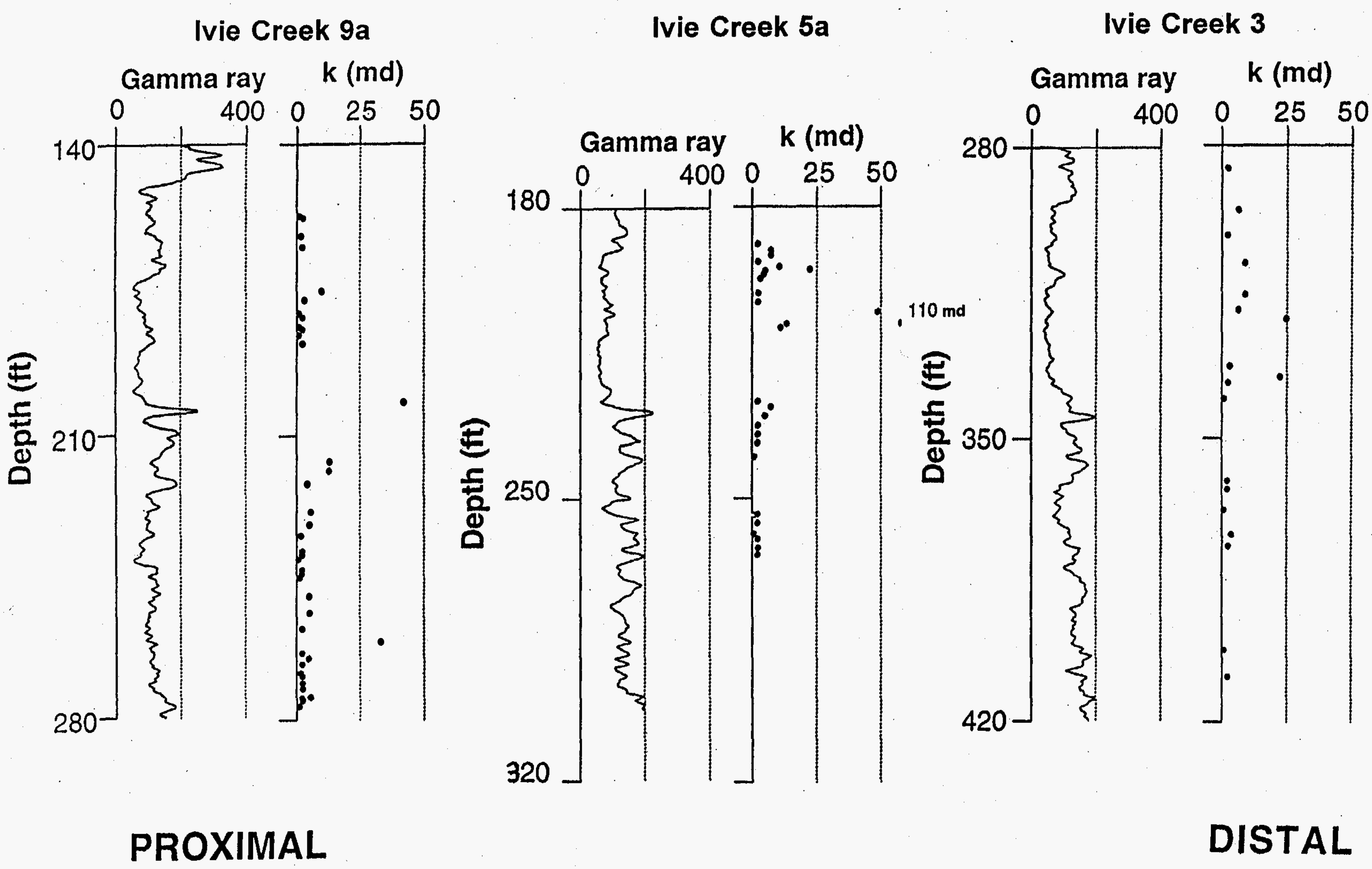


Figure 3.17. Reconnaissance permeability data and corresponding gamma-ray measurements, in API units, obtained for the Ivie Creek Nos. 9a, 5a, and 3 core holes. Plots are arranged to present changes in permeability (k, in millidarcies [md]) and gamma-ray profiles that are present when moving from proximal to distal positions within the Kf-1a parasequence.

provided a reasonable probability that we could obtain a detailed sequence of permeability variation with values above the resolution of the instrument (above 1-2 md).

Results of the detailed permeability testing and corresponding gamma-ray profiles are shown for Ivie Creek Nos. 9a, 5a, and 3 in figure 3.18. Visual inspection indicates that the gamma-ray profiles fail to capture variations that correspond to the detailed permeability variations. Additional work is required to more fully explore relationships between the permeability and gamma-ray results. The detailed mini-permeameter measurements capture characteristic patterns of permeability associated with internal elements of the Kf-1 and Kf-2 parasequence sets. Overall, the results are similar to those obtained from outcrop-derived core plugs.

3.5.2.3 Mini-Permeameter Data from Kf-1a Talus Slope Blocks. Due to difficulties in accessing the cliff face, twenty core plugs were collected during the latter part of 1994 from blocks on talus slopes that appear to have fallen from the Kf-1a parasequence in the eastern part of the study area. Permeability measurements taken from these core plugs should aid understanding of permeability variations in what is inferred to be the most proximal exposure of the Kf-1a delta-front sandstones.

Mini-permeameter tests on the talus slope core plugs, yielded the results shown in table 3.1. Samples were tested two ways. First, the samples were tested after only brushing off the drill cuttings (unprepared). Second, each sample was washed then dried in an oven for two days in an effort to ensure that all moisture was removed from the samples prior to testing. Apparently, for the samples tested, sample preparation method has little impact on permeability test results.

Permeability test results shown in table 3.1 are consistent with results obtained for transects T4 and T3 located at progressively more distal positions in the Kf-1a lithofacies (see figure 3.10 for transect locations). Although the T3 and T4 test results did yield k values in excess of 40 md, the higher permeability values typically fall in the range 10 to 20 md.

3.5.2.4 Results of 1995 Mini-Permeameter Data Collection. A large quantity of new permeability data was collected during the 1995 field season from both the Kf-1 and Kf-2 parasequence sets along 15 permeability transects (in addition to the seven transects from the 1994 field season) in the Ivie Creek case-study area (figure 3.10). A total of 1,954 tests were performed on 1,622 core plugs taken along the transects. Core plug locations in 1995 were selected to accomplish several goals: (1) better characterize permeability distributions within clinoforms found within the Kf-1a parasequence (figure 3.19), (2) evaluate both north-south and east-west variations in permeability structure within the Kf-2 parasequence set, and (3) evaluate two-dimensional and three-dimensional permeability anisotropy within different units of the Kf-2.

Core plugs were collected from typical Kf-1a clinoform features along six short vertical transects (T9, T10, T11, T12, T14, and T15) and one horizontal transect (T16) in the vicinity of the 1994 transects T3 and T4 (circled area in figure 3.10). In addition, a series of vertical and horizontal core plug pairs were collected near transects T9, T10, T12, and T14 to develop a better understanding of permeability anisotropy in the vertical plane associated with specific sedimentary structures found within the clinoforms.

The site of transect T9 was chosen to sample much higher permeability rocks within the Kf-1a than were found in the 1994 field season. Permeability values for several core plugs exceeded 300 md. More than 50 percent of the cores yielded permeability values in the 10 to

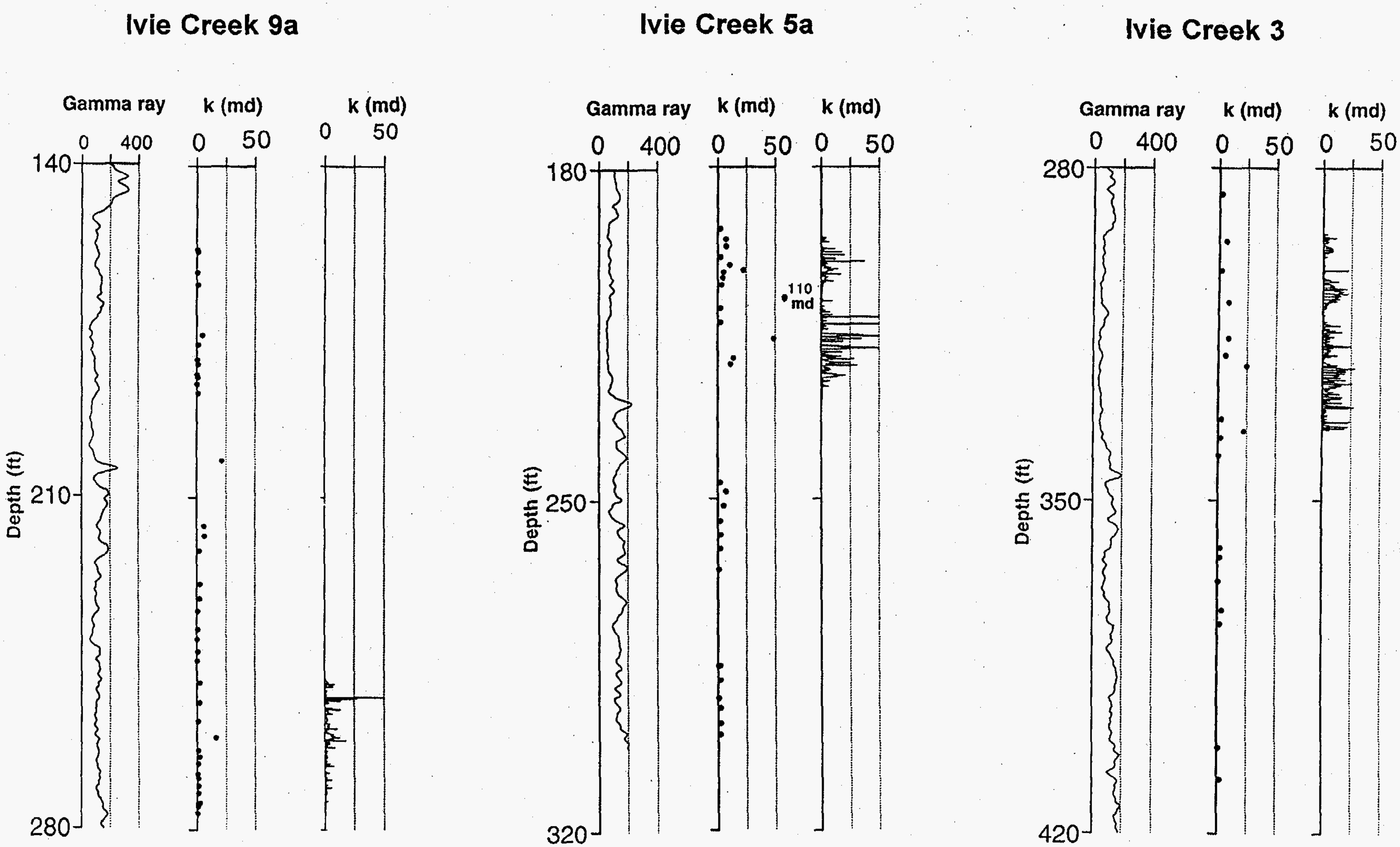


Figure 3.18. Gamma-ray profile, in API units, and results of both reconnaissance permeability tests, in md, on whole core (center graph) and automated permeability tests (right graph) on slabbed core for Kf-1 and Kf-2 sandstones for the Ivie Creek Nos. 9a, 5a, and 3 core holes.

Table 3.1. Results of permeability tests (k, in millidarcies [md]) for cores from talus slope blocks of the Kf-1a at the Ivie Creek case-study area.

Core No.	Unprepared k (md)	Rinsed and Dried k (md)
1	22.55	21.69
2	13.41	10.16
3	2.78	2.17
4	22.85	23.77
5	27.15	31.54
6	6.12	4.93
7	22.07	22.35
8	6.35	5.11
9	10.9	16.9
10	19.62	18.47
11	3.66	3.79
12	0.82	0.8
13	0.83	0.79
14	6.47	11.78
15	1.87	2.05
16	14.42	13.23
17	2.99	3.76
18	2.21	2.26
19	35.53	34.59
20	2.93	2.26

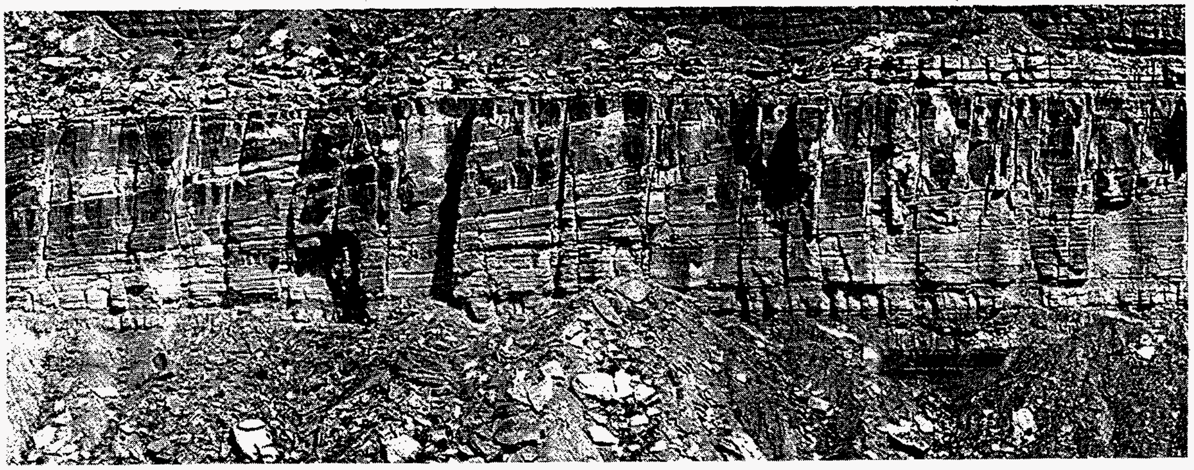


Figure 3.19. An east-west oriented photomosaic of the Ivie Creek case-study area, north to the view, showing typical clinoforms in the Kf-1a parasequence. Outcrop in photomosaic located in SW1/4SW1/4NE1/4 section 16, T. 23 S., R. 6 E., Salt Lake Base Line, Emery County, Utah.

40 md range. Although permeability results obtained for transects T12, T14, T15, and T16 did not generally exceed 100 md, more than 50 percent of the cores yielded permeability values in the 10 to 40 md range. These results suggest that higher-permeability regions are present at more proximal positions within the clinoform structures of the Kf-1a. Transects T10 and T11 yielded lower-permeability results that confirm the expectation that more distal positions within the clinoform structures contain relatively low permeability rocks.

North-south variations in permeability within the Kf-2 parasequence set are being assessed using the results of testing performed on core plugs collected at vertical transects T8, T20, and T22 (figure 3.10). In each case, the transects were placed to yield core plugs throughout the upper 50 to 100 percent of Kf-2. Horizontal core plugs were collected along transects T20 and T22 at 0.3-foot (0.1-m) spacing. Horizontal core plugs were collected along transect T8 at a 0.5-foot (0.15-m) spacing.

The south-to-north (proximal to distal) transition within the upper Kf-2 is clearly seen when comparing the results of testing T8 and T20 (figure 3.20). The 0.5 mile (0.8 km) distance between transects T8 and T20 leads one to infer that important permeability transitions can occur at typical interwell distances. West-to-east transitions in the upper Kf-2c parasequence are indicated by comparing the results obtained at T20 and T19 (figure 3.20).

East-west variations in permeability within the Kf-2 are being assessed using the results of testing performed on horizontal core plugs collected at vertical transects T13, T17, T18, T19, T20, T21, and T22 (figure 3.10). The relatively short vertical transects T18 and T19 were designed to provide insight into lateral variations inferred within the Kf-2c. Transects T13, T20, T21, and T22 were placed to yield core plugs throughout the upper 80 to 100 percent of Kf-2. Transect T17 was placed to characterize a short vertical distance through a high-permeability features found within the Kf-2b parasequence. Core plugs were collected at 0.3-foot (0.1-m) spacing along each transect. Although more detailed analysis must await the detailed geological model, it is clear that the anticipated west-to-east reduction in permeability was observed between T20 and T19.

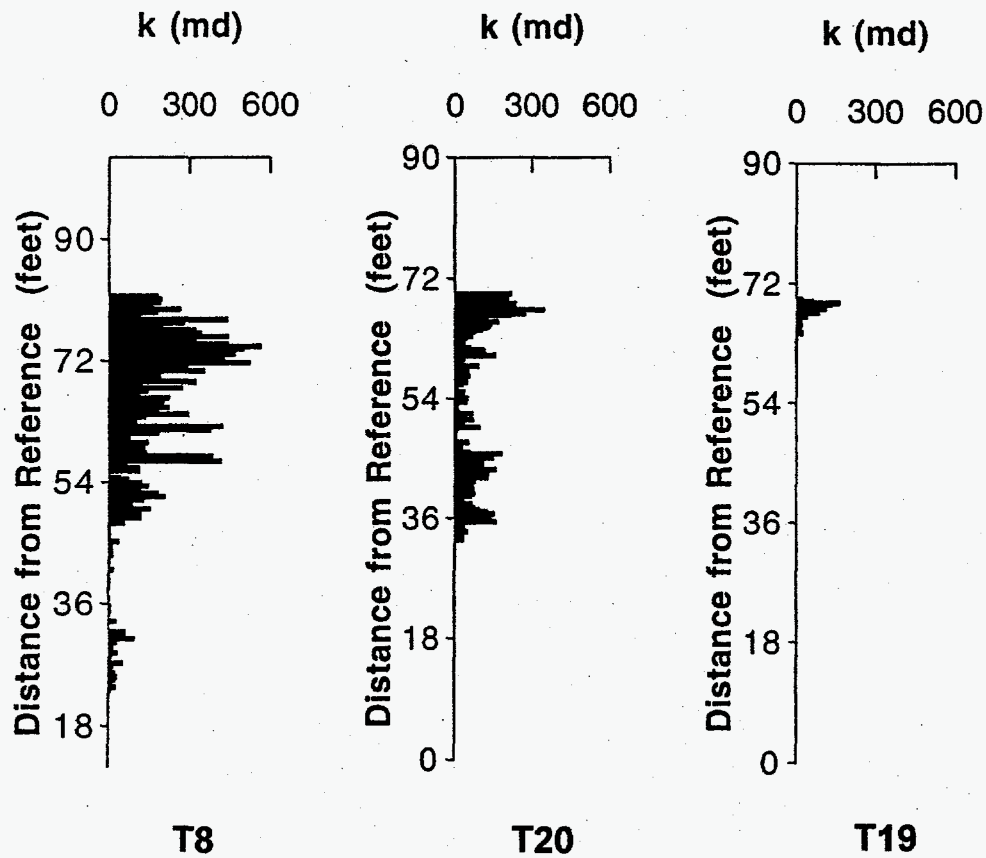


Figure 3.20. Permeability as a function of vertical position within Kf-2 sandstones at transects T8, T20, and T19.

Core plugs were also collected from several locations in the Kf-2 to obtain insight into the two-dimensional and three-dimensional permeability anisotropy associated with specific sedimentary structures. The DC series of plugs (figure 3.10) were collected to study the influence of cross bedding and soft-sediment deformation structures on anisotropy. Preliminary interpretation suggests that permeability anisotropy is less than one order of magnitude and may range from 2 to 5.

In addition to the horizontal core plugs, vertical core plugs were collected from the upper 60 percent of transect T8, at a 0.5-foot (0.15-m) spacing, to provide insight into the vertical anisotropy variations associated with the more permeable units of the Kf-2. Permeability profiles obtained for both the horizontal and vertical core plugs are shown in figure 3.21. Although the overall pattern of decreasing permeability with increasing depth is similar in both profiles, anisotropy is difficult to assess. Figure 3.22 shows that sometimes the vertical core-plug tests provide lower permeability values than the horizontal core-plug tests and sometimes the reverse is true. On average over the entire profile, however, the mean bulk permeability of the horizontal values (134 md) is similar to the mean of the vertical values (128 md). A cross-plot of permeability values obtained for adjacent horizontal and vertical core plugs (figure 3.23) shows that permeability values are often similar for each core plug pair or the horizontal value exceeds the vertical value by about a factor of 2.

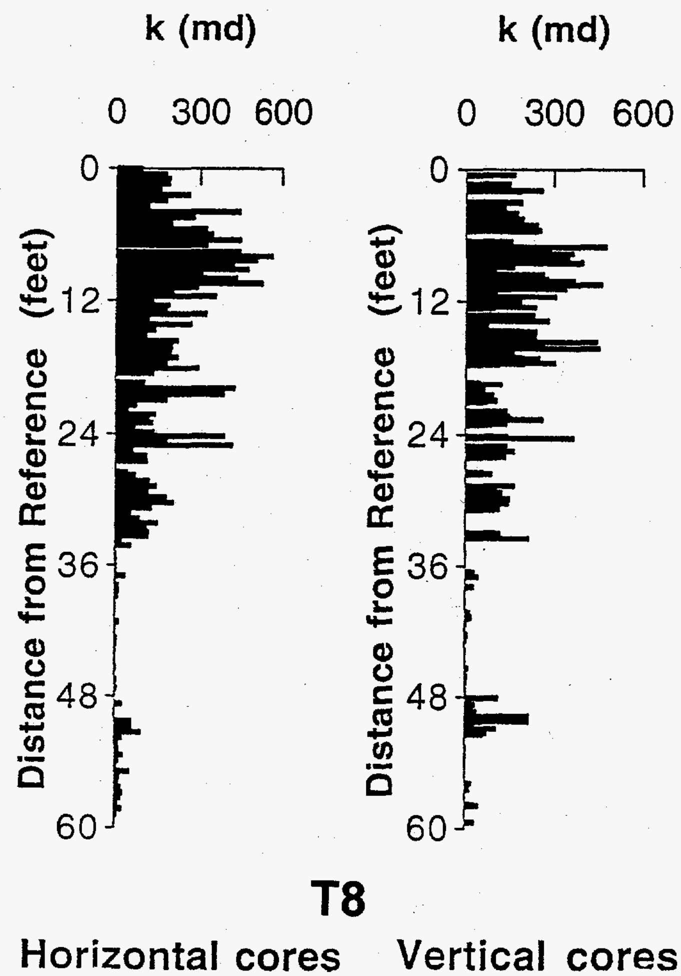


Figure 3.21. Permeability as a function of vertical position within Kf-2 sandstones at transect T8. Results obtained for both horizontal and vertical core plugs are shown.

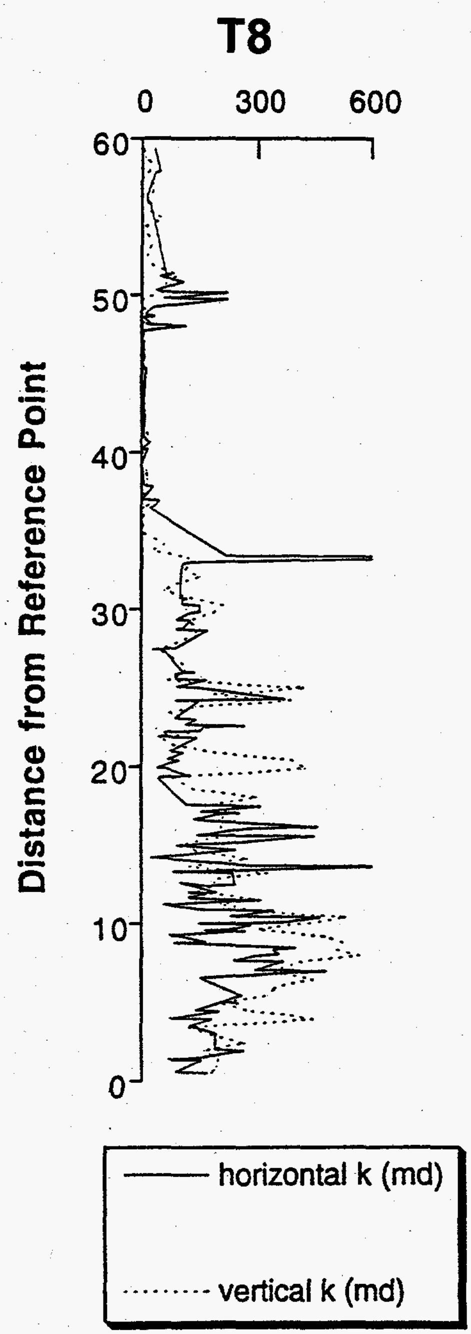


Figure 3.22. Comparison of permeability values for horizontal and vertical core plugs obtained within the Kf-2 at transect T8.

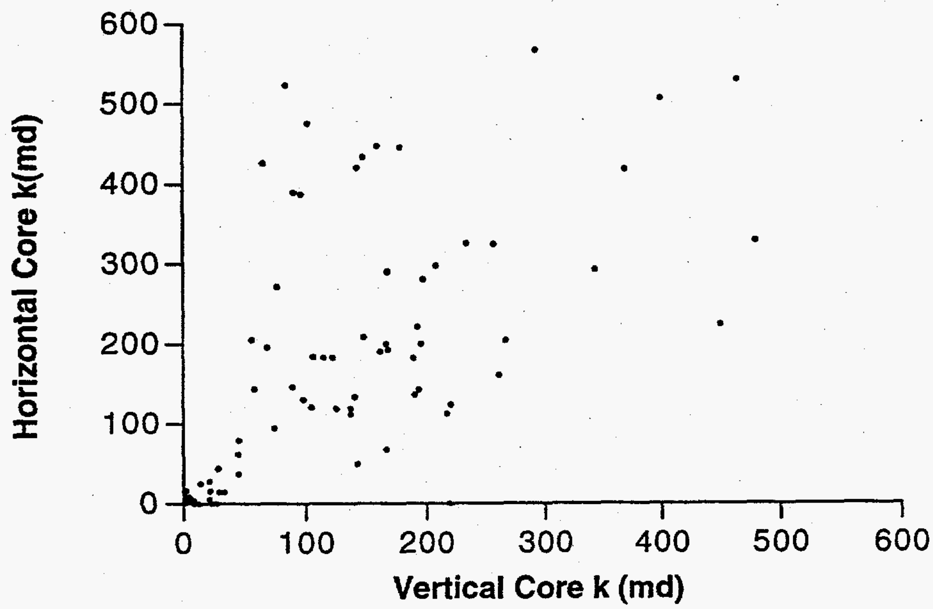


Figure 3.23. Crossplot showing permeability for horizontal and vertical core plugs drilled at approximately the same vertical position within Kf-2 at transect T8.

In the final evaluation of the permeability profiles for transects T8, T20, and T19 (figure 3.20), it is important to note that much higher permeabilities are found in the more wave-modified facies of the Kf-2 when compared to the fluvial-dominated facies of the Kf-1. Even in the absence of correlations with geological data it is clear that strong vertical variations in permeability are indicated within the Kf-2. It is expected that many distinct permeability transitions will correspond to specific stratigraphic boundaries.

3.6 Petrophysical and Geostatistical Analysis

The objective of the petrophysical analysis of the Ferron Sandstone is to characterize the basic petrographic parameters, at the sweep scale or smaller, of the primary reservoir lithofacies typically found in fluvial-dominated reservoirs. Core plugs and thin sections selected from outcrop and core-hole sampling in the Ivie Creek case-study area were analyzed to determine vertical and lateral variations in the petrophysical properties. The interrelations among these properties in the Kf-1 and Kf-2 parasequence sets are being evaluated.

Spatial variations in lithofacies, stratigraphic thickness, sedimentary structures, and permeability data are being quantified through geostatistical analysis. The statistical variability of this information is needed for defining individual petrophysical units within the Ivie Creek case-study area and for predicting the three-dimensional distribution of each unit. The statistical modeling is an important step in developing procedures for "scaling up" from the observational scale to that of a typical reservoir.

3.6.1 Methods

Petrophysical measurements were made on 182 Ferron core plugs collected during the 1994 field season using Amoco Production Research's Geoscience Evaluation Module (GEM). The measurements consisted of: (1) saturated, dry, and grain densities (figure 3.24a), (2) effective and Boyle's Law porosities (figure 3.24b), (3) air permeability (figure 3.24c), (4) magnetic susceptibility, (5) qualitative and quantitative mineralogy, (6) compressional and shear wave velocities as a function of effective pressure, and (7) thin-section-image analysis. The specific details of the GEM procedures used are given by Sondergeld and Rai (1988, 1993a, and 1993b). Velocities were measured using the pulse transmission technique of Schreiber and others (1973) and mineralogy was determined using a transmission infrared technique described by Griffiths and de Haseth (1986). Thin sections were made and described from selected core plugs having varied lithology, clinoform position, and permeability values in the Kf-1a parasequence.

Geostatistical analysis required quantification of field data and synthesis of defined lithofacies. The UGS database, composed of geological and petrophysical megascopic observations within the defined lithofacies, was used to generate graphical representations showing spatial variations and relationships of sedimentary structures, grain size, and sand/shale ratios.

3.6.2 Results of Petrophysical Analysis

The major findings from preliminary analyses of these data are: (1) microfractures affect the compressional and shear-wave velocities of all samples; however, microfractures have little significant influence on permeabilities, except perhaps for the least permeable samples; (2) permeability is very closely related to porosity, with a linear relationship between porosity and the logarithm of permeability (figure 3.25a) that is roughly similar to those found from other high-porosity sedimentary rocks. That relationship, however, varies so much between formations in different parts of the world that it must be locally determined. The relationship for the Ferron Sandstone is much better than was anticipated based on porosity/mini-permeameter measurements made at the University of Utah (figure 3.25b), and it extends to permeabilities far below the 2-md threshold for useful mini-permeameter measurements. This relationship means that permeability can be estimated for all core-plug samples for which measured porosity has been obtained. In addition, permeability logs can be estimated from density well logging; and (3) the dominant mineralogic control on velocity, porosity, and therefore permeability appears to be calcite cementation, not clay content, at least for the low-clay samples that have been measured to date. Quartz cementation probably also affects these parameters, but the Amoco measurements cannot distinguish quartz grains from quartz cement. Clay content certainly does decrease porosity and permeability, but this influence is not as linear as had been anticipated. For example, comparisons of outcrop gamma-ray measurements with mini-permeability results, as well as comparisons of Amoco determined mineralogy to Amoco determined permeability, show only a rough, qualitative correspondence. Consequently, one cannot expect to use the gamma-ray traverses to quantitatively estimate permeability, though they can indicate locations of minimal-permeability shales and fluid-flow bounding units.

In thin section the samples are quartz-rich sandstones with a complex diagenetic history. The sandstones show considerable compaction (squashed rock fragments and concavo-convex contacts) and little remaining primary porosity (figure 3.26). Where porosity is present, it is

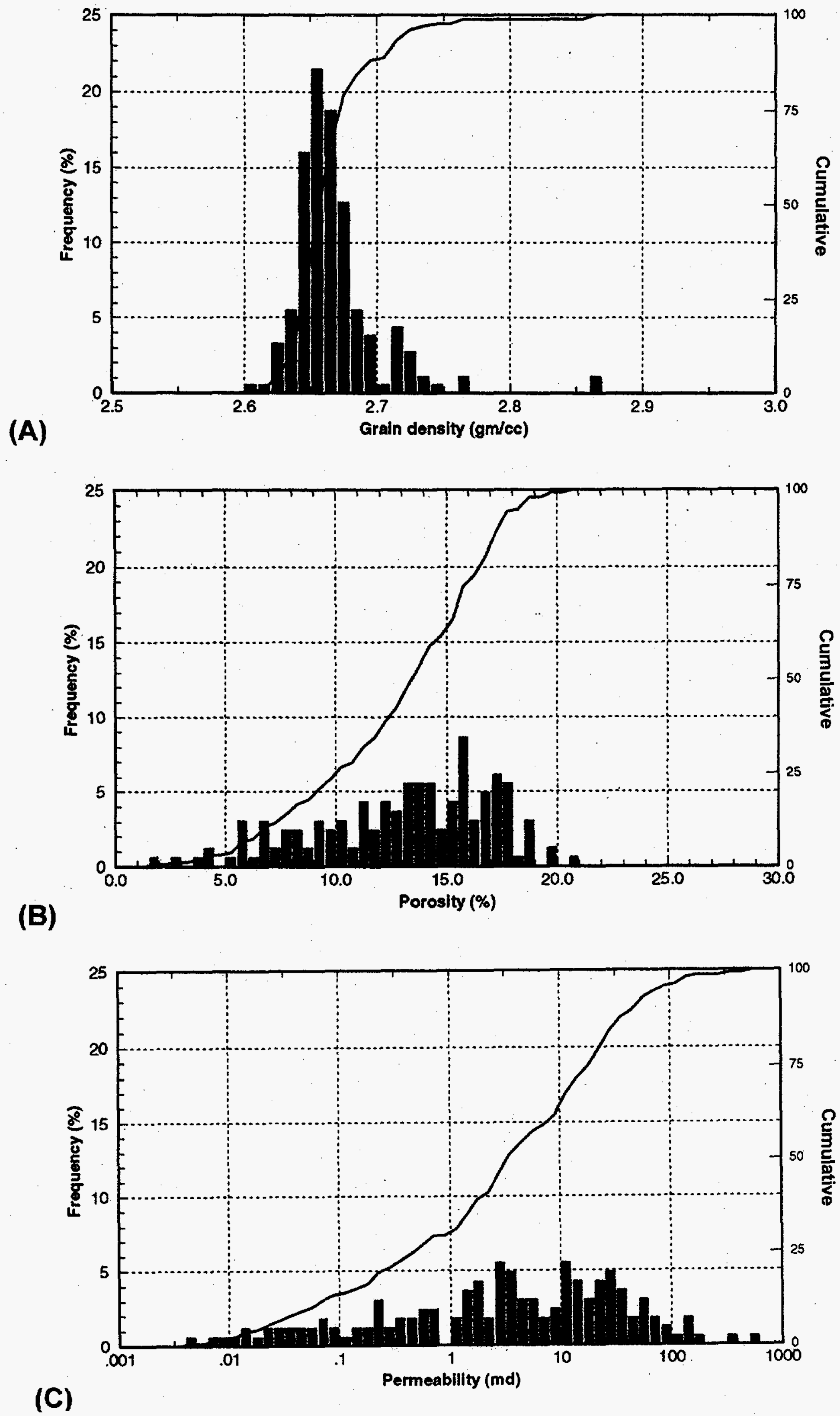
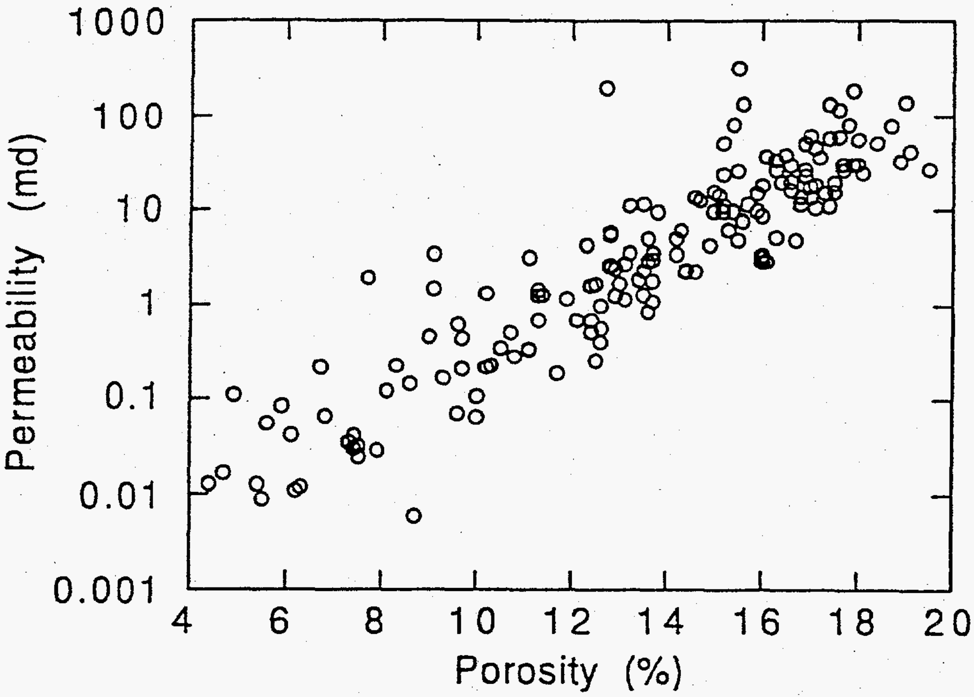
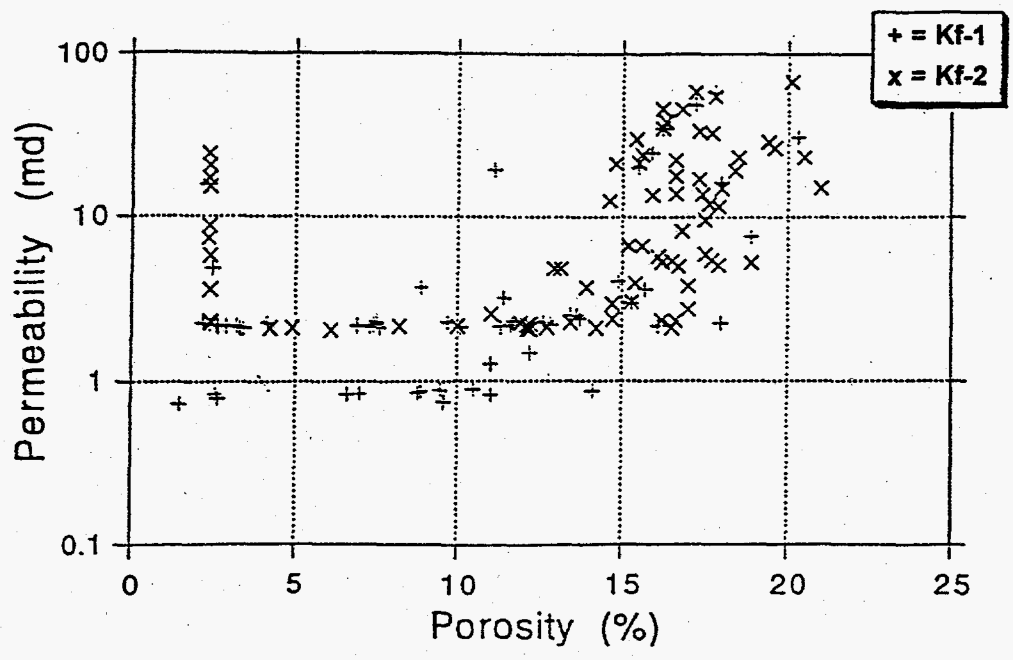


Figure 3.24. Histograms of: (A) grain densities, (B) porosity, and (C) permeability, along with their respective cumulative frequency distributions (sloped line) for 182 Ferron core plugs collected during the 1994 field season and processed through Amoco Production Research's Geoscience Evaluation Module (GEM).



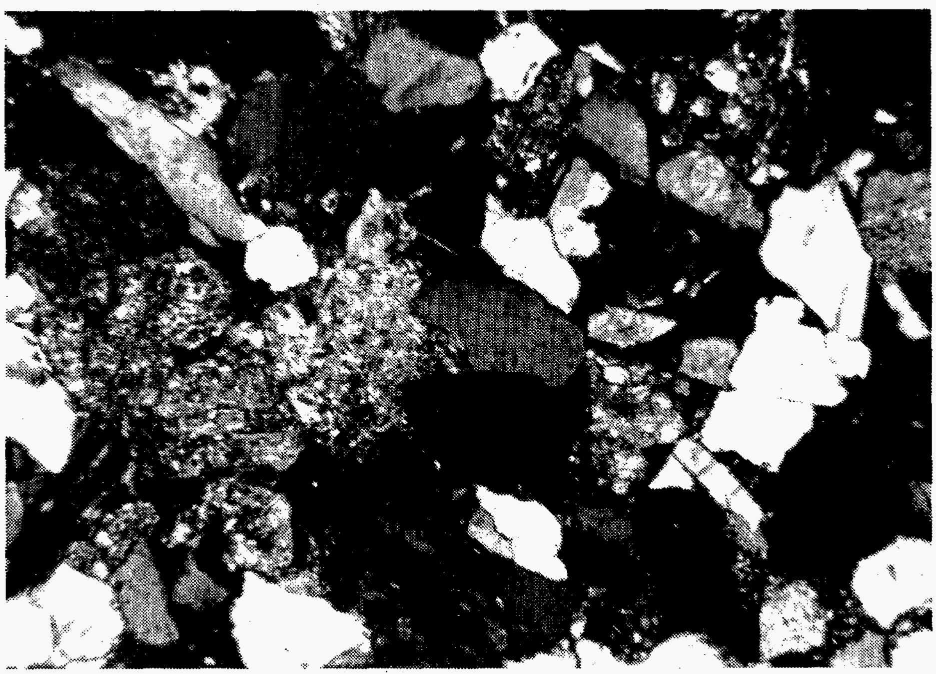
(A)



(B)

Figure 3.25. Relationship between permeability and porosity, based on core-plug measurements of the Ferron Sandstone: (A) overall permeability and porosity from GEM processing. (B) permeability and porosity comparing the Kf-1 and Kf-2 sandstones processed at the University of Utah (where permeability was measured using a mini-permeameter). Note the inaccuracy of the mini-permeameter for <5 md, and the strong linear relationship identified by the GEM measurements.

(A)



(B)

Figure 3.26. Photomicrographs of a thin section from a permeability plug. Field of view in the horizontal direction is approximately 2 mm across. (A) Plane light view; squashed rock fragment in the left center indicating a high degree of compaction. The porosity is intergranular, much of which is probably secondary from the dissolution of carbonate cements. (B) Crossed nicols view of A.

largely secondary porosity developed from the dissolution of carbonate and dolomite cement. Early cements appear to be calcite, dolomite, and kaolinite. Iron (hematite) cement appears to be the last diagenetic cement. As expected medium- to coarse-grained sandstones have better porosity than fine-grained sandstones to siltstones.

An "unexpected" find was from a rippled sandstone with a relatively high permeability value that can be attributed to small (microscopic) veins (approximately 0.2-0.4 mm thick) of gypsum. These gypsum veins run parallel to the bedding and contain porosity in between some of the gypsum crystals (figure 3.27). These veins probably act as conduits for fluid migration despite the fact that the sample is fine-grained with its intergranular porosity occluded by calcite and dolomite cements. The presence of the gypsum was recognized by its optical properties in thin sections, and then further verified by x-ray diffraction (XRD) analysis. Bulk sample XRD analysis also confirmed the presence of identified grain mineralogy (quartz, microcline, albite, and mica) as well as the diagenetic phases (gypsum, calcite, dolomite, and kaolinite cements) (figure 3.28).

3.6.3 Results of Geostatistical Analysis

The Kf-1a parasequence in the Ivie Creek case-study area has been subdivided into three general facies: proximal delta front, medial delta front, and distal delta front. A detailed block of outcrop from the south-facing Ivie Creek photomosaic (figures 3.4 and 3.19) was selected for statistical analysis. The net footage and relative percentage of each sedimentary structure, biologic structure, average megascopic grain size, and sandstone/shale ratio were calculated for the three facies (figures 3.29-31). Horizontal bedding is the most common sedimentary structure in all three facies (figure 3.29). Ripple cross-laminated beds are the second most common sedimentary structure in the distal delta-front and medial delta-front facies while trough cross-stratified beds are second in proximal delta-front facies. As expected, the proximal delta-front facies contains the coarsest material and highest net portion of sandstone while the distal delta-front facies contains the finest material and lowest portion of sandstone (figures 3.30 and 3.31).

3.7 References

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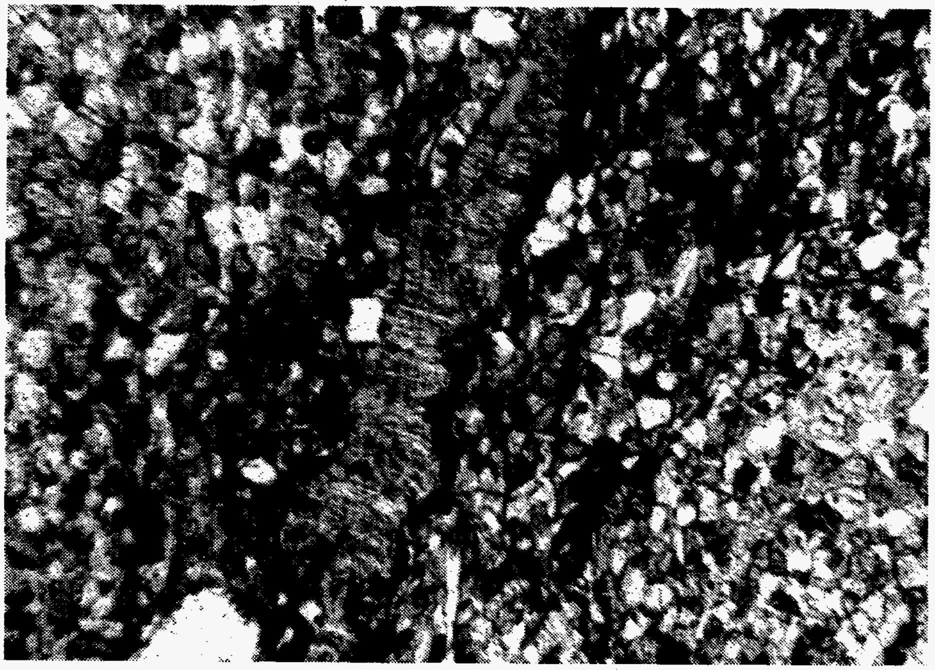
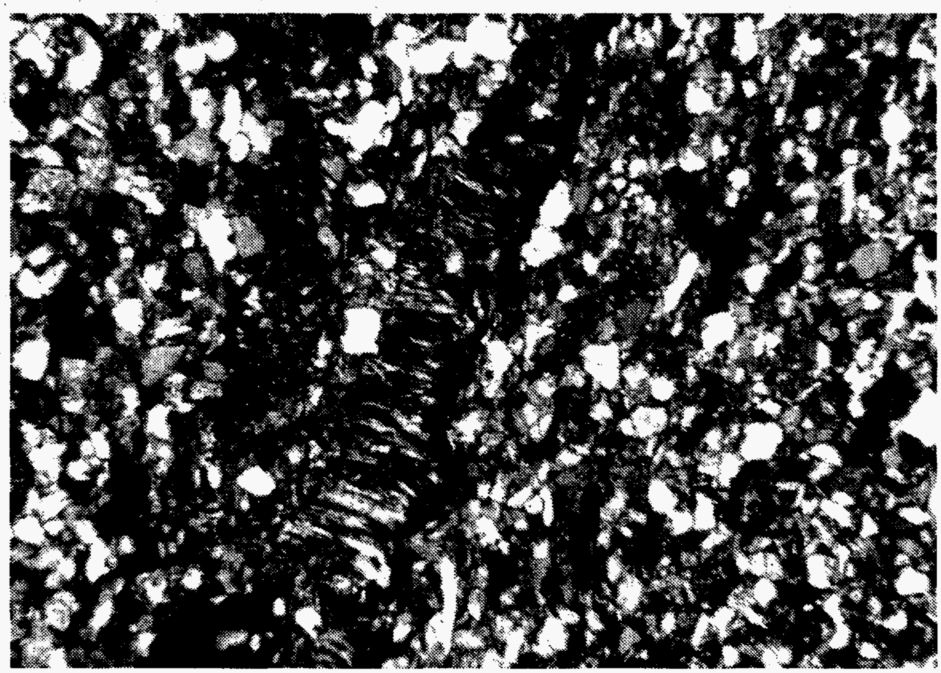


(A)



(B)

Figure 3.27. Photomicrographs of a thin section from a permeability plug. Field of view in the horizontal direction is approximately 2 mm across. (A) Plane light view; gypsum vein in center of photo. Note the organic material along right side of the vein and the presence of secondary porosity from the dissolution of gypsum. (B) Crossed nicols view of A.

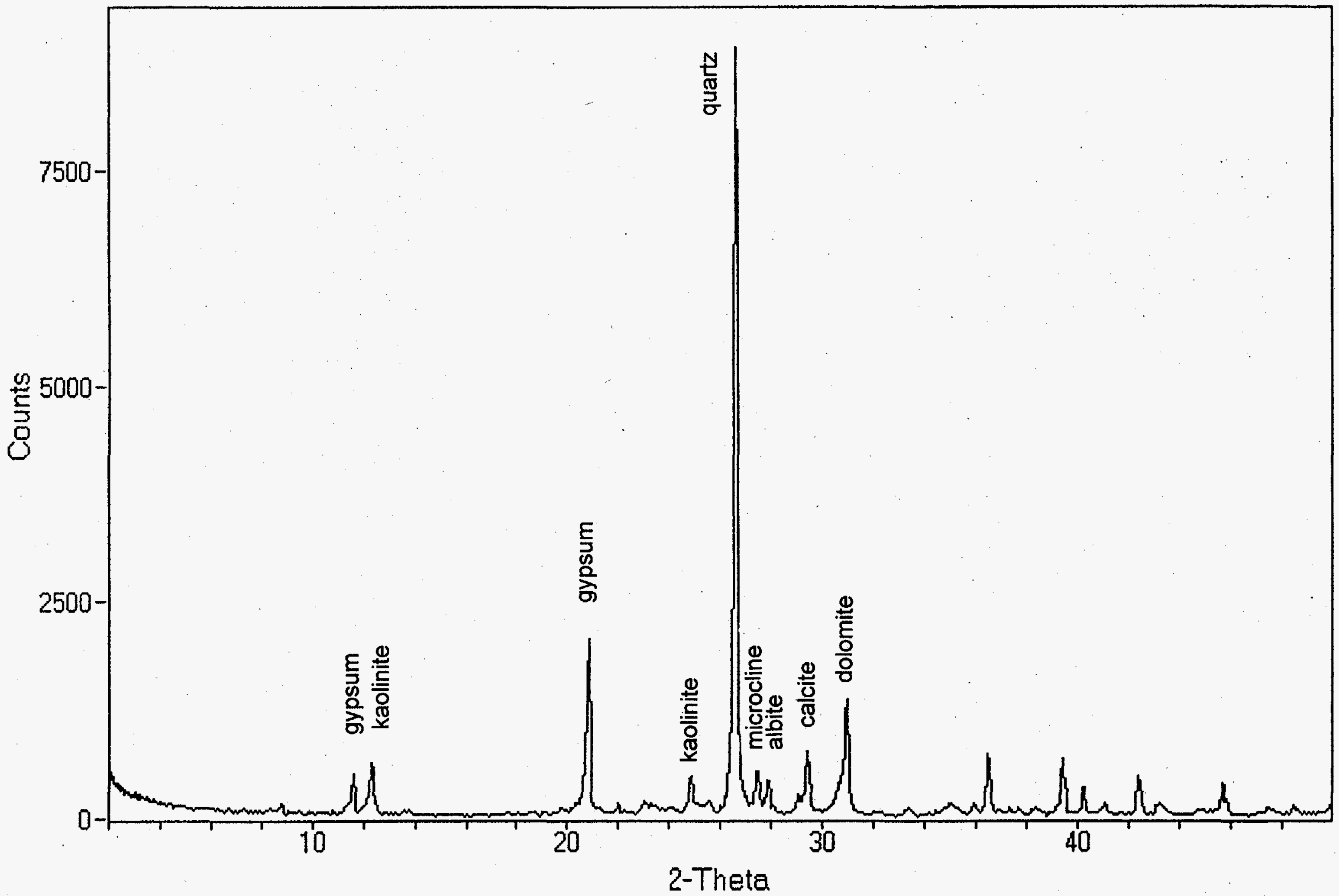


Figure 3.28. XRD pattern of sample shown as a thin section in figure 3.27, indicating the presence of gypsum as well as other mineral phases.

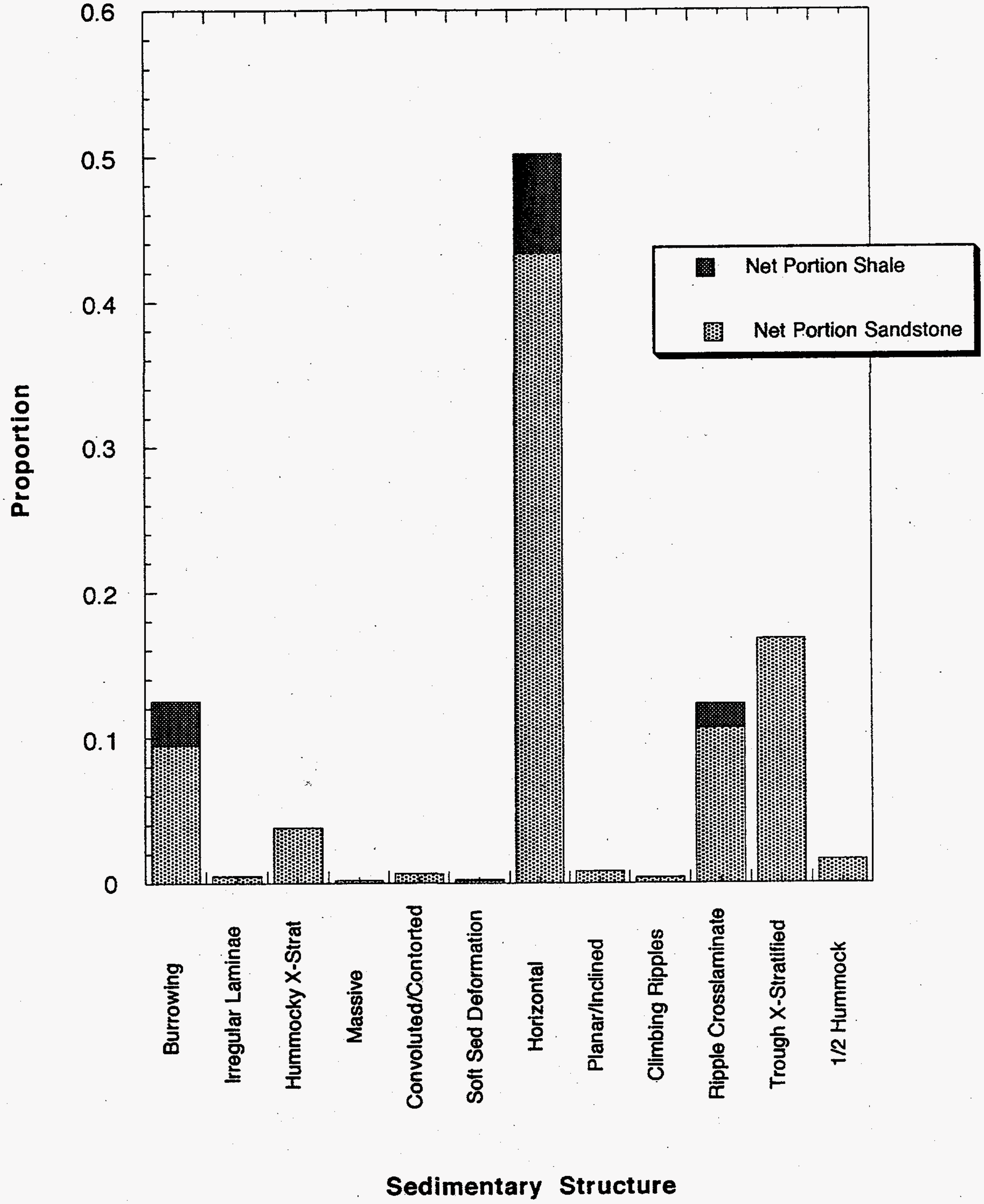


Figure 3.29. Statistical analyses of a detailed block of the Kf-1a parasequence in the Ivie Creek case-study area showing net sandstone versus sedimentary structure.

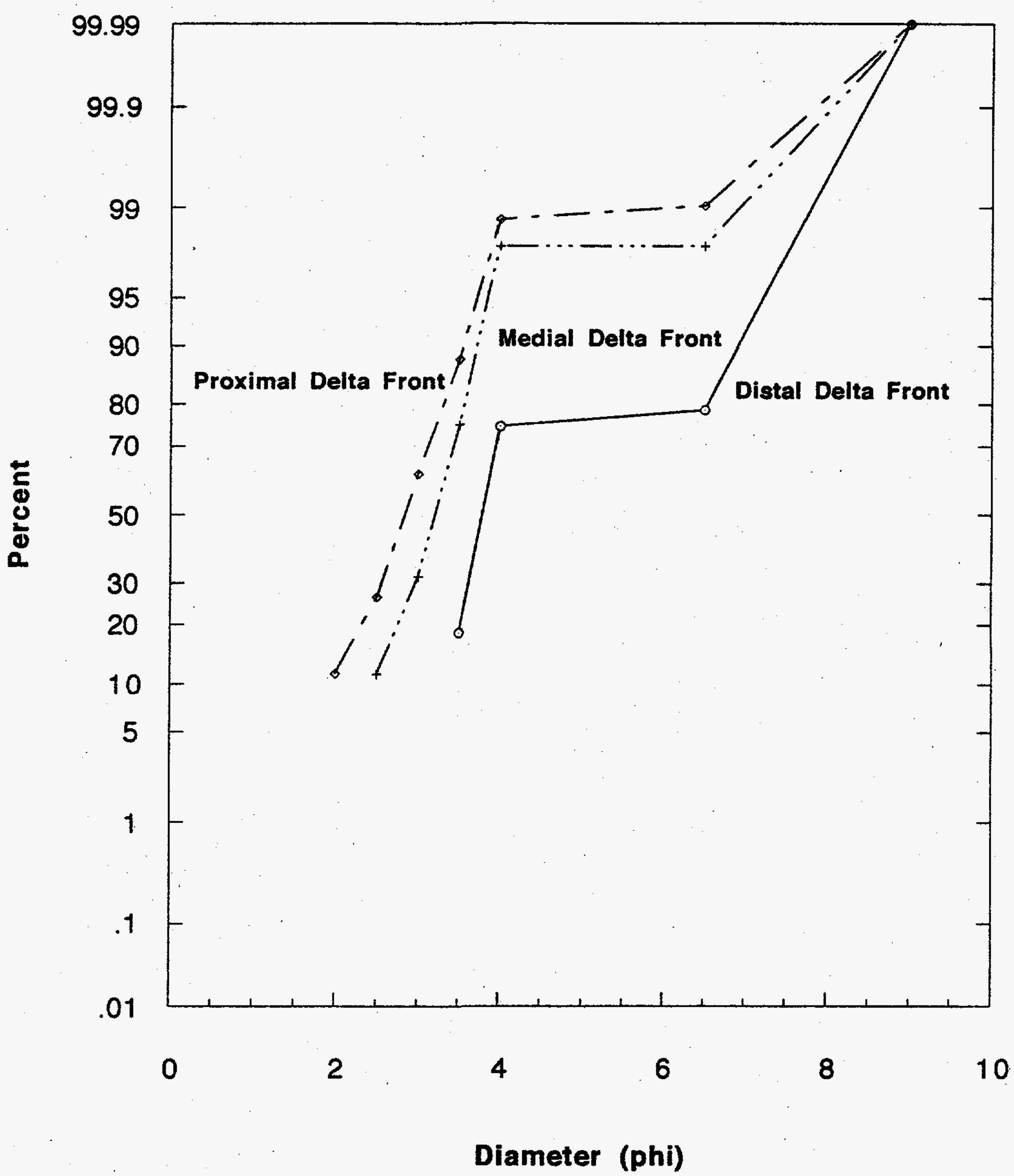


Figure 3.30. Statistical analyses of a detailed block of the Kf-1a parasequence in the Ivie Creek case-study area showing cumulative frequency of grain size (based on average megascopic observations) for each facies.

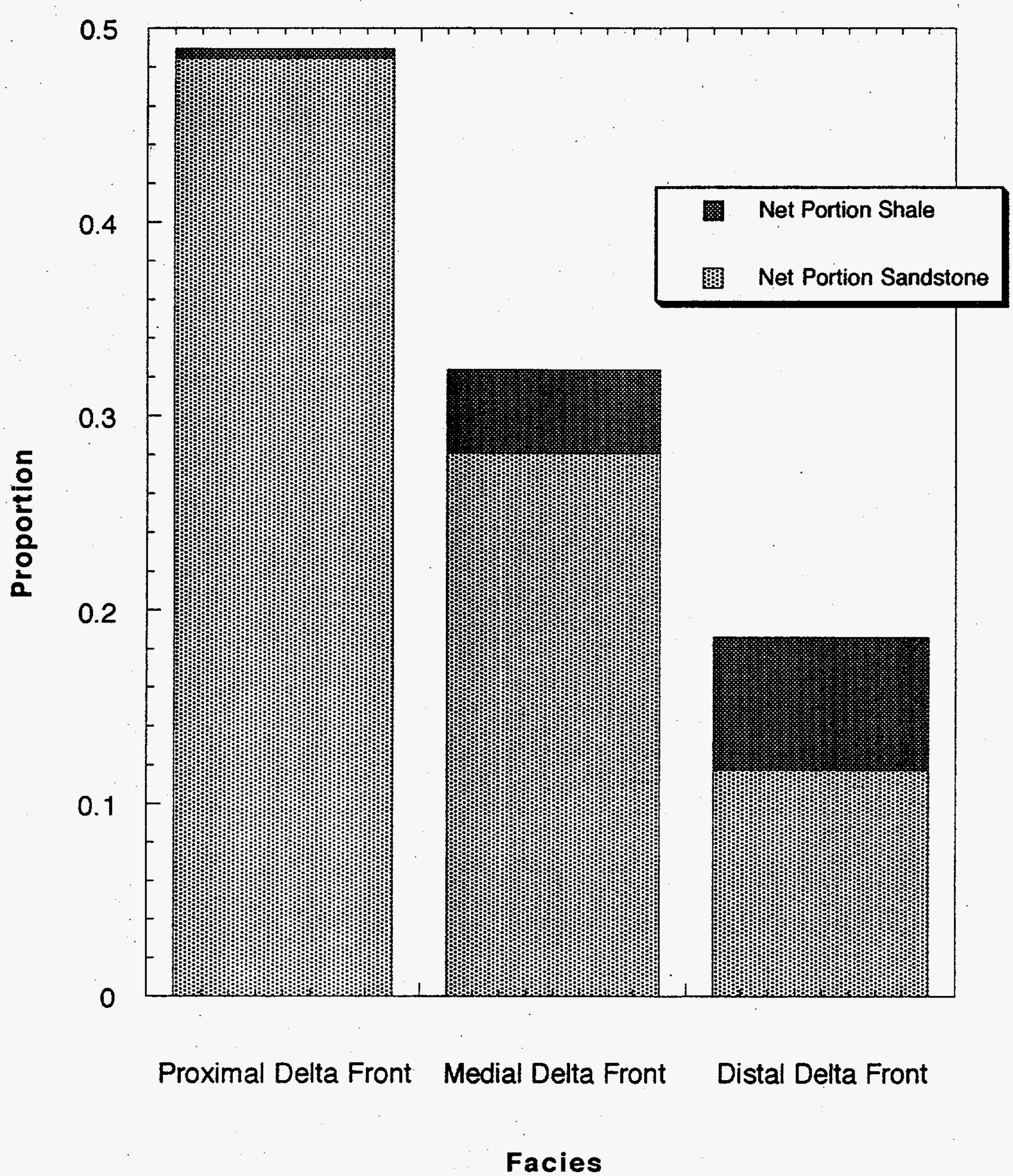


Figure 3.31. Statistical analyses of a detailed block of the Kf-1a parasequence in the Ivie Creek case-study area showing net sandstone versus facies.

4. STOCHASTIC MODELING AND FLUID-FLOW SIMULATION

A 2-mile by 2-mile (3.2-km by 3.2-km) block (figures 3.7 and 4.1) was selected as the site where detailed, three-dimensional geological and petrophysical models will be developed as input to a series of reservoir simulations for the Ivie Creek case-study area. Data needed for these models was obtained by geological mapping, outcrop gamma-ray logging, petrophysical measurements on core plugs, and mini-permeameter testing of slabbed core from the Ivie Creek Nos. 3, 5a, and 9a. The simulation study area encompasses both river-dominated and wave-modified sedimentary facies (Kf-1 and Kf-2 parasequence sets) with thickness less than 200 feet (61 m). In addition, a well-defined distributary channel cuts through the upper Kf-2 parasequence set (figure 3.6).

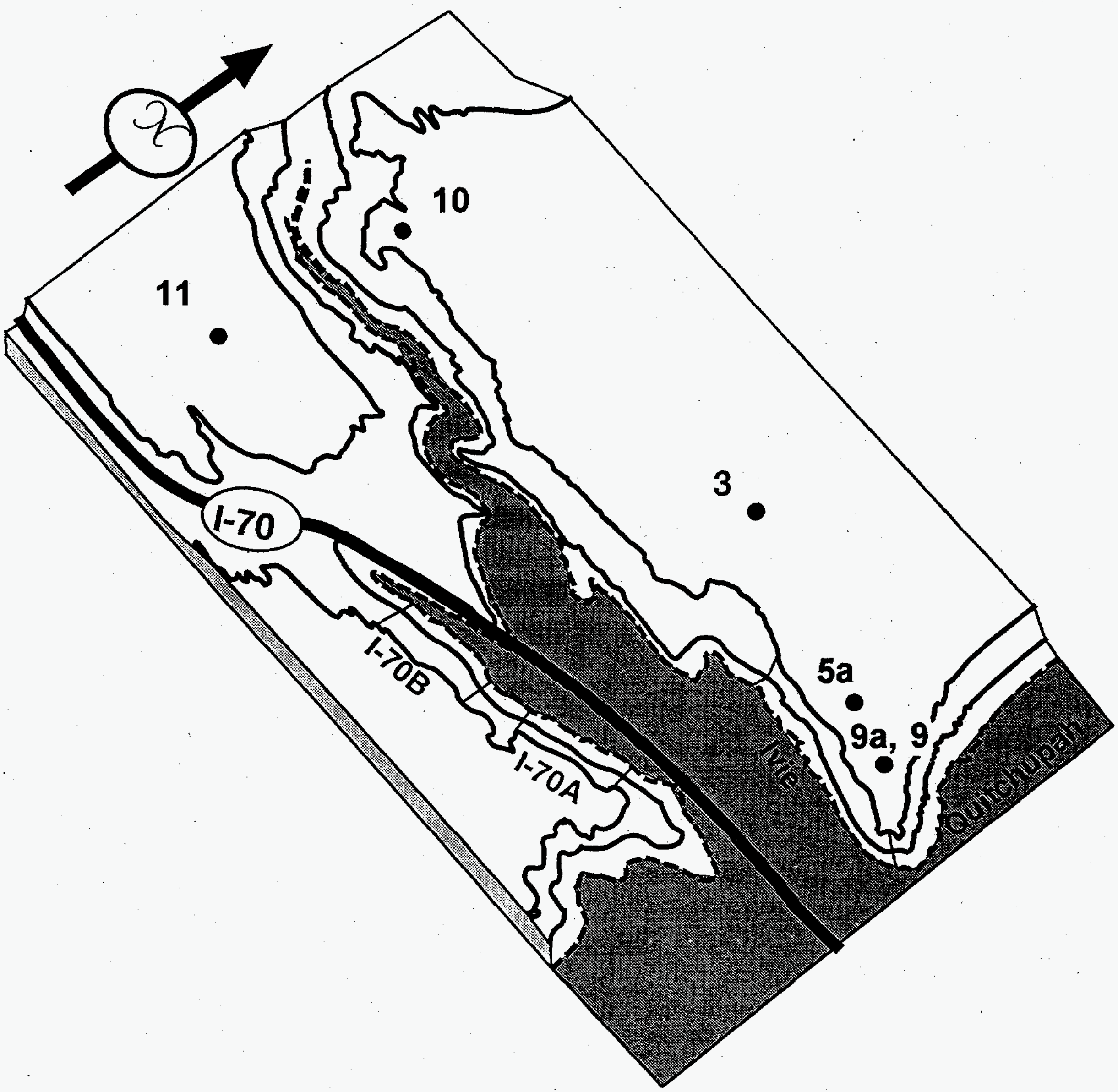


Figure 4.1. Perspective view of the Ivie Creek case-study area with core-hole locations shown.

We anticipate simulating fluid flow through at least three rock volumes at two different scales. We will begin at the interwell scale with a very detailed model of the Kf-1a clinoform features found in the vicinity of core holes Ivie Creek Nos. 5a and 9a. At the larger, reservoir scale we will simulate the dynamic interaction between Kf-1, Kf-2, and the associated distributary channel. A scaling-up procedure will be used to homogenize and transfer petrophysical information from the very detailed interwell-scale models to the reservoir scale.

4.1 Methods

A combination of methods will be used to develop the three-dimensional geological models needed to define permeability and porosity distributions in the reservoir simulator. A deterministic approach will be used to build geological models for each of the three model volumes. This effort involves manual determination of facies architecture within the three-dimensional volumes. Once the architecture is determined, values of permeability and porosity are stochastically distributed according to "rules" derived from outcrop observations.

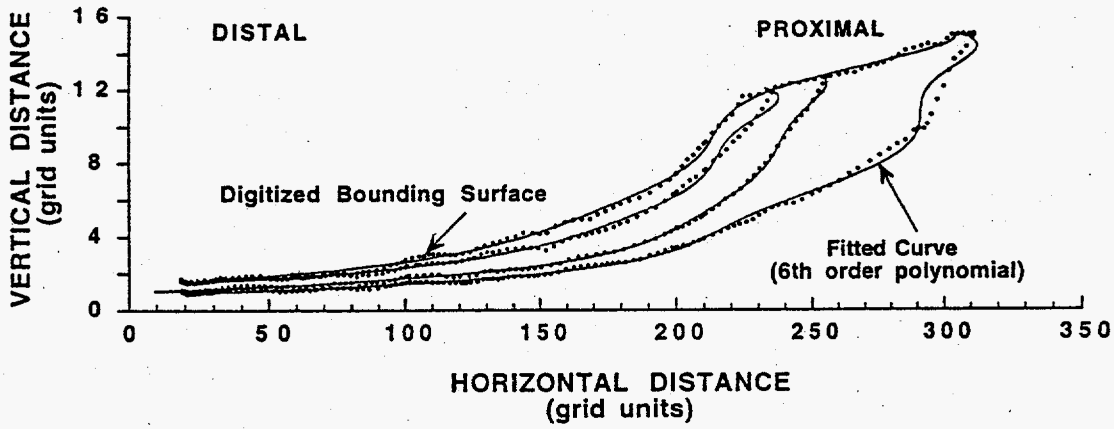
A first step in the process needed to develop stochastic rules is shown in figure 4.2. The interpretations of three characteristic inclined bedforms observed at the Ivie Creek case-study area have been digitized and stored for analysis (dotted lines shown in figure 4.2A). The solid lines shown in figure 4.2A indicate that mathematical functions could be derived to recreate similar inclined bedforms in a synthetic two-dimensional model. Although fitting a sixth order polynomial to the digitized curves represents none of the physical processes involved in creating the bedform, a simple fitting process like this could provide a satisfactory basis for generating a set of similar bedforms.

Information contained in figure 4.2B indicates general trends in factors, that reflect the origin of the bedforms, which control permeability distributions within the inclined bedforms. We anticipate that further study will show that these preliminary inferences will lead to workable rules for generating synthetic permeability distributions within specific facies elements.

The following section outlines the modeling procedure and illustrates a test of the methodology using a two-dimensional data set collected by Barton (1994) at the Cedar Ridge II location approximately 5 miles (8 km) northeast of Ivie Creek. When completed, our modeling study will include a significant three-dimensional modeling component at the Ivie Creek case-study area. The modeling methodology was developed and tested at Mobil's Exploration and Producing Center in Dallas, Texas. Modeling steps include the following:

A. Construct a two-dimensional, deterministic, geologic model.
B. Use outcrop-based petrophysical data to select flow units and construct a two-dimensional model of flow unit architecture that corresponds to the deterministic geologic architecture.
C. Assign permeability values within each architectural element using a stochastic modeling approach.
D. Perform fluid-flow simulations that illustrate the influence of reservoir architecture and permeability structure on oil production.
E. Use a homogenization approach to average and upscale the detailed permeability structures.

(A)



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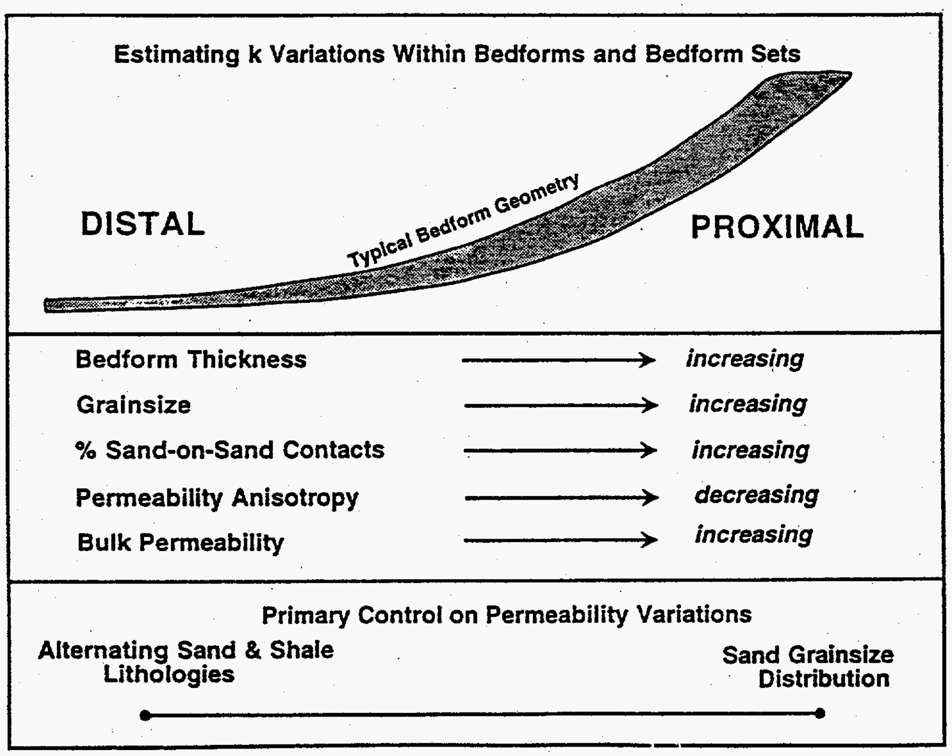


Figure 4.2. Developing rules for representing clinoform features within the Ivie Creek case-study area Kf-1a parasequence involves: (A) digitizing typical bounding surfaces to derive geometrical rules, and (B) identifying geological and petrophysical factors that vary in characteristic ways within individual bedforms and bedform sets. K = permeability in md.

4.1.1 Steps A and B - Construct Two-Dimensional Geological and Flow-Unit Models

In developing and testing our modeling procedures we used permeability and architectural data from the Cedar Ridge II location presented by Barton (1994) (figure 4.3). This data set was selected because architectural data collected at the Ivie Creek case-study area by the project team during the 1994 field season were not yet available. Barton's Cedar Ridge II data were particularly attractive because the field site is located within the Kf-5 parasequence set that, at one time, was considered as a possible target for detailed study during the UGS Ferron Sandstone project. Because the project team has since determined that the Ivie Creek case-study area will provide sufficient insight into the reservoir characteristics of several parasequence sets, the Cedar Ridge II location will not receive focused geological study during the project.

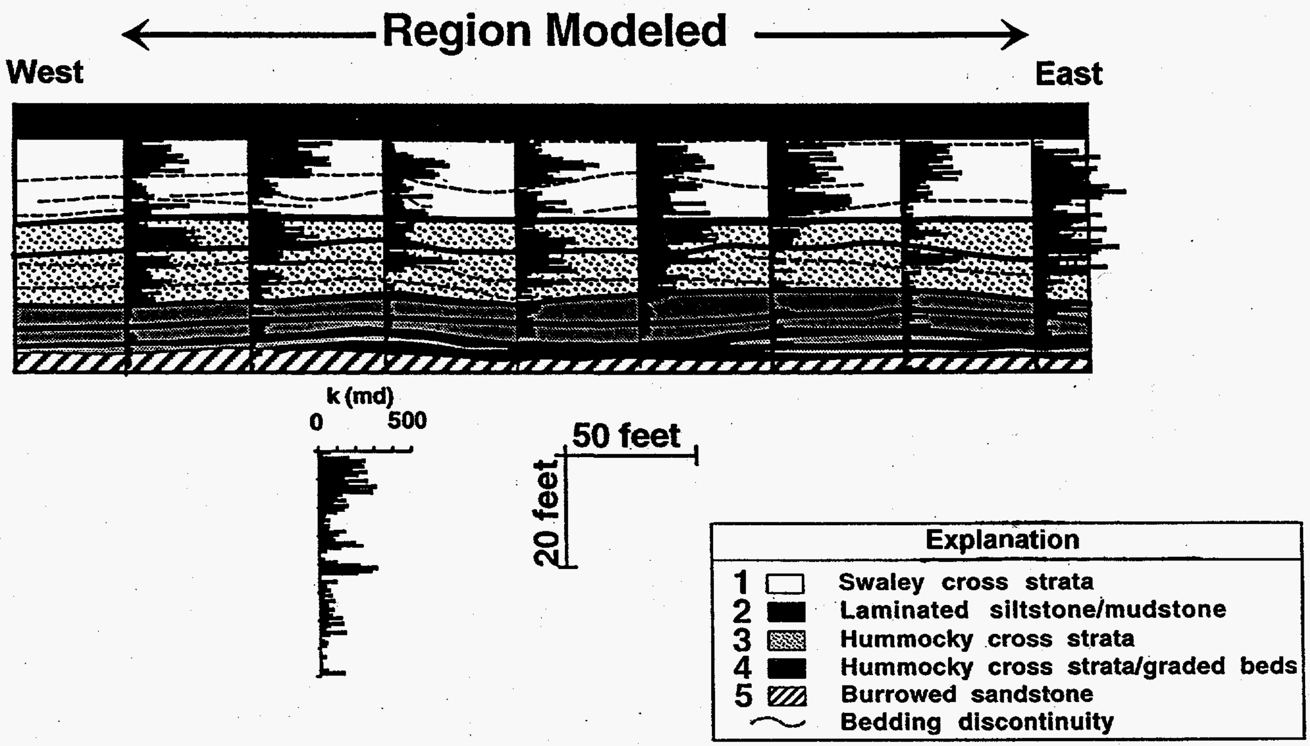
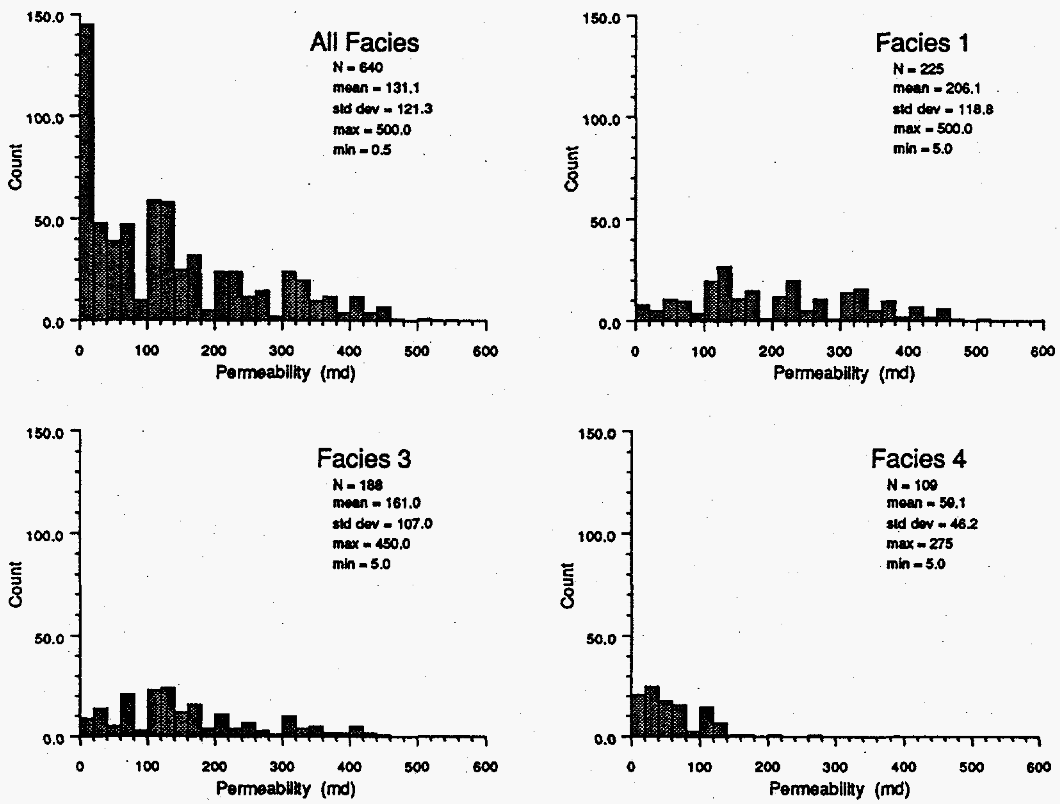


Figure 4.3. Facies architecture and permeability distribution at the Cedar Ridge II location (after Barton, 1994).

Figure 4.3 shows a strike-oriented cross section of laterally continuous Kf-5 delta-front deposits with lower to upper shoreface facies associations. A strong, layered appearance is exhibited in this strike-oriented section. Detailed permeability measurements made by Barton (1994) on the vertical outcrop face indicate an increasing upward trend that is very consistent across the entire section (figure 4.3). Maximum permeability values range up to 450 md and are found in the upper, swaley cross-stratified unit.

The first step in characterizing the permeability structure of a lithofacies map or section is to plot permeability values in both histograms and variograms to get quantitative variations of permeability in each facies. Permeability values associated with each of the more permeable facies types shown in figure 4.3 are plotted as histograms in figure 4.4. It is important to note that the histogram plotted for samples obtained from all facies has a log-normal character. This result is consistent with the common observation that permeability histograms developed from reservoir data can often be fitted to a log-normal distribution. The individual histograms plotted for facies 1, 3, and 4; however, each appear to deviate from the log-normal distribution and may be better fitted by a normal distribution. This result, obtained because a large number of permeability values are available within each facies, suggests that the log-normal character typical of reservoir permeability values may reflect the mixing of different permeability distributions associated with each of the different facies.



Histograms for Facies 2 (k = .5 md) and Facies 5 (k = 10 md) are not shown. This is why the count for all facies of the permeability intervals [0,10) and [10,20) is greater than indicated by the individual histograms.

Figure 4.4. Permeability by facies plotted for the entire set of permeability values and for individual facies 1, 3, and 4 at the Cedar Ridge II location.

Both vertical and horizontal variograms are calculated for facies 1, 3, and 4. Sample variograms for facies 1 are shown in figure 4.5. Experimental variograms constructed for the vertical permeability transects were each fitted using a spherical variogram model (figure 4.5A). The horizontal variogram shown in figure 4.5B exhibits a poorly defined sill and range because only eight horizontal locations are available for calculating the variogram. The horizontal variogram model shown in figure 4.5B is empirically defined assuming a high level of correlation in permeability values separated by distances up to 200 feet (61 m). The high degree of lateral correlation is assumed to result from the apparent lateral continuity of the lithofacies units observed in outcrop.

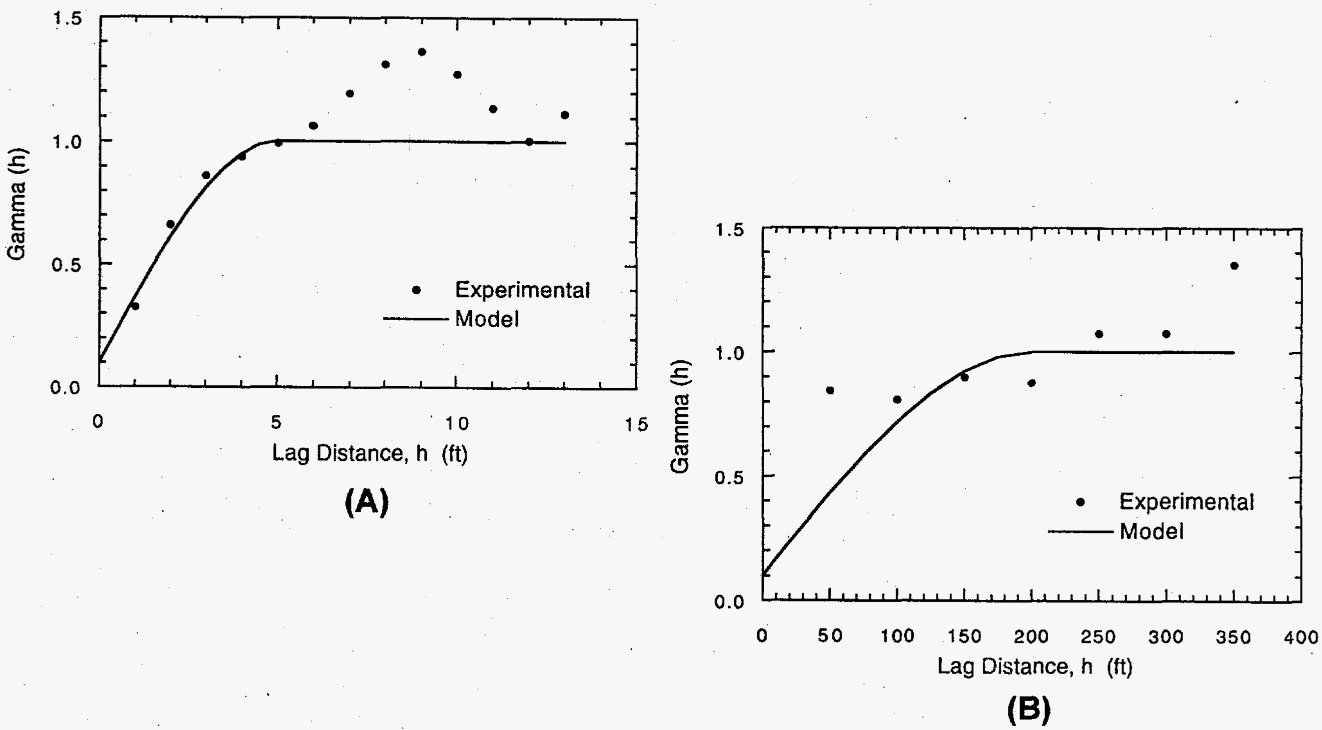


Figure 4.5. Experimental variograms, (A) vertical and (B) horizontal, with corresponding variogram models computed for facies 1 at the Cedar Ridge II location.

4.1.2 Step C - Assign Permeability Values Using a Stochastic Approach

Three methods of assigning permeability and porosity in two dimensions to each facies model are used to explore how each step might influence oil production when applied to lithofacies with the particular characteristics of those shown in figure 4.3. Figure 4.6 shows a digitized version of the facies architecture illustrated in figure 4.3. A two-step procedure is used to construct the permeability models shown in figure 4.6. First, either the facies-specific bounding surfaces derived from the mapped architecture of figure 4.3 are explicitly included in the model (for example, the facies-specific models of figure 4.6.A and 4.6.B) or permeability values are assigned without reference to the facies architecture (for example, the non-facies-specific permeability model of figure 4.6.C). Second, permeability distributions are computed and assigned to mimic the distribution of values shown in figure 4.3.

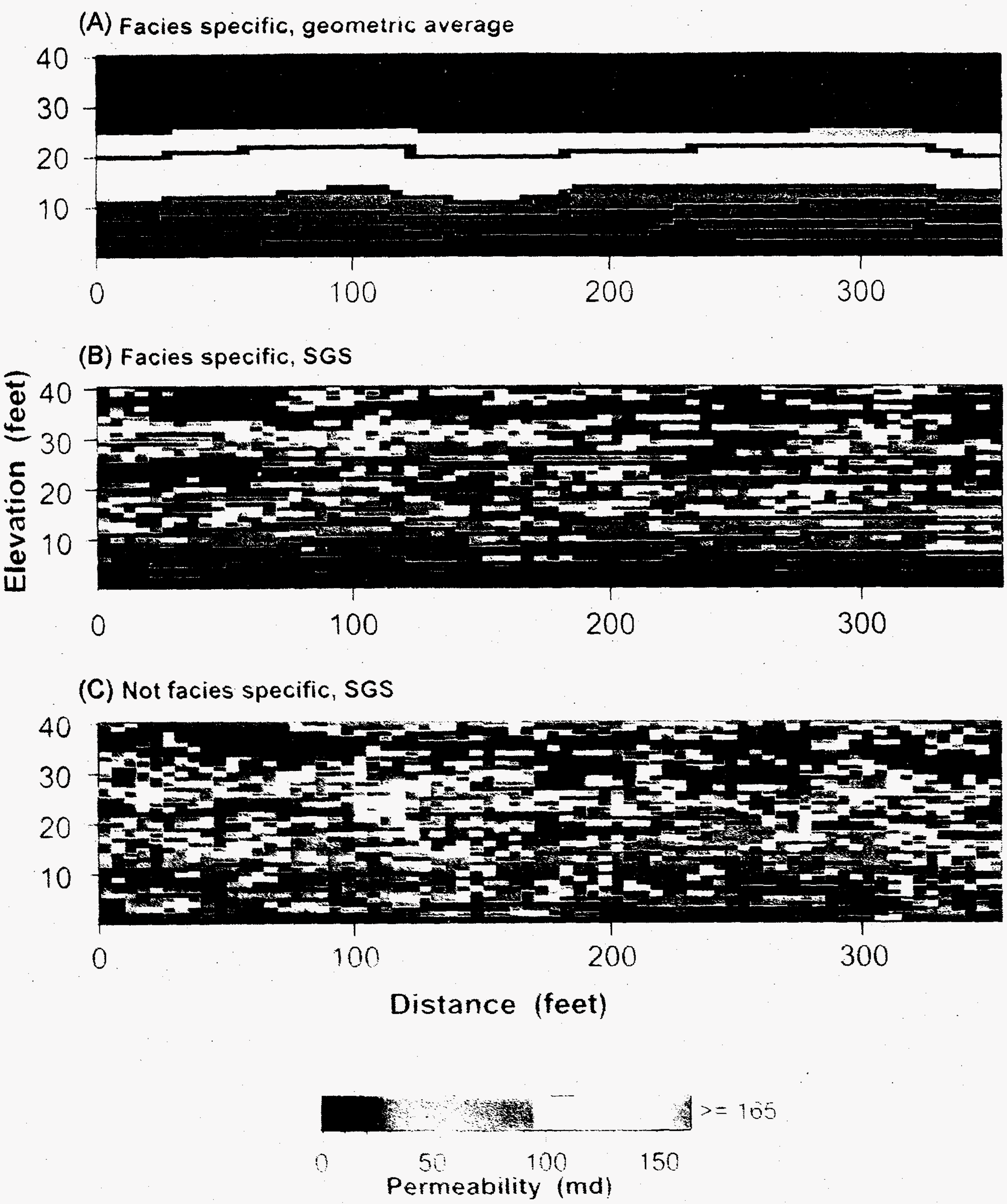


Figure 4.6. Three different permeability models constructed from the Cedar Ridge II data set by: (A) assigning a facies-specific geometric mean k to each of facies 1, 3, and 4, (B) generating a stochastic, facies-specific k distribution within each facies using sequential Gaussian simulation, and (C) generating a stochastic, non-facies-specific k distribution using sequential Gaussian simulation. In the facies-specific models the laminated siltstone/mudstone (facies 2) is assigned a uniform k of 0.5 md and the burrowed sandstone (facies 5) is assigned a uniform k of 10 md.

Two methods are adopted to distribute permeability values within each model domain. In the first facies-specific case (figure 4.6.A) the geometric mean permeability (k) of measured k values is computed and assigned separately to each of facies 1, 3, and 4. Computed mean k values are 165, 120, and 45 md for facies 1, 3, and 4, respectively. The laminated siltstone/mudstone (facies 2) is assigned a uniform k of 0.5 md and the burrowed sandstone (facies 5) is assigned a uniform k of 10 md. Facies 2 forms the thin, low-permeability layers that separate the other more permeable layers shown in figure 4.3.

A stochastic approach is used to assign permeability values for the second facies-specific case (figure 4.6.B) and for the non-facies-specific case (figure 4.6.C). In both cases a sequential Gaussian simulation (SGS) method is used to compute the spatial variation in permeability between the measured values. In the facies-specific case the SGS method is applied within each facies using the appropriate, facies-specific variogram model. As in the previous facies-specific case, facies 2 is assigned a uniform k of 0.5 md and facies 5 is assigned a uniform k of 10 md. The non-facies-specific k distribution shown in figure 4.6.C is computed using horizontal and vertical variograms derived for the entire data set. Although facies-specific bounding surfaces are not preserved in constructing figure 4.6.C, the general trend of increasing permeability with increasing elevation is preserved by applying a vertical variogram model in the SGS method.

4.1.3 Steps D and E - Perform Fluid-Flow Simulations and Use a Homogenization Approach

The permeability models shown in figure 4.6 are input into a numerical simulator to explore the way that each model might influence the production of oil in a waterflood scenario. The characteristics of the model are shown in figure 4.7. A relatively simple model is used in this test of our methodology. For example, a uniform porosity of 15 percent is applied and a simple injection-withdrawal regime is imposed. The finite difference code TETRADv10 is used to compute the evolution of oil and water saturations through time as water is injected on the left hand side and oil is extracted on the right hand side of the model domain (figure 4.7).

RESERVOIR ROCK AND FLUID PROPERTIES

Initial Pressure	5000 psia
Oil gravity	45 °API
Residual water saturation	0.3
Porosity	0.15
Formation compressibility	2×10^{-6} psi^{-1}
Oil compressibility	9×10^{-5} pis^{-1}
Water compressibility	2×10^{-5} psi^{-1}
μ_{oil}	2.5 cp
μ_{water}	1 cp
Well flowing pressure	3500 psia
Water injection rate	10 STB H_2O/day
Isotropic Permeability Tensor ($k_x = k_z$)	
Dead oil, no free gas	
TETRAD v10	

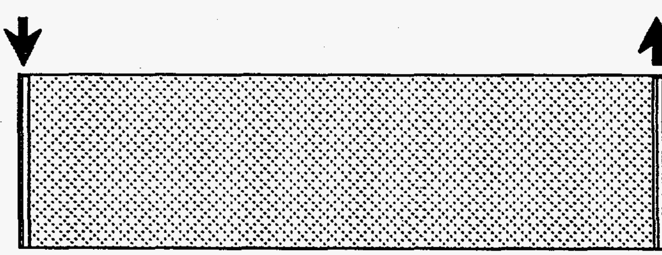


Figure 4.7. Initial value problem used to numerically explore the way that each permeability distribution influences waterflood-assisted oil production from the model domain. The left hand injection well and right hand production well are each perforated over the entire model section.

Figure 4.8 illustrates the computed migration of a waterflood through the non-facies-specific permeability model of figure 4.6.C at times of 60, 180, and 360 days. The permeability structure clearly influences the effectiveness of the waterflood with the upper-level, higher permeability facies providing a preferred pathway for migration.

Figure 4.9 provides a comparison of the oil and water saturations obtained for each permeability model after 360 days of injection and production. Although each result shown in figure 4.9 is similar, the facies-specific models (figures 4.9A and 4.9B) clearly show the localized influence of the laterally continuous, low permeability facies on oil and water saturations. The summary results shown in figure 4.10 confirm that there is little effective difference between each simulation result. For example, cumulative oil production computed for the facies-specific cases is only slightly less than that computed for the non-facies-specific permeability model (figure 4.10). The similarity between model results suggests that, for strongly layered permeability structures where a long horizontal correlation length relative to the length of the model domain is assigned, a stochastic approach may be unnecessary if specific bounding surfaces and facies-based permeabilities can be included in the model. In the absence of a realistic architectural model; however, it may be necessary to use the stochastic, non-facies-specific approach in an effort to preserve the obvious vertical variation in permeability illustrated in figure 4.3. Additional simulations, including the equivalent homogeneous case, will be run to more fully explore this issue.

4.1.4 Summary

We have established and tested a methodology for using a numerical modeling approach to explore the influence of reservoir architecture and permeability structure on oil production. Detailed architectural and permeability models will be based on the high-resolution field work which was performed in our outcrop-based studies of the Ferron Sandstone. Permeability and architectural data collected in the 1995 field season will be combined with our 1994 data as a basis for developing a series of three-dimensional flow-unit models using the methods discussed in this report. Although our methodology is tested in a two-dimensional mode, this approach is readily extended to a three-dimension mode.

4.2 Homogenization Code

The homogenization code for one-, two-, and three-dimensional problems was completed and tested extensively. The tests involved approximately 100 individual cases in one, two, and three dimensions. The test cases involved data sets with well known solutions and random examples to test the codes on more realistic problems. In addition to the homogenization codes, algorithms for computing the arithmetic, harmonic, and geometric averages of the permeability data were implemented to aid in testing the homogenization codes. The homogenization results should always be between the arithmetic and harmonic averages. This method is useful for testing the random cases even though the exact answer is not known. The codes were written in a form that is easy to install and test. All the test data sets are available and are generated in a self-contained program. The subroutines that compute the homogenized permeabilities can be plugged in at any point to a code with at most a minor amount of translation between data structures. The two-dimensional code was written to simulate Ferron lithofacies and will be used as a means of extrapolating the outcrop data to both two and three dimensions. The permeability data from the transects collected from the Ivie Creek case-study area has been obtained and is

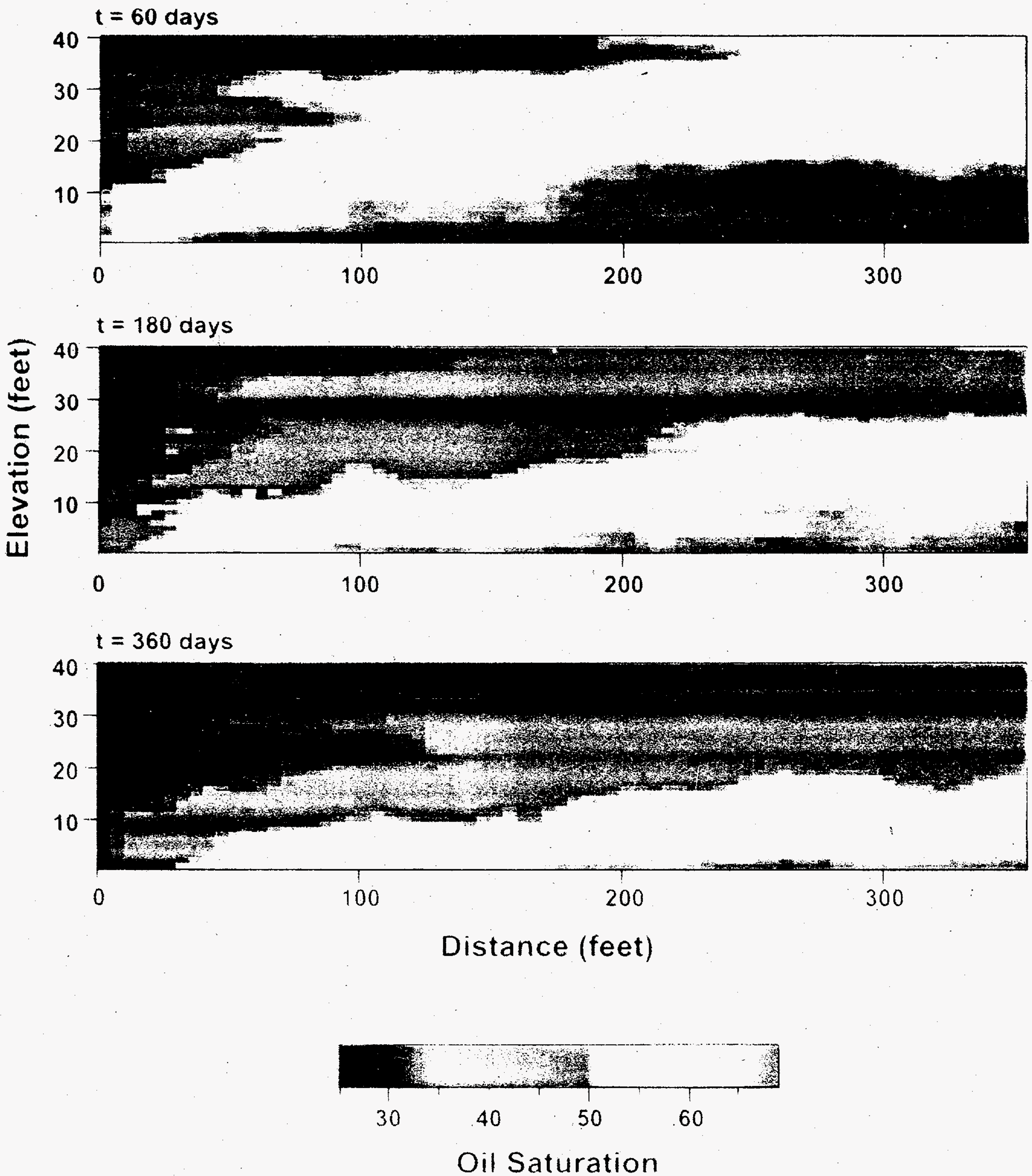


Figure 4.8. Computed evolution of a waterflood at three times after the start of water injection (t = 60, 180, and 360 days) for the non-facies-specific permeability model of figure 4.6.A.

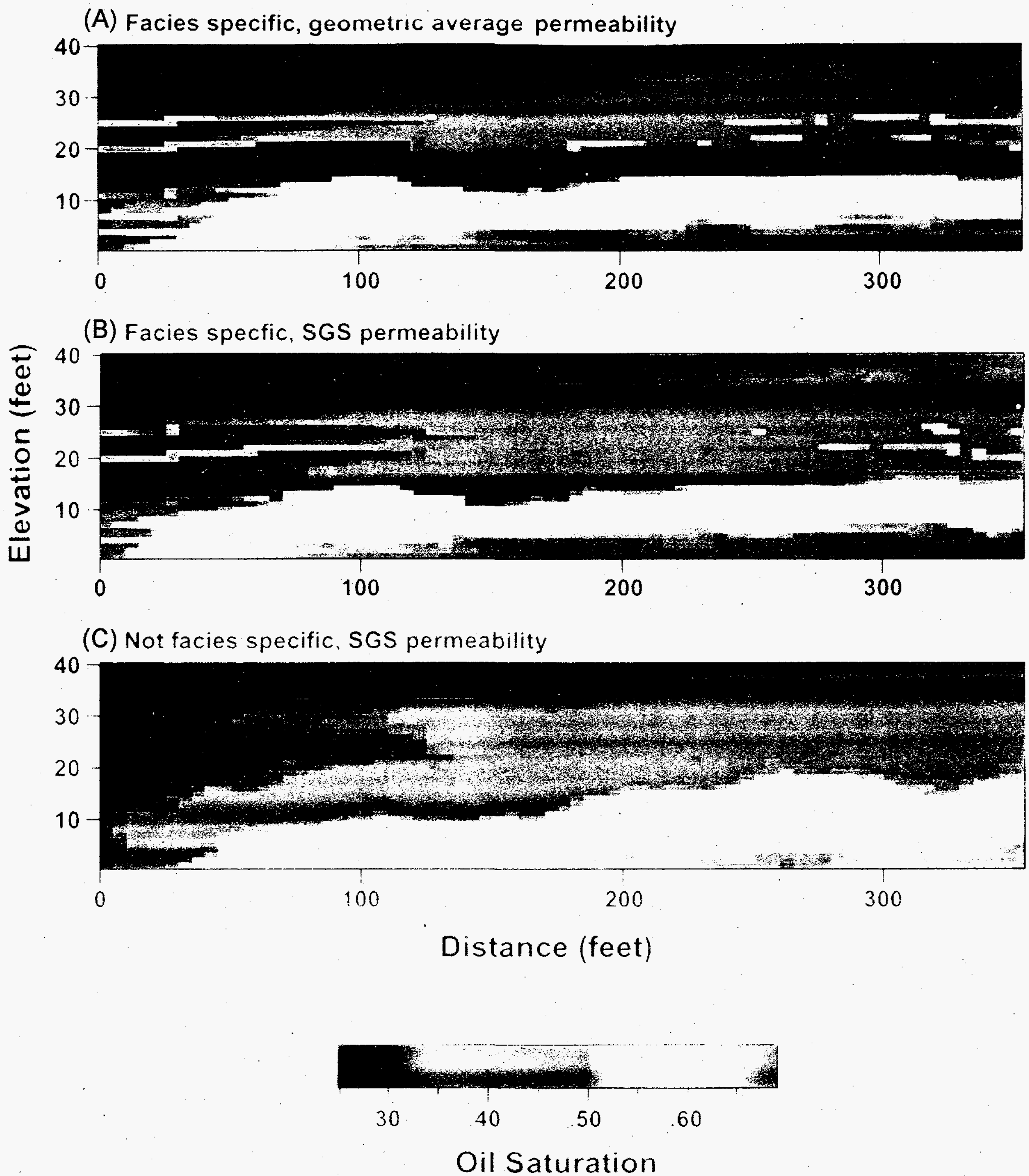


Figure 4.9. Computed distribution of oil and water at 360 days for each of the three permeability models shown in figure 4.6.

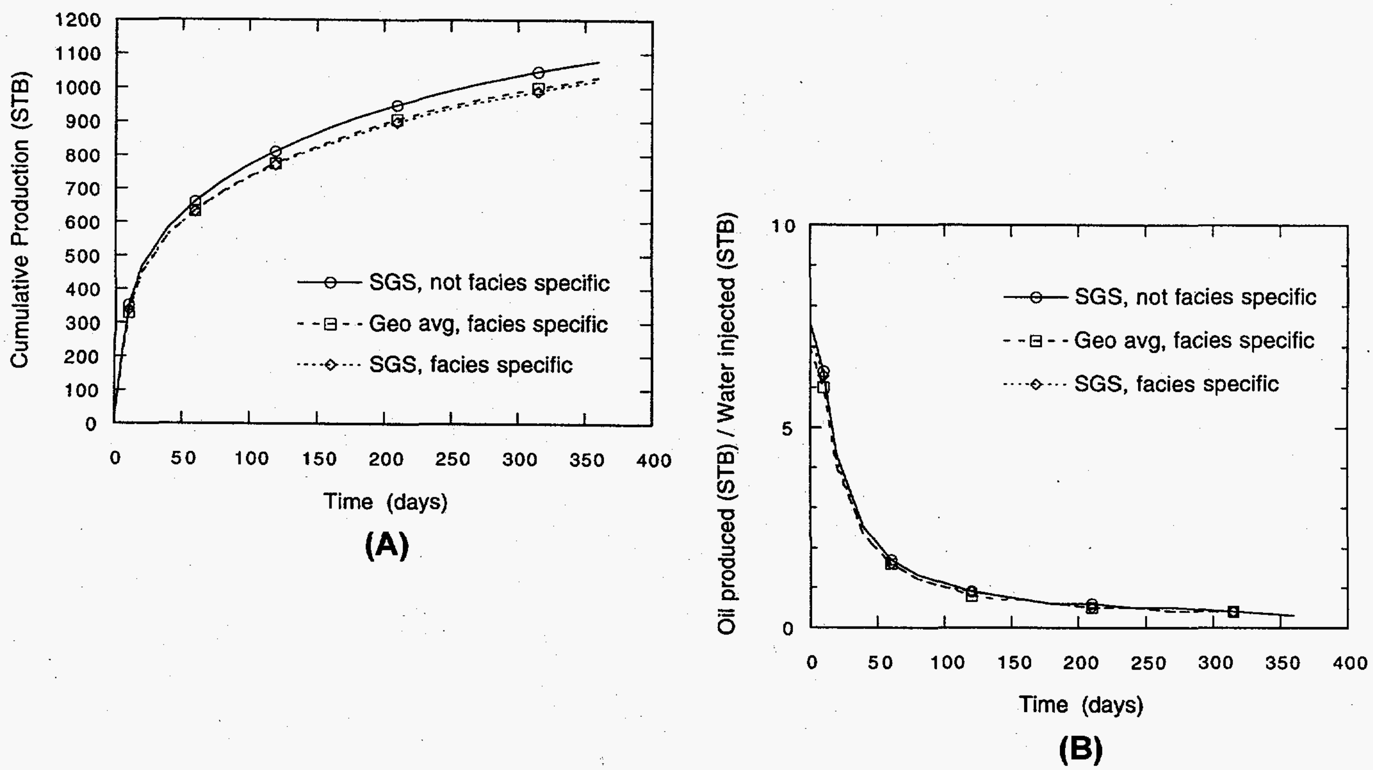


Figure 4.10. Comparison of computed cumulative oil production (A) and cumulative water cut (B) for each of the three permeability models shown in figure 4.6.

being analyzed. The analysis involves the use of spectral decompositions and possibly wavelet representation. This data is being used to build depositional models.

A group of three-dimensional homogenization codes were written to determine effective permeabilities for porous media problems. The codes include four different averaging methods; (1) homogenization, (2) arithmetic averaging, (3) geometric averaging, and (4) harmonic averaging (table 4.1). The homogenization method implemented in the code was originally developed by Bourgeat (1984). The other averaging techniques are implemented to provide a basis for comparing effective permeabilities determined using traditional methods to the homogenization results. The code package includes a finite element formulation of a black oil simulator that solves the fluid-flow equations on a rectangular grid. Because the homogenization method is flow based, it provides an improved methodology for averaging and upscaling the fine-scale permeability information. A comprehensive report entitled *Documentation and Installation Guide for HomCode: A Code for Scaling up Permeabilities Using Homogenization* was prepared and will be released as a UGS contract report in the near future.

Work was initiated on including the homogenization routine in the TETRAD3-D black oil simulator, and the first phase of developing a stochastic approach for creating synthetic groups of clinoforms was completed. These numerical routines will be used during the final project year to complete the fluid-flow simulation tasks.

Table 4.1. Effective permeability values computed by the four different averaging methods. The only method which returns a full tensor is the homogenization method.

Averaging Method	Type of Effective Tensor	Tensor Values
Homogenization	Full Tensor	$K^{\#} = \begin{bmatrix} 6.949 & -0.3482 \\ -0.3482 & 6.949 \end{bmatrix}$
Arithmetic Average	Diagonal Tensor	$K^{A} = \begin{bmatrix} 7.75 & 0.0 \\ 0.0 & 7.5 \end{bmatrix}$
Harmonic Average	Diagonal Tensor	$K^{H} = \begin{bmatrix} 3.077 & 0.0 \\ 0.0 & 3.077 \end{bmatrix}$
Geometric Average	Diagonal Tensor	$K^{G} = \begin{bmatrix} 5.623 & 0.0 \\ 0.0 & 5.623 \end{bmatrix}$

4.3 Creating Synthetic Clinoforms

Data collected during 1995 suggests that sufficient information has been obtained to create synthetic patterns of permeability within clinoform shapes. A stochastic code has been developed and is being tested for generating packages of stacked clinoform-like objects that resemble the features mapped in the Kf-1a parasequence. Originally developed using Mathematica, the code was reformulated in FORTRAN to ensure portability.

The code uses geometrical parameters (such as slope, total height, and total length) from photomosaic measurements to create a series of two-dimensional clinoform-like objects. Figure 4.11 shows two typical results. Note the degree of variability in thickness, character of pinchouts, and general clinoform style within each model domain. Additional work is required to more completely integrate the geological interpretations with the mathematical routines. The goal is to use this code to generate synthetic clinoform structures then distribute permeability values within each object using rules derived from the permeability transects and detailed geological mapping. The resulting permeability structure will form the basis for a series of fluid-flow simulations that demonstrate the impact of the clinoform features on oil production.

4.4 References

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Bourgeat, A.P., 1984, Homogenization method applied to the behaviour of a naturally fissured reservoir, *in* Gross, K.I., editor, Mathematical methods in energy research: Society of Industrial and Applied Mathematics, p. 181-193.

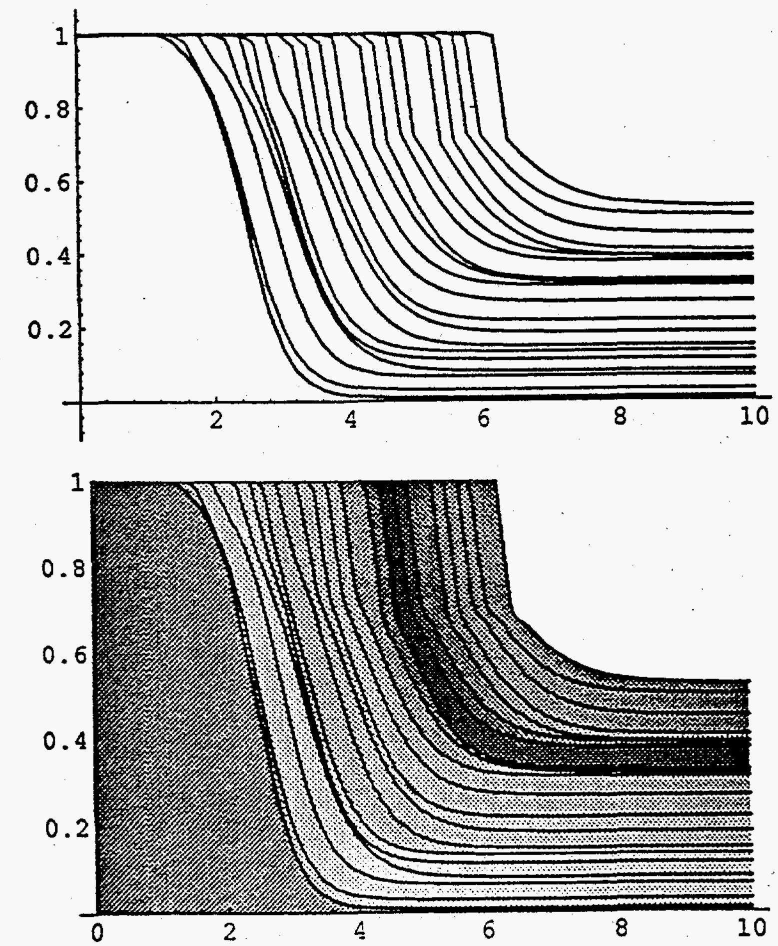

Figure 4.11. Sample of a set of clinoform-like objects created using a stochastic approach (in arbitrary length units). Slightly different rules were used to generate the two different realizations. Note that the top of each clinoform meets the upper boundary of the domain at a relatively shallow angle in the upper realization.

5. TECHNOLOGY TRANSFER

The UGS is the Principal Investigator for three government-industry cooperative petroleum-research projects including the Ferron Sandstone project. The projects are designed to improve recovery, development, and exploration of the nation's oil and gas resources through use of better, more efficient technologies. The projects involve detailed geologic and engineering characterization of several complex heterogeneous reservoirs. Two of the projects will include practical oil-field demonstrations of selected technologies. The U.S. Department of Energy (DOE) and multidisciplinary teams from petroleum companies, petroleum service companies, universities, and State agencies are co-funding the three projects.

The UGS will release all products of the Ferron Sandstone project in a series of formal publications. These will include all the data as well as the results and interpretations. Syntheses and highlights will be submitted to refereed journals as appropriate, such as the *American Association of Petroleum Geologists (AAPG) Bulletin* and *Journal of Petroleum Technology*, and to trade publications such as the *Oil and Gas Journal*, as well as the UGS *Petroleum News* and *Survey Notes* (figure 5.1).

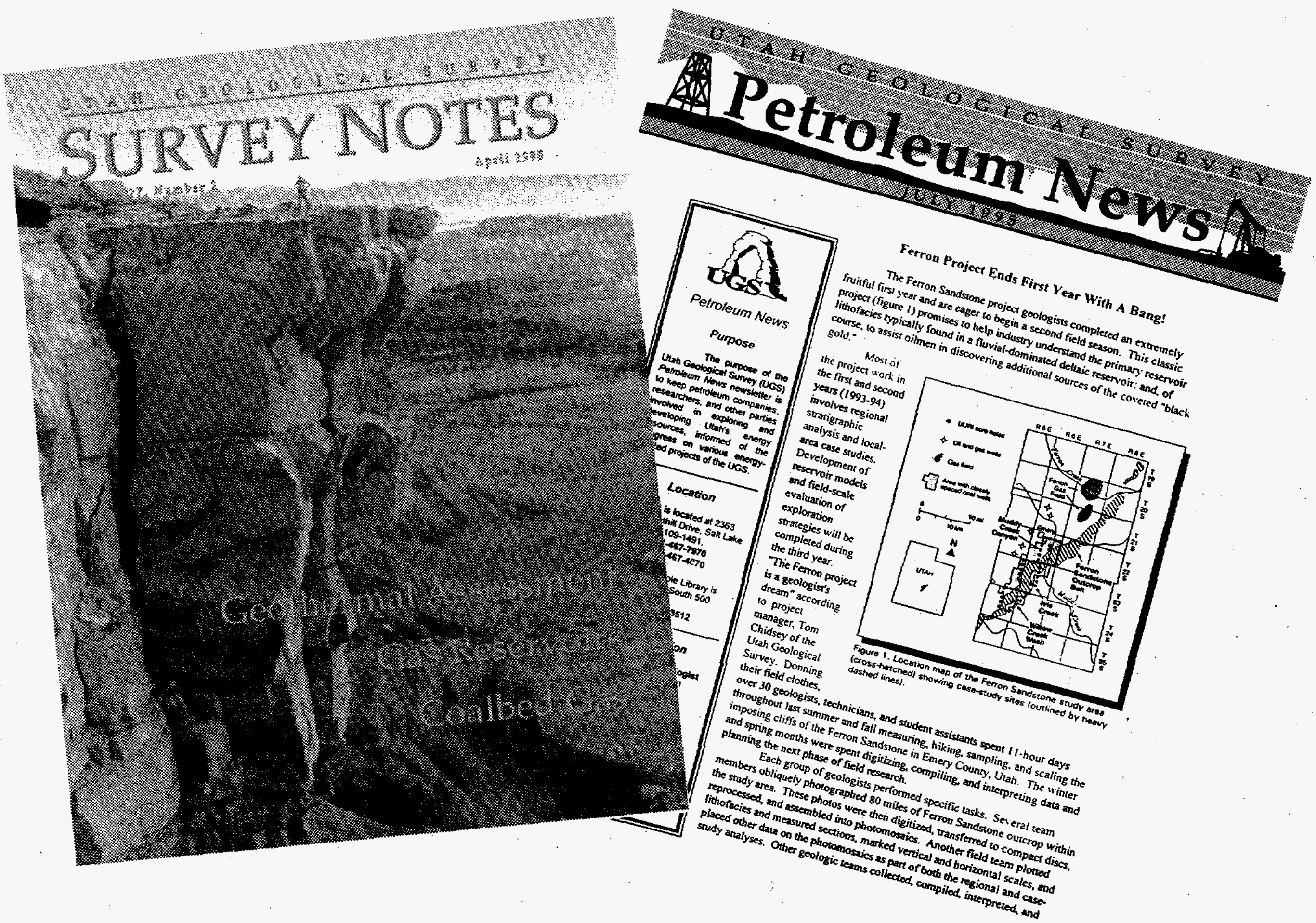

Figure 5.1. UGS *Survey Notes* and *Petroleum News* provide project updates, publication notices, and announcements of presentations to both the industry and lay public.

Project materials, plans, and objectives were displayed at the UGS booth during the 1995 annual national convention of the AAPG in Houston, Texas; the 1995 AAPG Rocky Mountain Section meeting in Reno, Nevada; and at the 1995 regional convention of the Society of Petroleum Engineers in Denver, Colorado. Three to four UGS scientists staffed the display booth at these events. Abstracts were submitted for technical presentations at future AAPG national and regional meetings.

During this project year, technology transfer activity for the Ferron Sandstone project has yielded an additional, unexpected benefit. The project was originally submitted to the DOE as a study of a surface analogue to fluvial-dominated deltaic oil reservoirs. Since that time, the Ferron Sandstone itself has become a major coalbed methane play in Utah. Databases, strip logs, and maps produced from the project have become very useful to the numerous operators exploring and developing this new resource (figure 5.2). Based on data generated in this project we estimate the play will support 3,400 wells, nearly doubling the total number of producing wells in Utah. The UGS released all subsurface drill-hole data (489 wells) collected as part of the Ferron project in an open-file report. This report is available in both hard copy and a computer-readable format.

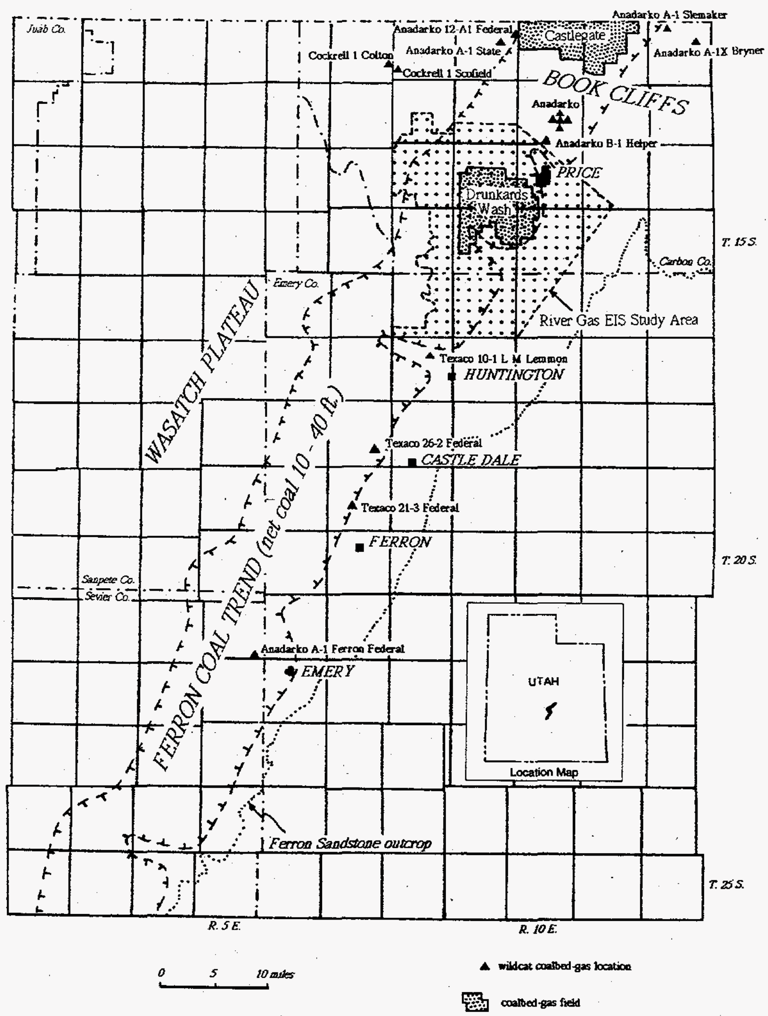

Figure 5.2. Location of the Ferron coalbed gas "fairway", Drunkards Wash field, and drilling prospects, Carbon, Emery, Sanpete, and Sevier Counties, Utah.

5.1 Utah Geological Survey *Petroleum News* and *Survey Notes*

The purpose of the UGS *Petroleum News* newsletter is to keep petroleum companies, researchers, and other parties involved in exploring and developing Utah energy resources, informed of the progress on various energy-related UGS projects. The UGS *Petroleum News* contains articles on: (1) DOE-funded and other UGS petroleum project activities, progress, and results, (2) current drilling activity in Utah including coalbed methane, (3) new acquisitions of well cuttings, core, and crude oil at the UGS Sample Library, and (4) new UGS petroleum publications. The purpose of *Survey Notes* is to provide nontechnical information on contemporary geologic topics, issues, events, and ongoing UGS projects to Utah's geologic community, educators, state and local officials and other decision makers, and the public. *Survey Notes* is published three times yearly and *Petroleum News* is published semi-annually. Single copies are distributed free of charge and reproduction (with recognition of source) is encouraged.

5.2 Presentations

The following technical and nontechnical presentations were made during the year as part of the Ferron Sandstone project technology transfer activities. These presentations described the Ferron project in general and gave detailed information on sequence stratigraphy, methods, and reservoir models.

"Response of Delta Morphology and Progradational Style to Changes in Accommodation, Sedimentation, and Basin Topography: Ferron Sandstone, East-Central Utah" by R.D. Adams and F.W. Stapor; Geologic Society of America Annual Meeting, Seattle, Washington, October, 1994.

"Influence of Tectonics, Sea Level, and Basin Topography on the Geometry of a Deltaic System: Ferron Sandstone, East-Central Utah" by R.D. Adams; Distinguished Lecture Series, University of Utah Department of Geology and Geophysics, November, 1994.

"The Ferron Reservoir Characterization Project: Using Outcrop Analogues to Characterize Fluvial-Deltaic Reservoirs at the Interwell Scale" by S.H. Snelgrove, Guest Lecturer; Los Alamos National Laboratory, Los Alamos, New Mexico, February, 1995.

"Exciting New Oil and Gas Activities in Utah and Overview of Utah Geological Survey Reservoir Characterization Projects" by M.L. Allison; Utah Association of Petroleum & Mining Landmen, Salt Lake City, Utah, March, 1995.

"Integrated Multidisciplinary Reservoir Characterization of a Deltaic System-1: Architecture and Lithofacies of the Cretaceous-age Ferron Sandstone, East-Central Utah" by R.D. Adams, T.C. Chidsey, Jr., and M.D. Laine; American Association of Petroleum Geologists Annual Convention, Houston, Texas, March, 1995.

"Integrated Multidisciplinary Reservoir Characterization of a Deltaic System-2: Developing a Petrophysical Model for Reservoir Simulation Using Data from the Ferron

Sandstone, Utah" by S.H. Snelgrove, C.B. Forster, and J.V. Koebbe; American Association of Petroleum Geologists Annual Convention, Houston, Texas, March, 1995.

"Depositional Environments, Sequence Stratigraphy, and Reservoir Quality of a Portion of the Ferron Sandstone, East-Central Utah" by J.A. Dewey, Jr., Spring Research Conference, College of Physical and Mathematical Sciences, Brigham Young University, and the American Chemical Society, Provo, Utah, March, 1995.

"Geological and Petrophysical Characterization of the Ferron Sandstone (Utah), for 3-D Simulation of a Fluvial-Deltaic Reservoir" by T.C. Chidsey, Jr., Guest Lecturer; Geoscience Technology Division staff of Amoco Production Research Company, Tulsa, Oklahoma, June, 1995.

"The Cretaceous Ferron Sandstone of East-Central Utah: a Tale of Three Different Morphologies for Deltaic Parasequences" by R.D. Adams; American Association of Petroleum Geologist Rocky Mountain Section Meeting, Reno, Nevada, July, 1995.

"A Methodology for Obtaining Detailed Geologic Descriptions to Constrain 3-D Reservoir Fluid-Flow Simulation Models in Delta-Front Lithofacies" by R.D. Adams, S.H. Snelgrove, and C.B. Forster; American Association of Petroleum Geologist Rocky Mountain Section Meeting, Reno, Nevada, July, 1995.

"Proposed Revisions to Parasequence-Set Nomenclature of the Upper Cretaceous Ferron Sandstone Member of the Mancos Shale" by P.B. Anderson and T.A. Ryer; American Association of Petroleum Geologist Rocky Mountain Section Meeting, Reno, Nevada, July, 1995.

"Geological and Petrophysical Characterization of the Ferron Sandstone in Utah, For 3-D Simulation of a Fluvial-Deltaic Reservoir" by T.C. Chidsey, Jr.; American Association of Petroleum Geologist Rocky Mountain Section Meeting, Reno, Nevada, July, 1995.

"Constraining Reservoir Models of Fluvial- vs. Wave-Dominated Delta-Front Sandstones through High Resolution and High Density Sequence Stratigraphic Analysis, Ferron Sandstone, Utah" by J.A. Dewey, Jr., T.H. Morris, and T.A. Ryer; American Association of Petroleum Geologist Rocky Mountain Section Meeting, Reno, Nevada, July, 1995.

"Parasequence Sets, Parasequences, Facies Distributions, and Depositional History of the Upper Cretaceous Ferron Deltaic Clastic Wedge, Utah" by T.A. Ryer and P.B. Anderson; American Association of Petroleum Geologist Rocky Mountain Section Meeting, Reno, Nevada, July, 1995.

"Distinguishing Allocyclic and Autocyclic Causes of Parasequence-Level Cyclicity--Lessons from Deltaic Strata of the Upper Cretaceous Ferron Sandstone, Central Utah" by T.A. Ryer, J.A. Dewey, Jr., and T.H. Morris; American Association of Petroleum Geologist Rocky Mountain Section Meeting, Reno, Nevada, July, 1995.

A project overview was presented on July 14, 1995 to the UGS Board of Directors, Emery County commissioners and planning officials, industry representatives, and the local press. The project objectives and description, accomplishments, and potential benefits were discussed. The presentation was followed by a field trip to the Ivie Creek case-study area. On August 17, 1995, information on the coalbed methane potential of the Ferron Sandstone (currently the most active gas play in Utah) was presented at a public meeting sponsored by the U.S. Bureau of Land Management in Price, Utah. The Ferron project was reviewed and derivative resource maps were displayed and discussed. Three television networks carried coverage of the meeting; media coverage generated numerous inquiries.

5.3 Publications

Adams, R.D., 1995, The Cretaceous Ferron Sandstone of east-central Utah: a tale of three different morphologies for deltaic parasequences (abs.): American Association of Petroleum Geologist Bulletin, v. 79, no. 6, p. 914.

Adams, R.D., Snelgrove, S.H., and Forster, C.B., 1995, A methodology for obtaining detailed geologic descriptions to constrain 3-D reservoir fluid-flow simulation models in delta-front lithofacies (abs.): American Association of Petroleum Geologist Bulletin, v. 79, no. 6, p. 914.

Adams, R.D., Chidsey, T.C., Jr., and Laine, M.D., 1995, Integrated multidisciplinary reservoir characterization of a deltaic system-1: architecture and lithofacies of the Cretaceous-age Ferron Sandstone, east-central Utah (abs.): 1995 Annual Convention of the American Association of Petroleum Geologists, Official Program, p. 1A.

Anderson, P.B., and Ryer, T.A., 1995, Proposed revisions to parasequence-set nomenclature of the Upper Cretaceous Ferron Sandstone Member of the Mancos Shale (abs.): American Association of Petroleum Geologists Bulletin, v. 79, no. 6, p. 914-915.

Allison, M.L., 1995, Geological and petrophysical characterization of the Ferron Sandstone for 3-D simulation of a fluvial-deltaic reservoir - annual report for the period September 29, 1993 to September 29, 1994: U.S. Department of Energy, DOE/BC/14896-6, 49 p.

Chidsey, T.C., Jr., 1995, Geological and petrophysical characterization of the Ferron Sandstone in Utah, for 3-D simulation of a fluvial-deltaic reservoir (abs.): American Association of Petroleum Geologists Bulletin, v. 79, no. 6, p. 916.

Dewey, J.A., Jr., Morris, T.H., and Ryer, T.A., 1995, Constraining reservoir models of fluvial- vs. wave-dominated delta-front sandstones through high resolution and high density sequence stratigraphic analysis, Ferron Sandstone, Utah (abs.): American Association of Petroleum Geologists Bulletin, v. 79, no. 6, p. 917.

Hucka, B.P., Sommer, S.N., Sprinkel, D.A., and Tabet, D.E., 1995, Ferron Sandstone drill-hole database, Ferron Creek to Last Chance Creek, Emery and Sevier Counties, Utah: Utah Geological Survey Open-File Report 317, 1130 p., 9 pl.

Hucka, B.P., Sommer, S.N., Sprinkel, D.A., and Tabet, D.E., 1995, Ferron Sandstone drill-hole database, Ferron Creek to Last Chance Creek, Emery and Sevier Counties, Utah: Utah Geological Survey Open-File Report 317DF, 5 p., 2 diskettes.

Ryer, T.A., and Anderson, P.B., 1995, Parasequence sets, parasequences, facies distributions, and depositional history of the Upper Cretaceous Ferron deltaic clastic wedge, Utah (abs.): American Association of Petroleum Geologists Bulletin, v. 79, no. 6, p. 924.

Ryer, T.A., Dewey, J.A., Jr., and Morris, T.H., 1995, Distinguishing allocyclic and autocyclic causes of parasequence-level cyclicity--lessons from deltaic strata of the Upper Cretaceous Ferron Sandstone, central Utah (abs.): American Association of Petroleum Geologists Bulletin, v. 79, no. 6, p. 924.

Snelgrove, S.H., Forster, C.B., and Koebbe, J.V., 1995, Integrated multidisciplinary reservoir characterization of a deltaic system-2: developing a petrophysical model for reservoir simulation using data from the Ferron Sandstone, Utah (abs.): 1995 Annual Convention of the American Association of Petroleum Geologists, Official Program, p. 90-91A.

Tabet, D.E., 1995, Utah's 1994 coalbed methane gas developments: Utah Geological Survey, Survey Notes, v. 27, no. 2, p. 7-9.

Tabet, D.E., 1995, CBM in 'dry county' coalbed gas development expands in Utah: Coalbed Methane Review, issue 3, p. 11-13.

Utah Geological Survey, 1995, Ferron project ends first year with a bang!: Utah Geological Survey Petroleum News (July), p. 1-2.

U.S. Department of Energy, 1994, Geological and petrophysical characterization of the Ferron Sandstone for 3-D simulation of a fluvial-deltaic reservoir, *in* Contracts for field projects and supporting research on enhanced oil recovery, reporting period October-December 1993: Progress Review No. 77, DOE/BC--94/1, p. 84-86.

U.S. Department of Energy, 1995, Geological and petrophysical characterization of the Ferron Sandstone for 3-D simulation of a fluvial-deltaic reservoir, *in* Contracts for field projects and supporting research on enhanced oil recovery, reporting period January-March 1994: Progress Review No. 78, DOE/BC--94/2, p. 101-103.

APPENDIX

Parasequences of the Ferron Sandstone (Recognized as of July, 1995)

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf	Ferron Sandstone Member of the Mancos Shale	Lupton, 1916	Ferron Sandstone is recognized as a member of the Mancos Shale. No type section has been designated. The name is derived from the town of Ferron, Utah, but it is clear from Lupton's work that he would have chosen the outcrops farther south, east, and south of the town of Emery, as representative of the member where it is most typically developed. The name Ferron Sandstone is presently used on outcrops around the San Rafael Swell, in the Henry Mountains basin, and beneath Castle Valley and the Wasatch Plateau. Controversy exists about whether "Ferron" or "Juana Lopez" is a more appropriate designation for thinly interbedded sandstones and shales of Ferron age on the east side of the San Rafael Swell near the town of Green River and eastward into Colorado.
Kf-Clw	Clawson unit of Ferron Sandstone	Cotter, 1975	The Clawson unit of the Ferron extends from the northern part of San Rafael Swell southward along its western flank, through Molen Reef, finally feathering out westward toward Muddy Canyon in the "Molen Amphitheatre." The Clawson and overlying Washboard units of the Ferron together constitute the "lower Ferron" of Ryer and McPhillips (1983), and the lower part of the "Hyatti sequence" of Gardner (1994). They are shelf sandstones with a northern source. Lowering of sea level during middle Turonian time facilitated southward transport of very-fine and fine-grained sand onto a shoal area that marks the eastern hinge of the foredeep developed in front of the Sevier Orogenic belt. The shoal may represent a peripheral bulge. In addition to feathering out southward, both the Clawson and Washboard units lose sand content and disappear toward the west in the area stretching from the "Molen Amphitheatre" southward to Mesa Butte and westward to the "Tri-Canyon" area and "Cowboy Mesa." A gentle structural flexure has been recognized in this area, suggesting the presence of a down-to-the-west basement fault. The fact that Cretaceous rocks were flexed but not broken by movement on the proposed fault (unlike the younger faults associated with Tertiary extension) suggests that this fault moved during Cretaceous time in response to thrust loading. The westward loss of sand in the Clawson and Washboard units suggest that it was active during lower Ferron deposition. Facies content of shoreline unit: shelf sand body.
Kf-Wsb	Washboard unit of Ferron Sandstone	Cotter, 1975	The Washboard unit extends from the northern part of San Rafael Swell southward to Mesa Butte, slightly farther than does the underlying Clawson unit. Same origin as Clawson unit; same comments apply. Facies content of shoreline unit: shelf sand body.

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf-LC	Last Chance unit of Ferron Sandstone	This study	The type section of the Last Chance unit of the Ferron is at Last Chance Creek, where the shoreline unit, together with overlying Kf-1-Ls, forms vertical cliffs approximately 200 feet high. Kf-Last Chance displays inclined bedsets that appear to onlap, or possibly downlap against a surface that may represent a paleotopographic high, resulting in very rapid seaward thinning to a feather edge. The high may represent the upthrown side of a down-to-the-west fault that was active during Ferron deposition. (A problem with this interpretation is that the thick section represented by Kf-LC can be mapped as having a northwest-southeast trend based on limited subsurface data, whereas faults that formed along the eastern hinge of the foredeep would be expected to have a north-south orientation). No contemporaneous channel deposits have yet been identified. Kf-Last Chance corresponds to the upper part of the "Hyatti sequence" of Gardner (1994). Type section: Limestone Cliffs at Last Chance, NW1/4 section 9, T. 25 S., R. 5 E., Salt Lake Base Line. Landward limit: not known; may be covered by basalt of Fish Lake Plateau. Seaward limit: Limestone Cliffs, approximately NE1/4 section 3, T. 25 S., R. 5 E., Salt Lake Base Line. Facies content of shoreline unit: wave-modified coast, possibly strand plain.
Kf-1	Kf-1 parasequence set of Ferron Sandstone	Ryer, 1981; 1982	Kf-1 extends from outcrops south of Last Chance Creek to the southeastern side of "Cowboy Mesa" in the southern part of the Coal Cliffs. Its landward limit has not been accurately defined. Seven parasequence are presently recognized. The sub-A coal zone belongs to Kf-1. Only minor amounts of coal are contained in it, most of the coal occurring in the Last Chance area. The seaward limit of coal is present at the mouth of the canyon of Quitchupah Creek.
Kf-1-Ls	Kf-1 Limestone Cliffs parasequence of Ferron Sandstone	This study	Kf-1 Limestone Cliffs is defined in the southern part of the Limestone Cliffs, at present only on the basis of oblique air photos. <Kf-1-Ls> extends from Last Chance Creek northward into the Limestone Cliffs. It is probably the youngest parasequence of Kf-1, although relationships south of Last Chance Creek have not been worked out. Proposed type section: southern part of Limestone Cliffs, somewhere in section 3, T. 25 S., R. 5 E., Salt Lake Base Line. Landward limit: south of Last Chance Creek, position not determined. Seaward limit: Limestone Cliffs, approximately SE1/4 section 34, T. 24 S., R. 5 E., Salt Lake Base Line. Facies content of shoreline unit: not yet determined; wave-modified coast judging by photos.

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf-1-IC-a	Kf-1-Indian Canyon-a parasequence of Ferron Sandstone	This study	Kf-1-Indian Canyon-a is defined in the southern part of Indian Canyon, where the Kf/Ktnk contact reaches the canyon bottom. Only the seaward part of <Kf-1-IC-a> is exposed in Indian Canyon. Both seaward and landward limits have been tentatively identified in the Limestone Cliffs on the basis of photomosaics and oblique air photos. Although the Limestone Cliffs exposures would constitute a better type section, Indian Canyon was chosen because of ease of access and because the relationships between units Kf-1-IC-a,b,c, and d are quite clear there. A shortcoming of using Indian Canyon as a type area for <Kf-1-IC-a> is that the unit lacks upper shoreface/foreshore facies in Indian Canyon. A thick, extensively burrowed middle shoreface indicates that it was deposited on a wave-modified coastline. The seaward feather edge can be projected from the Limestone Cliffs through the subsurface to Indian Canyon and trends generally northwestward. The top of <Kf-1-IC-a> may be cut by meanderbelts belonging to <Kf-1-IC-d> locally in the Limestone Cliffs exposures. Type section: Indian Canyon, NE1/4NW1/4 section 26, T. 24 S., R. 5 E., Salt Lake Base Line. Landward limit: Limestone Cliffs, approximately SE1/4 section 34, T. 24 S., R. 5 E., Salt Lake Base Line. Seaward limit: Indian Canyon, SW1/4SW1/4SW1/4 section 24, T. 24 S., R. 5 E., Salt Lake Base Line; Limestone Cliffs, approximately NW1/4SE1/4 section 25, T. 24 S., R. 5 E., Salt Lake Base Line. Facies content of shoreline unit: wave-modified coast, probably strand plain.
Kf-1-IC-b	Kf-1-Indian Canyon-b parasequence of Ferron Sandstone	This study	Kf-1-Indian Canyon-b is defined in Indian Canyon at the south end of the canyon and referred to as "The Wall." Landward and seaward limits of <Kf-1-IC-b> are tentatively defined in the Limestone Cliffs utilizing photomosaics and oblique air photos. The landward pinch-out is not exposed in Indian Canyon; the seaward feather edge is poorly defined in northern part of Indian Canyon owing to similarity of facies content of <Kf-1-IC-b> and overlying <Kf-1-IC-c>. The landwardmost part of the transgressive surface of erosion between these two is a remarkably steep surface, well exposed on the east side of Indian Canyon, opposite the south end of "The Wall." Type section: Indian Canyon, east side, just beneath landward pinch-out of the overlying <Kf-1-IC-c>, SW1/4SW1/4 section 24, T. 24 S., R. 5 E., Salt Lake Base Line. Landward limit: Limestone Cliffs, approximately NW1/4SE1/4 section 25, T. 24 S., R. 5 E., Salt Lake Base Line. Seaward limit: Indian Canyon, CSW1/4 section 24, T. 24 S., R. 5 E., Salt Lake Base Line; Limestone Cliffs, approximately CNE1/4 section 25, T. 24 S., R. 5 E., Salt Lake Base Line. Facies content of shoreline unit: wave-modified coast, probably strand plain.

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf-1-IC-c	Kf-1-Indian Canyon-c parasequence of Ferron Sandstone	This study	Defined on the west side of Indian Canyon, <Kf-1-IC-c> is responsible for forming "The Wall." It extends from south end of "The Wall" in Indian Canyon northward into Willow Springs Wash, feathering out gradually in the Coyote Basin- "Swell Point" area. Because the unit feathers out seaward so gradually, choosing an exact point on the map for its seaward limit is difficult and arbitrary. The landward pinch-out is fairly well exposed on the east side of Indian Canyon, but has been cut out by a channel on the west side. A substantial bay or lagoon existed behind the shoreline unit, as made evident by mudstones bearing oyster shells. A channel mouth or tidal inlet deposit that cuts <Kf-1-IC-c> locally very near its landward pinch-out probably connected this body of water with the sea. <Kf-1-IC-c> is very much a wave-modified unit. Its top is cut locally by meanderbelt deposits that belong to the younger Kf-1-IC-d. Type section: "The Wall" along the west side of Indian Canyon, SW1/4, SW1/4 section 24, T. 24 S., R. 5 E., Salt Lake Base Line. Landward limit: Limestone Cliffs, approximately CNE1/4 section 25, T. 24 S., R. 5 E., Salt Lake Base Line. Seaward limit: South of Coyote Basin, approximately SW1/4NE1/4 section 18, T. 24 S., R. 5 E., Salt Lake Base Line. Facies content of shoreline unit: wave-modified coast, probably strand plain.
Kf-1-IC-d	Kf-1-Indian Canyon-d parasequence of Ferron Sandstone	This study	<Kf-1-IC-d> is recognized in the North Fork of Indian Canyon and the northernmost part of "The Wall" in Indian Canyon. It is also present, though difficult to distinguish with certainty, on the cliffs east of the mouth of Indian Canyon ("Boot Point"). Although clearly definable in the field, the boundary between Kf-1-IC-c and Kf-1-IC-d is not a transgressive or "marine-flooding" surface. But the two shoreline sandstone bodies are distinct and have been given different names. <Kf-1-IC-d> prograded toward the northwest and represents a river-dominated delta front deposited in a low-wave-energy setting. The change in depositional style marked by the contact between <Kf-1-IC-d> and underlying <Kf-1-IC-c> is the result of avulsion of a river system into the area and transformation of the wave-modified, straight coastline into a protected bay into which a delta lobe subsequently prograded. The "County Line Channel" studied so extensively by Mobil appears to belong to this unit, as determined by correlation of carbonaceous shales and a thin bed of coal within the sub-A coal zone. (Note: J. Garrison, personal communication, has come to a different conclusion on the basis of his work: that the "County Line Channel" fed <Kf-1-RC>). Type locality: mouth of the North Fork of Indian Canyon, north side, NW1/4NE1/4 section 24, T. 24 S., R. 5 E., Salt Lake Base Line. Landward limit: well defined on west wall of Indian Canyon, SE1/4NW1/4 section 24, T. 24 S., R. 5 E., Salt Lake Base Line and in North Fork of Indian Canyon, NW1/4NW1/4 section 24, T. 24 S., R. 5 E., Salt Lake Base Line. Seaward limit: "Swell Point", SE1/4 section 8, T. 24 S., R. 6 E., Salt Lake Base Line. Facies content of shoreline unit: river-dominated delta, specifically a delta lobe that built into a bay that was well protected from fair-weather waves.

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf-1-RC	Kf-1-Rock Canyon parasequence of Ferron Sandstone	This study	Kf-1-Rock Canyon is defined on the cliffs south of Rock Canyon area. Outcrops of Kf-1-Rock Canyon in this area are only fair, being partially covered with debris, but become better in the cliffs to east, on the south side of "Overhand Point." <Kf-1-RC> has a well defined landward pinch-out on the south-facing cliffs east of Coyote Basin, on the south side of "Swell Point." There, it splits the sub-A coal zone, one split of carbonaceous mudstone passing below the transgressive surface, and the other passing onto the root-penetrated top of <Kf-1-RC>. A tidal channel deposit rich in oysters, some of which are in growth position, cuts <Kf-1-RC> near its pinch-out. The seaward limit of< Kf-1-RC> has not yet been determined, but it appears that it extends all the way to Ivie Creek. If so, its seaward feather edge is present near the northern end of Blue Trail Canyon, where strata of <Kf-1-Iv-a> onlap it from the north. The landward part of <Kf-1-RC> is strongly wave modified, and this may well be true for the entire unit. Type section: south side of "Swell Point", CSE1/4 section 8, T. 24 S., T. 6 E., Salt Lake Base Line. Landward limit: south side of "Swell Point", NW1/4SE1/4 section 8, T. 24 S., R. 6 E., Salt Lake Base Line. Facies content of shoreline unit: wave-modified coast; proximal part probably strand plain; distal part may include deltaic deposits.
Kf-1-Iv	Kf-1-Ivie Creek parasequence of Ferron Sandstone	This study	Kf-1-Ivie Creek is localized in the Ivie Creek-Quitchupah Creek Canyon area. It has been referred to as Kf-1-Ivie Creek-a in our detailed analysis of the Ivie Creek case-study site. Unit <Kf-1-Iv-b> may be been dropped, however, because it probably represents no more than a phase of slow sedimentation following abandonment of the delta represented by the former <Kf-1-Iv-a>. Thus, it does not warrant parasequence designation. Without the -b unit, the -a designation will be dropped. <Kf-1-IV> is characterized by distinctive, steeply-sloping clinoform surfaces in the younger of its two recognizable parts. This active deltaic deposit has an arcuate shape, having prograded toward the south at the mouth of Blue Trail Canyon, toward the west in the amphitheatre north of Ivie Creek, and toward the north in the southern part of Quitchupah Canyon. It disappears to the east, across the mouth of Quitchupah Canyon, but exactly how it does this and its relationship to <Kf-1-QC> are not yet clear. It is possible that the odd characteristics of <Kf-1-Iv> can be attributed to its location at the flexure described for the Clawson unit. If this flexure marks the hinge of the foredeep, flexure of strata caused by movement of a basement fault may have brought about the deep-water bay into which <Kf-1-Iv> prograded, the meanderbelt from which its feeder channel came having been situated on the high side of the flexure. Type section: amphitheatre north of Ivie Creek, SW1/4NE1/4 section 16, T. 23 S., R. 6 E., Salt Lake Base Line. Landward limit: not yet determined; relationships to strata on Cowboy Mesa remain unclear. Seaward limit: west side of Quitchupah Canyon, SW1/4SW1/4 section 16, T. 23 S., R. 6 E., Salt Lake Base Line.

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf-1-QC	Kf-1-Quitchupah Canyon parasequence of Ferron Sandstone	This study	Kf-1-Quitchupah Canyon is defined in Quitchupah Creek Canyon. It is best developed in the area where Kf-1 approaches and dives beneath the alluvium at the canyon floor. It may include the beds previously included in Kf-1-Ivie Creek-c. Relationships on the west side of Quitchupah remain somewhat unclear, despite a great deal of study. If more than one parasequence is ultimately distinguished, <Kf-1-QC-a> and <Kf-1-QC-b> are possible names for them. Relationships between units recognized in Quitchupah Canyon and those on Cowboy Mesa also remain unclear owing to very complicated stratigraphy. <Kf-1-QC> may be the youngest parasequence of Kf-1, in which case it includes the strata that feathers out seaward on the southeast side of "Cowboy Mesa." Type section: Quitchupah Creek Canyon, SE1/4 section 4, T. 23 S., R. 6 E., Salt Lake Base Line. Landward limit: not presently defined. Beds of apparent shallow-marine origin exposed above <Kf-1-Iv> in the amphitheatre north of Ivie Creek (attributed earlier to <Kf-1-Iv-d>) may belong to <Kf-1-QC>. Pronounced thickening is present along the walls of Quitchupah Creek Canyon.
Kf-2	Kf-2 parasequence set of Ferron Sandstone	Ryer, 1981; 1982	Kf-2 is characterized by very complicated stratigraphy at the parasequence level. The transgressive surface that marks the boundary between <Kf-2-MC-a> and <Kf-2-MC-b> is extensive enough that it might be justifiable to divide Kf-2 into two parasequence sets (Kf-2-early and Kf-2-late?) utilizing this surface. The associated A-coal zone contains thick coal beds south of Willow Springs Wash and in the Quitchupah Creek Canyon area. Much of the thickness of the C-coal bed, originally assigned to Kf-3, has recently been determined to belong to the youngest part of Kf-2. The seaward limit of C-coal deposition is in the Dry Wash area, the lower split of the coal (previously referred to as A-coal) extending somewhat farther than the upper split, which is present in Kf-3. Considering the widespread distribution and substantial thickness of the main A- and C-coal seams, Kf-2 probably ranks as the most important coal-bearing parasequence set (or sets) of the Ferron. Old, abandoned mines that produced coal for local consumption are numerous and range from Willow Springs Wash on the south to "Grassy Valley" on the north. The "Reefer 3" mineral claim and adit on the south side of Dry Wash are on carbonaceous mudstones of the lower split of the C-coal zone.

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf-2-WS	Kf-2-Willow Springs parasequence of Ferron Sandstone	This study	Kf-2-Willow Springs is defined on the north side of Willow Spring Wash, at its mouth. The landward edge of <Kf-2-WS> is present in the same area, a short distance west of the mouth. Thickening of the unit toward the northeast onto the point that lies north of the mouth of the wash occurs rapidly, surprisingly so since the amount of overall climbing of Kf-2 from here to where it passes beyond the seaward edge of Kf-1 is relatively small. The landward pinch-out is cut by a shale-filled channel, possibly of tidal origin. The seaward extent of <Kf-2-WS> has not yet been determined, but probably is present in the vicinity of "Swell Point." Along the east-facing cliffs south of Coyote Basin, the tip of <Kf-2-WS> has been eroded and replaced by predominantly fine-grained deposits, some of which include "inclined heterolithics" indicative of channel deposition. This scour may be related to the areally more restricted scour that is present near the pinch-out. Relationships here require more study. A younger erosional surface that cuts <Kf-2-RC-a and b> in Coyote Basin area reaches the top of <Kf-1-WS> locally. Type locality: mouth of Dry Wash, north side, CSE1/4 section 18, T. 24 S., R. 6 E., Salt Lake Base Line. Landward limit: mouth of Dry Wash, north side, CSW1/4 section 18, T. 24 S., R. 6 E., Salt Lake Base Line. Seaward limit: not known accurately, approximately at "Swell Point", SE1/4 section 18, T. 24 S., R. 6 E., Salt Lake Base Line. Facies content of shoreline unit: wave-modified coast, probably strand plain.
Kf-2-RC-a	Kf-2-Rock Canyon-a parasequence of Ferron Sandstone	This study	Kf-2-Rock Canyon-a is distinguished on the south side of "Swell Point." There, Kf-2 thickens dramatically toward the east with addition of first <Kf-2-RC-a> and then <Kf-2-RC-b> over a short distance. <Kf-2-RC-a> and <Kf-2-RC-b> are readily distinguished only near their landward pinch-outs. There, on the south side of "Swell Point", a lenticular channel deposit that cuts into the top of <Kf-2-RC-a> is in turn bevelled off by the transgressive surface of erosion at the base of <Kf-2-RC-b>. Elsewhere, the two shoreline units lie one above the other, sharing a contact that places middle shoreface on middle shoreface, making them essentially indistinguishable. For this reason, it will be difficult or impossible to determine the seaward extent of <Kf-2-RC-a>. The landward pinch-outs of both units were eroded and replaced by sandy, fluvial strata, so their exact locations are not known. Type section: south side of "Swell Point", SW1/4SW1/4 section 8, T. 24 S., R. 6 E., Salt Lake Base Line. Landward limit: south side of "Swell Point", approximately SW1/4SW1/4 section 8, T. 24 S., R. 6 E., Salt Lake Base Line. Seaward limit: not known; possibly near or north of Rock Canyon. Facies content of shoreline unit: not determined, probably wave-modified delta.

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf-2-RC-b	Kf-2-Rock Canyon-b parasequence of Ferron Sandstone	This study	See discussion of <Kf-2-RC-a>. <Kf-2-RC-b> appears to extend northward a great distance, perhaps all the way to Ivie Creek. If this proves to be so, <Kf-2-RC-b> and <Kf-2-Iv-a> may be equivalents. Type section: south side of "Swell Point", SW1/4SW1/4 section 8, T. 24 S., R. 6 E., Salt Lake Base Line. Landward limit: south side of "Swell Point", approximately SW1/4SW1/4 section 8, T. 24 S., R. 6 E., Salt Lake Base Line. Seaward limit: not known; may extend to Ivie Creek. Facies content of shoreline unit: not determined, probably wave-modified delta.
Kf-2-Iv-a	Kf-2-Ivie Creek-a parasequence of Ferron Sandstone	This study	<Kf-2-Iv-a> is distinguished in the amphitheatre north of Ivie Creek. It is separated from overlying <Kf-2-Iv-b> by a surface that was initially interpreted to be a "marine-flooding surface" because it appeared to separate two vaguely upward-coarsening depositional sequences. Truncation of channel deposits in the lower part of Ivie Creek Canyon has subsequently been recognized at the top of <Kf-2-Iv-a>, firming up the initial interpretation. <Kf-2-Iv-a> appears to be a wave-modified unit. Its relationship to <Kf-2-RC-b> is unclear and it is possible that these two units are equivalents. Suggested type section: near mouth of Ivie Creek Canyon, NE1/4SE1/4 section 17, T. 23 S., R. 6 E., Salt Lake Base Line. Landward limit: not yet determined. Seaward limit: not yet determined. Facies content of shoreline unit: not determined, probably wave-modified delta.
Kf-2-Iv-b	Kf-2-Ivie Creek-b parasequence of Ferron Sandstone	This study	See comments for <Kf-2-Iv-a>. Suggested type section: Same location as <Kf-1-Iv-a>, near mouth of Ivie Creek Canyon, NE1/4SE1/4 section 17, T. 23 S., R. 6 E., Salt Lake Base Line. Landward limit: not yet determined. Seaward limit: not yet determined. Facies content of shoreline unit: not determined, probably strand plain and wave-modified delta.

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf-2-Iv-c	Kf-2-Ivie Creek-c parasequence of Ferron Sandstone	This study	The type area of <Kf-2-Iv-c> is the mouth of Ivie Creek Canyon. This unit undoubtedly warrants designation as a parasequence inasmuch as the associated transgressive surface is clearly recognizable both in Ivie Creek Canyon and to the south in the I-70 roadcut. The pinch-out of <Kf-2-Iv-c> trends just slightly west of north. The shoreline sandstone unit displays some interesting and unusual changes at the mouth of Ivie Creek Canyon, changing over about 100 yards from a strongly wave-modified shoreface unit to a much lower wave energy unit that contains mud interbeds and finer sand, and that has a silvery-gray color on outcrop. This change suggests a change from a coast directly facing the sea to one that was sheltered from wave energy. In some respects, this resembles the change from <Kf-1-IC-c> to <Kf-1-IC-d>. The relationships between <Kf-2-Iv-c> and <Kf-2-Mi-a,b> are presently unknown. It can be speculated, however, that <Kf-1-Mi-a> represents the western margin of a major delta that provided the sheltering from wave energy (see below). Suggested type section: Ivie Creek Canyon, NW1/4SE1/4 section 17, T. 23 S., R. 6 E., Salt Lake Base Line. Seaward limit: not determined. Facies content of shoreline unit: wave-modified coast, probably shoreface in the proximal part, transforming to low-wave-energy coast, possibly bay shoreline.
Kf-2-Mi-a	Kf-2-Miller Canyon-a parasequence of Ferron Sandstone	Anderson, 1993; Gustason, 1993; and Ryer, 1993	The type area of Kf-2-Miller Canyon-a is the mouth of Miller Canyon. The boundary between this unit and overlying Kf-2-Mi-b is difficult to recognize in many places, but is very apparent where rotated slump blocks, which are generally restricted to <Kf-2-Mi-a> in this area, are present. The transgressive surface is perfectly apparent where it has bevelled the tops of the rotated blocks, which are common enough to facilitate tracing the contact throughout the "Tri-Canyon" area. The landward limit of <Kf-2-Mi-a> has not been determined. Its seaward feather-edge can be approximately located in Miller Canyon and in the lower part of Muddy Creek Canyon, near the "Upper Gooseneck." It has a general northeast trend, suggesting that this parasequence built northwestward, probably as a deltaic lobe. The deltaic complex from which this lobe built may have provided the sheltering from wave energy noted for <Kf-2-Iv-c>. Rotated blocks are present in <Kf-2-Mi-a> in the Coal Cliffs south of Miller Canyon, in the lower part of Muddy Creek Canyon, and are particularly well exposed in "Grassy Canyon." A few are present on the east side of "Dino Head Point" on the western margin of the "Molen Amphitheatre." Failure of the rotated blocks is consistently toward the northwest, the direction that the delta lobe appears to have prograded. The abundance of rotated blocks, which are relatively rare entities elsewhere in the Ferron, in the particular area may once again be related to a zone of flexure. Tilting toward the west may have encouraged failure of the delta-front. Type section: near mouth of Miller Canyon, south side, NE1/4NE1/4 section 36, T. 22 S., R. 6 E., Salt Lake Base Line. Landward limit: not determined. Seaward limit: Miller Canyon, NE1/4SW1/4 section 26, T. 22 S., R. 6 E., Salt Lake Base Line; Muddy Creek Canyon, CNW1/4 section 24, T. 22 S., R. 6 E., Salt Lake Base Line. Facies content of shoreline unit: river-dominated delta.

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf-2-Mi-b	Kf-2-Millier Canyon-b parasequence of Ferron Sandstone	Anderson, 1993; Gustason, 1993; and Ryer, 1993	Kf-2-Mi-b includes the shoreline sandstone that forms the massive cliffs in the lower parts of Miller and Muddy Creek Canyons. It appears to be a very strongly wave-modified unit. The landward pinch-out of <Kf-2-Mi-b> has not yet been located. It thins toward the northwest into "Grassy Canyon" and the "Molen Amphitheatre", finally disappearing into marine shale in the southern part of Molen Reef along with overlying <Kf-2-MC-a>. In Muddy Creek Canyon (but not yet elsewhere), it is possible to subdivide <Kf-2-Mi-b> into two subunits bounded by a distinctive surface. The southern subunit is wave modified, the northern one very strongly wave modified. The surface that separates these subunits could be a transgressive surface, but the overlying transgressive surface beneath <Kf-2-MC-a> has removed any direct evidence. In the absence of compelling evidence to the contrary, it is assumed the surface marks some change of autocyclic origin. Type section: same as <Kf-2-Mi-a>, near the mouth of Miller Canyon, south side, NE1/4NE1/4 section 36, T. 22 S., R. 6 E., Salt Lake Base Line. Landward limit: not determined. Seaward limit: Molen Reef, CSE1/4 section 29, T. 22 S., R. 7 E., Salt Lake Base Line. Facies content of shoreline unit: wave-modified, probably strand plain in proximal part; may include deltaic deposits in medial and distal parts.
Kf-2-MC-a	Kf-2-Muddy Canyon-a parasequence of Ferron Sandstone	Anderson, 1993; Gustason, 1993; and Ryer, 1993	Kf-2-Muddy Canyon-a forms ledges and lesser cliffs above the grander cliffs formed by <Kf-2-Mi-b> throughout most of the lower part of Muddy Creek Canyon and into the southern Coal Cliffs to the south. Most of the thickness of <Kf-2-MC-a> has been cut out by meanderbelt deposits. Although very sandy in some areas, much of the meanderbelt deposit consists of "inclined heterolithics." Two distinct meanderbelt units are distinguished on the basis of paleocurrent directions, the southern one being the younger of the two. At one locality on the west side of Muddy Creek Canyon north of the "Lower Gooseneck", the fluvial erosional surface rises to reveal a river-dominated delta-front sequence. On the east side of "Dino Head", near the southern mouth of "Pinion Jay Valley", the meanderbelt deposit ends and the delta-front unit, only about 20 feet in thickness, appears. It grades from marine mudstone at the base to predominantly sandstone in the upper part and can be traced continuously through the "Molen Amphitheatre" to a point where it disappears into marine shale in the southern part of Molen Reef. Although a landward pinch-out of <Kf-2-MC-a> cannot be located because of the fluvial erosion, there can be no question that the surface that separates <Kf-2-MC-a> from the underlying <Kf-2-Mi-b> is a transgressive surface: it places offshore marine shale directly upon upper shoreface sandstone and, locally, has planed off small channels within the top of <Kf-2-Mi-b>. Type section: southern part of Muddy Creek Canyon, NW1/4SW1/4 section 24, T. 22 S., R. 6 E., Salt Lake Base Line. Landward limit: cannot be determined owing to erosion by fluvial facies. Facies content of shoreline unit: river-dominated delta; probably represents a low-wave-energy delta that prograded into a protected bay.

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf-2-MC-b	Kf-2-Muddy Canyon-b parasequence of Ferron Sandstone	Anderson, 1993; Gustason, 1993; and Ryer, 1993	Kf-2-Muddy Canyon-b is defined on the basis of a shoreline sandstone unit that has a distinctive white color. The landward pinch-out of <Kf-2-MC-b> is present in the southern Coal Cliffs just north of "Bear Gulch", at the mouth of Miller Canyon, and is almost reached in the bend opposite the "Lower Gooseneck" in Muddy Creek Canyon. Near the pinch-out, the unit is characterized by large-scale, inclined surfaces that dip to the north, essentially parallel to the trend of the pinch-out (strike of inclined surfaces perpendicular to shoreline trend). The surfaces are interpreted to represent a series of tidal inlets that were driven northward by longshore drift. Equivalent flood tidal delta and lagoonal deposits have been tentatively identified in Miller Canyon and "Bear Gulch." <Kf-2-MC-b> thickens rapidly eastward, attaining thicknesses in excess of 75 feet in "Grassy Canyon." It extends eastward into Molen Reef, where it is a major cliff former, and northward to Dry Wash. Its seaward limit has not been precisely identified. The areal distribution of this unit is very large compared to most Ferron parasequences, and it is possible that it can be divided. Type section: southern part of Muddy Creek Canyon, NW1/4SW1/4 section 24, T. 22 S., R. 6 E., Salt Lake Base Line. Landward limit: southern Coal Cliffs north of "Bear Gulch", CSE1/4 section 35, T. 22 S., R. 6 E, Salt Lake Base Line; mouth of Miller Canyon, NE1/4NE1/4 section 35, T. 22 S., R. 6 E. and SE1/4SE1/4 section 26, T. 22 S., R. 6 E., Salt Lake Base Line; Muddy Creek Canyon, SW1/4SE1/4 section 23, T. 22 S., R. 6 E., Salt Lake Base Line. Seaward limit: near Dry Wash, approximately NE1/4SW1/4 section 2, T. 22 S., R. 7 E., Salt Lake Base Line, if <Kf-2-MR> is determined to constitute a parasequence (see below). Facies content of shoreline unit: wave-modified coast in proximal part, probably strand plain; may include deltaic deposits in distal part.
Kf-2-MR	Kf-2-Molen Reef	This study	The Kf-2 cliffs in the Molen Reef outcrops south of Dry Wash include two distinct upward-coarsening units. They appear to constitute distinct parasequences, the lower being <Kf-2-MC-b>, and the upper <Kf-2-MR>, but no clear evidence has yet been found to demonstrate that the boundary between them is a transgressive surface. The name is listed here in anticipation that it will be assigned parasequence status. Type section: Molen Reef south of Dry Wash, NW1/4 section 11, T. 22 S., R. 7 E., Salt Lake Base Line. Landward limit: not determined, but approximately NE1/4 section 15, T. 22 S., R. 7 E.,, Salt Lake Base Line. Seaward limit: not determined; somewhere north of Dry Wash. Facies content of shoreline unit: probably deltaic.

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf-2-DW	Parasequence Kf-2-Dry Wash	This study	Kf-2-Dry Wash is defined on the basis of a shoreline sandstone unit whose landward pinch-out crosses the northern edge of the cliffs of the Molen Reef south of Dry Wash and intercepts the cliffs on the north side of the wash, defining a northwest shoreline trend. The pinch-out is less distinct than most others, possibly because of development of a flood tidal delta in this area. A large lagoon/bay complex lies landward of the pinch-out and can be traced for several miles southward in the Molen Reef outcrops and westward to the limit of Kf-2 outcrops in Dry Wash. The lagoon/bay unit is bracketed by splits of the lower C coal that under- and overlie it. The seaward limit of <Kf-2-DW> has not been determined. It is, at present, the youngest known parasequence of Kf-2. Numerous channel deposits, including three large, lenticular channel bodies in Dry Wash and several in the Molen Reef cliffs appear to belong to <Kf-2-DW>. Type section: cliffs north of Dry Wash, SW1/4 section 35, T. 21 S., R. 7 E., Salt Lake Base Line. Landward limit: Dry Wash, SW1/4 section 2, T. 22 S., R. 7 E. and SW1/4SW1/4 section 35, T. 21 S., R. 7 E., Salt Lake Base Line. Seaward limit: not determined. Facies content of shoreline unit: wave-modified, probably strand plain in proximal part; distal part not yet studied.
Kf-3	Kf-3 parasequence set of Ferron Sandstone	Ryer, 1981; 1982	Shoreline sandstones of Kf-3 extend from the "Molen Amphitheatre" northward beyond Dry Wash. At present, only two parasequences are distinguished. It is likely that one or more additional parasequences will eventually be defined in the northern part of the area of distribution of Kf-3. Much of the thickness of the C-coal bed, previously considered as belonging to Kf-3, has now been reassigned to Kf-2. The uppermost approximately one foot of coal of the C-coal zone, including the thick tonstein bed, extends over the top of <Kf-3-MR-a> near the mouth of "Gnat Canyon" in the "Molen Amphitheatre." Details of coal correlations farther north have not been worked out. With reassignment of most of the coal of the C-coal zone to Kf-2, Kf-3 becomes one of the leanest parasequence sets in the Ferron with respect to its coal content.

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf-3-MR-a	Kf-3-Molen Reef-a parasequence of Kf-3	This study	The type area for <Kf-3-Mr-a> is the large "Molen Amphitheatre." The landward pinch-out of <Kf-3-Mr-a> is very well exposed on the cliffs just to the west of the mouth of "Gnat Canyon." The pinch-out takes place into the C-coal zone, with about 1 foot of coal passing above, and the remaining 6 to 7 feet passing below. Only 100 feet to the south, there is no trace of the unit within the C-coal zone, which carries its full compliment of tonsteins. This is a remarkable situation. In the majority of cases, transgression of the sea across the Ferron coastal/delta plain led to formation of bays or lagoons that are preserved landward of the pinch-outs of the subsequently deposited shoreline sandstones. In the case of <Kf-3-Mr-a>, the transgressing shoreface cut into and partially eroded a mass of peat. The top of the peat must have lay far enough above sea level to preclude inundation southwest of the shoreline. Peat accumulation was only briefly interrupted, if at all, before progradation of the shoreline occurred. Several well-exposed, lenticular channel deposits filled with "inclined heterolithics" complicate the stratigraphy of <Kf-3-MR-a> in the vicinity of its landward pinch-out. Type section: at mouth of "Gnat Canyon" NE1/4SW1/4 section 30, T. 22 S., R. 7 E., Salt Lake Base Line. Landward limit: just W of mouth of "Gnat Canyon": CSW1/4 section 30, T. 22 S., R. 7 E., Salt Lake Base Line. Seaward limit: not determined. Facies content of shoreline unit: wave-modified, probably strand plain in proximal part; distal part may include deltaics.
Kf-3-MR-b	Kf-3-Molen Reef-b	This study	Kf-3-Molen Reef-b lies above <Kf-3-MR-a> in the "Molen Amphitheatre", being separated from it by a thin zone of carbonaceous mudstone. The landward pinch-out of <Kf-3-MR-b> occurs on the floor of "Gnat Canyon" and so is not exposed, although its position can be determined to within one to two hundred feet. As is true for <Kf-3-MR-a>, channels are numerous in the landward part of <Kf-3-MR-b>. <Kf-3-MR-a> and <Kf-3-MR-b> merge to form the Kf-3 cliff along the Molen Reef, but the parasequences have not yet been distinguished there. Thus, the seaward extent of these two parasequences are not known. <Kf-3-MR-b> is strongly wave modified in its landward part. Suggested type section: east side of "Gnat Canyon" where it merges into the cliffs of the "Molen Amphitheatre." Type section: "Molen Amphitheatre", east of "Gnat Canyon", NE1/4 section 31, T. 22 S., R. 7 E., Salt Lake Base Line. Landward limit: at mouth of "Gnat Canyon", NE1/4SW1/4 section 30, T. 22 S., R. 7 E., Salt Lake Base Line. Seaward limit: not determined. Facies content of shoreline unit: wave-modified coastline, probably strand plain, in proximal part; distal part may include deltaics.

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf-4	Kf-4 parasequence set of Ferron Sandstone	Ryer, 1981; 1982	Compared to the parasequence sets that preceded it, Kf-4 thickens very rapidly seaward, indicating a high rate of relative sea level rise during its deposition. Two parasequences are recognizable, although a third may prove to be distinguishable in the "Fracture Canyon" area. The associated G-coal zone only locally contains more than a few feet of coal, probably because peat accumulation could not keep up with the rapid relative rise of sea level that characterized this unit. Carbonaceous mudstones of the G-zone have been mined to produce a soil conditioner, locally referred to by the trade name "Live Earth", for about 20 years in Miller Canyon, although that mine appears to now be inactive.
Kf-4-Mi	Kf-4-Miller Canyon parasequence of Ferron Sandstone	This study	The type area of <Kf-4-Mi> is the mouth of Miller Canyon, where its shoreline sandstone body forms high cliffs. The landward pinch-out of <Kf-4-Mi> occurs just south of "Bear Gulch", but is somewhat obscured because the upper part of the unit is replaced by a meanderbelt deposit. The meanderbelt deposit is very widespread, being recognized throughout the "Tri-Canyon" area and eastward into the "Molen Amphitheatre." It is also relatively coarse-grained, being made up of medium- to coarse-grained sandstone that locally includes granules and, rarely, pebbles. The landwardmost part of <Kf-4-Mi> is strongly wave modified and this is probably true of the unit as a whole, although it is difficult to tell with the upper part of the unit removed. Type section: southern Coal Cliffs at the mouth of Miller Canyon, SE1/4SE1/4 section 26, T. 22 S., R. 6 E., Salt Lake Base Line. Landward limit: in Coal Cliffs south of "Bear Gulch", SW1/4NE1/4 section 2, T. 23 S., R. 6 E., Salt Lake Base Line. Seaward limit: not determined, probably in southern part of Molen Reef. Basic facies content: wave-modified shoreline--strand plain in proximal part to wave-modified delta in distal part.
Kf-4-MR	Kf-4-Molen Reef parasequence of Ferron Sandstone	This study	<Kf-4-MR> is defined on the basis of a shoreline sandstone unit that forms a striking, white wall throughout the "Molen Amphitheatre" area. The landward pinch-out of <Kf-4-MR> is well exposed just west of the mouth of " Gnat Canyon", almost directly above the landward pinch-out of <Kf-3-MR-a>. Pronounced landward thinning toward the pinch-out is also evident in "Pinion Jay Valley" and in the area north of "Molen Point." <Kf-4-MR> is extremely wave modified in its landward part. The more distal part, however, may include some lower-wave-energy shoreline deposits, some of which may represent river-dominated deltas. It may be that the latter constitute one or more additional, as yet undefined parasequences. Type section: Molen Reef, SE1/4SW1/4 section 29, T. 22 S., R. 7 E. or along white, south-facing wall in "Molen Amphitheater", SE1/4SE1/4 section 30, T. 22 S., R. 7 E., Salt Lake Base Line. Landward limit: mouth of "Gnat Canyon", NE1/4SW1/4 section 30, T. 22 S., R. 7 E., Salt Lake Base Line. Seaward limit: not determined. Probably extends most of the way up Molen Reef toward Dry Wash, where a younger parasequence may be present. Basic facies content: wave-modified shoreline--strand plain in proximal part to wave-modified delta in distal part.

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf-5	Kf-5 parasequence set of Ferron Sandstone	Ryer, 1981; 1982	Kf-5 thickens rapidly seaward from its landward limit in Muddy Creek Canyon. Its seaward feather edge lies in "Fracture Canyon" just south of Dry Wash. Kf-5 has, to date, defied division into parasequences. Almost everywhere, the upper part of the shoreline sandstone of Kf-5 has been cut out and replaced by meanderbelt deposits (among them the channel deposits so extensively studied by the Texas Bureau of Economic Geology in Muddy Creek Canyon, Grassy Valley, and "Cedar Canyon"). The presence of the meanderbelt deposits preclude recognition of the landward pinch-outs of any parasequences that Kf-5 contains. Most of the shoreline strata of Kf-5 appear to represent a wave-modified coast, probably a wave-modified delta front. The I-coal zone accumulated in a swamp, probably a "raised mire" that existed along the western margin of the Kf-5 meanderbelt that trends northward to northeastward across Muddy Creek Canyon. Coal in the I-zone reaches its maximum thickness in the area at and south of Christiansen Wash, where it combines with the overlying J-coal to form a 30-foot-thick seam. Although the A- and C-coal zones probably include more coal because of their greater areal distributions, the I-coal bed is the only one that has been mined on a large scale. The lower 20 feet of coal has been extensively mined by conventional, room-and-pillar techniques at the Emery mine. The upper 10 feet of coal, which tends to be higher in sulfur, has been left as roof. Consol estimates that about 100 million tons of combined I-J coal is strippable in the area south of Emery. Carbonaceous mudstones of the I-zone are being mined as "Live Earth" south of "Bear Gulch". Type section: none. Considered to be a parasequence set at present. If Kf-5 is ultimately considered to constitute a single parasequence, a good type section would be the west side of Muddy Creek Canyon, NE1/4SW1/4 section 13, T. 22 S., R. 6 E., Salt Lake Base Line. Landward limit: Muddy Creek Canyon, somewhat obscured because of overlying meanderbelt, approximately NW1/4 section 24, T. 22 S., R. 6 E., Salt Lake Base Line. Seaward limit: "Fracture Canyon", SW1/4 section 24, T. 21 S., R. 7 E., Salt Lake Base Line. Facies content of shoreline unit: river-dominated delta.
Kf-6	Kf-6 parasequence set of Ferron Sandstone	Ryer, 1991	Kf-6 extends from the upper part of Muddy Creek Canyon to Dry Wash. No parasequences are recognized at this time and it is likely that none will be. Contemporaneous channels are rare or absent and all of the shoreline strata of Kf-6 appear to have accumulated along a wave-dominated coast, probably a strand plain. Kf-6 is difficult to study in detail owing to the fact that it is generally exposed only on the lower part of the Molen dip slope and because outcrops are generally poor between the few significant canyons. Both the landward pinch-out at the head of Muddy Creek Canyon and the seaward feather edge at Dry Wash, however, are particularly well displayed. Type section: uppermost part of Muddy Creek Canyon, SE1/4NW1/4 section 13, T. 22 S., R. 6 E., Salt Lake Base Line. Landward limit: uppermost part of Muddy Creek Canyon, SE1/4NW1/4 section 13, T. 22 S., R. 6 E., Salt Lake Base Line. Seaward limit: Dry Wash, NE1/4NW1/4 section 34, T. 21 S., R. 7 E., Salt Lake Base Line. Facies content of shoreline unit: wave-modified coastline, probably strand plain.

Stratigraphic Unit ID	Stratigraphic Unit Name	Author	Description
Kf-7	Kf-7 parasequence set of Ferron Sandstone	Ryer, 1991	The landward limit of Kf-7 lies somewhere in the vicinity of Christiansen Wash, although it cannot be defined for lack of good outcrop and the fact that it has been cut out by a major meanderbelt deposit. It reaches a seaward feather edge in the northern part of Muddy Creek Canyon. No parasequences are presently distinguished and, because of outcrop limitation, it is likely that none will be. All well exposed parts of the shoreline unit of Kf-7 are of lower and middle shoreface strata. Dominance of hummocky-swaley cross stratification and planar lamination coupled with moderate bioturbation point to a wave-modified shoreline. The presence of the thick, multi-storied, contemporaneous meanderbelt deposit at Christiansen Wash demonstrates that a large river was actively feeding sediment to <Kf-7> in the area between Christiansen Wash and Miller Canyon. Type section : west side of Muddy Creek Canyon, NW1/4SW1/4 section 24, T. 22 S., R. 6 E., Salt Lake Base Line. Landward limit: cannot be determined owing to fluvial erosion, approximately at Christiansen Wash, NW1/4 section 33, T. 22 S., R. 6 E., Salt Lake Base Line. Seaward limit: upper part of Muddy Creek Canyon, SE1/4NW1/4 section 13, T. 22 S., R. 6 E., Salt Lake Base Line. Facies content of shoreline unit: wave-modified shoreline, probably strand plain in proximal part and certainly wave-modified delta in distal part.

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