GRI-95/0167

COMPARATIVE ANATOMY AND PETROPHYSICAL PROPERTY STRUCTURE OF SEAWARD- AND LANDWARD-STEPPING DELTAIC RESERVOIR ANALOGS, FERRON SANDSTONE, UTAH

TOPICAL REPORT

(June 1, 1993–August 31, 1994)

Prepared by

Mark D. Barton and Edward S. Angle
Bureau of Economic Geology
Noel Tyler, Director
The University of Texas at Austin
Austin, Texas 78713-8924

for

GAS RESEARCH INSTITUTE

Contract No. 5089-260-1902

GRI Project Manager, Richard A. Parker

May 1995

QAe7822

DISCLAIMER

LEGAL NOTICE This work was prepared by the Bureau of Economic Geology as an account of work sponsored by the Gas Research Institute (GRI). GRI, nor members of GRI, nor any person acting on behalf of either:

a. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

b. Assumes any liability with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this report.

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. GRI-95/0167	2.	3. Recipient's Accession No.
4. Title and Subtitle Comparative Anatomy and Petrophysical Property Structure of Seaward- and Landward-Stepping Deltaic Reservoir Analogs, Ferron Sandstone, Utah			5. Report Date August 31, 1994 6.
7. Author(s) Mark D. Barton and Edward Angle			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Bureau of Economic Geology The University of Texas at Austin University Station, Box X Austin Texas 78713-8924			10. Project/Task/Work Unit No. 11. Contract(C) or Grant(G) No. (C) 5089-260-1902 (GRI) (G)
12. Sponsoring Organization Name and Address Gas Research Institute 8600 West Bryn Mawr Avenue Chicago, IL 60631 Project Manager: Paul Wescott			13. Type of Report & Period Covered Topical Report June 1, 1993–August 31, 14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

The recovery of natural gas from fluvial-deltaic reservoirs is governed by complex internal architectures. To aid in the translation of outcrop geology to reservoir equivalents, all existing Ferron outcrop, petrophysical, and subsurface data have been integrated into a geologic model of reservoir heterogeneity that compares and contrasts seaward- and landward-stepping stratigraphic cycles.

Reservoir architecture varies in a predictable fashion between seaward- and landward-stepping stratigraphic cycles. Within seaward-stepping units, delta-front strata are highly compartmentalized by marine and marginal marine shales coincident with stratigraphic cycle, parasequence, and mouth-bar bounding surfaces. Coeval distributaries are volumetrically a minor component and are preserved as ribbonlike sand bodies encased in finer grained strata. By contrast, within landward-stepping units parasequences and component mouth-bar deposits are amalgamated into a lithologically homogeneous strike-elongate sand body. Coeval distributaries are volumetrically a major component and are preserved as a complex network of interconnected, lithologically diverse sand bodies. Internal heterogeneities, related to floodplain, abandoned channel fill, and mud-clast lag deposits, severely disrupt lateral and vertical continuity.

Analysis of the Ferron gas field reveals that favorable sites for stratigraphic entrapment occur where proximal and distal portions of parasequences pinch out into lagoonal and marine mudstones, respectively.

17. Document Analysis a. Descriptors

Bounding element architecture, Ferron gas field, Ferron Sandstone, fluvial-deltaic reservoirs, reservoir analog, permeability distribution, petrophysical property structure, sandstone architecture, well log correlation

b. Identifiers/Open-Ended Terms

comparative analysis of bounding element architecture and petrophysical property structure in seaward- and landward-stepping reservoir analogs, permeability analysis of outcrop reservoir analogs, sequence stratigraphic controls on petrophysical property distribution and bounding element architecture, sequence stratigraphic framework of Ferron gas field, sequence stratigraphic controls on gas production, well log correlation and recognition

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Release unlimited	Unclassified	59
	20. Security Class (This Page) Unclassified	22. Price

(See ANSI–Z39.18) *See Instructions on Reverse*

OPTIONAL FORM 272 (4-77)
(Formerly NTIS–35)
Department of Commerce

RESEARCH SUMMARY

Title Comparative Anatomy and Petrophysical Property Structure of Seaward- and Landward-Stepping Deltaic Reservoir Analogs, Ferron Sandstone, Utah

Contractor Bureau of Economic Geology, The University of Texas at Austin, GRI Contract No. 5089-260-1902, titled "Characterization and Quantification of Geological and Petrophysical Heterogeneity in Fluvial-Deltaic Reservoirs."

Principal Investigators Noel Tyler, R. Stephen Fisher

Objectives Natural gas recovery from shaly sandstone reservoirs is limited by complex internal architectures. The goal of this work is the translation of geologic heterogeneities into useful and transportable information for well log analysts, development geologists, and production engineers. Objectives of this study are (1) an orderly comparison and contrast of phase I results; (2) the translation of outcrop geology using available well log tools into delineation of barriers and seals; and (3) the demonstration of stratigraphic controls on compartmentalization and entrapment. In this report, all existing Ferron outcrop, petrophysical, and subsurface data are synthesized into an integrated architectural model of reservoir heterogeneity.

Technical Perspective This project focuses on the Cretaceous Ferron Sandstone as an outcrop analog to a heterogeneous group of reservoirs having significant potential for reserve growth. Fluvial-deltaic reservoirs are investigated because of the importance of remaining resources in this reservoir type in Gulf Coast, Midcontinent, and Alaska petroleum provinces and because of the potential for incremental recovery through accurate reservoir characterization. The low hydrocarbon recovery efficiencies in Texas fluvial-deltaic reservoirs indicate that substantial reserves remain and highlight the need for predicting the spatial distribution of interwell heterogeneities. Exposures of the Upper Cretaceous Ferron Member of the Mancos Shale provide the opportunity to quantify the three-dimensional architecture and petrophysical attribute structure of fluvial-deltaic sandstones within a sequence stratigraphic framework and to document the expression of such relationships within a subsurface setting.

Changes in permeability structure and bounding element architecture are related to the two stratigraphic processes that govern stratal architecture: accommodation and stratigraphic base level (Jervey, 1988; Cross and Gardner, 1989; van Wagoner and others, 1990). Relating reservoir description to processes that control stratal architecture provides a means for importing and calibrating outcrop-derived data to reservoirs from other geologic settings and/or reservoirs of different geologic ages. The Ferron was deposited under conditions of high sediment supply and accommodation. Consequently, geometric attributes described in this report are characteristics of high subsidence rate margins where base level is generally rising and preservation potential is high.

The projected long-term benefits of this project are improved methods in the translation of outcrop geology into delineation of barriers and seals, and a means to compare and predict the characteristics of seaward-stepping and landward-stepping deltaic reservoirs that would aid in the delineation of the residency of remaining gas resources in targeted reservoirs and in the development of effective strategies for recovery of this resource.

Technical Approach

In this report the anatomy and petrophysical property structure of fluvial-deltaic reservoir analogs deposited under contrasting conditions of accommodation are examined. Stratigraphic, sedimentological, and petrophysical data used in this comparative analysis were collected from outcrops of the Cretaceous Ferron Sandstone during phase I of the GRI-funded Ferron Sandstone project that extended from January 1, 1989, to December 31, 1992. A GRI topical report titled "Quantifying reservoir heterogeneity through outcrops characterization: 1. architecture, lithology, and permeability distribution of a landward-stepping fluvial-deltaic sequence, Ferron Sandstone (Cretaceous), central Utah" documents the architecture and permeability structure of a fluvial-deltaic reservoir analog deposited under conditions of relatively high accommodation and high sediment supply. A companion topical report titled "Quantifying reservoir heterogeneity through outcrops characterization: 1. architecture, lithology, and permeability distribution of a seaward-stepping fluvial-deltaic sequence, Ferron Sandstone (Cretaceous), central Utah" documents the architecture and permeability structure of a fluvial-deltaic reservoir analog deposited under conditions of relatively low accommodation and high sediment supply.

During current phase II of the GRI-funded Ferron sandstone project, the stratigraphic framework and facies architecture of outcrop analogs are integrated with wireline logs, core descriptions, and petrophysical information obtained from adjacent wells to emphasize their relationship to reservoir equivalents. Stratal architecture imaged from extensive outcrops is calibrated with nearby well log and core data. On the basis of such relationships, regional and local cross sections are constructed differentiating key bounding surfaces and lithofacies associations. This exercise illustrates the use of sequence stratigraphy and sedimentology in constraining reservoir models and provides identification criteria necessary for accurate reservoir characterization. In addition, the reservoir architecture of the Ferron gas field is examined. Subsurface data from the Ferron gas field and outcrop information from nearby exposures of the Ferron Sandstone are integrated to construct a geological description of the field. The exercise documents styles of stratigraphic entrapment and compartmentalization within the Ferron Sandstone.

Results

Stratigraphic cycles, parasequences, delta-front clinoforms, and major facies associations are resolvable using conventional well log, core, and dipmeter data. Marine mudstones and coastal plain carbonaceous shales coincident with stratigraphic cycle and parasequence bounding surfaces form correlatable horizons over the distance of several miles to tens of miles, respectively. Well log and core analysis provide sufficient information to distinguish landward- from seaward-stepping architectures. Within the coastal-plain strata, vertically stacked to landward-stepping system tracts display increases in cycle thickness, facies diversity, and sand:shale content relative to seaward-stepping cycles. Within the delta-front strata, seaward-stepping cycles display increases in cycle thickness, facies diversity, and shale:sand content relative to landward-stepping cycles.

A comparative analysis contrasting styles of heterogeneity within the Ferron Sandstone demonstrates that stratal characteristics, bounding element attributes, and petrophysical property structure vary in a predictable fashion between landward- and seaward-stepping stratigraphic cycles.

Delta-front strata within seaward-stepping units are highly compartmentalized by marine and marginal marine shales coincident with stratigraphic cycle and parasequence bounding surfaces. Shales subdivide the delta front into numerous discrete offlapping to vertically stacked, upward-shoaling shoreline successions (parasequences or delta lobes) that form a divergent but generally dip-oriented sandy framework. Lithologic variation is high and varies between wave- and fluvial-dominated delta front successions. Shales of lesser continuity include fine-grain bay-fill successions that replace and separate delta lobes laterally. Bay fills are best developed within the seaward-stepping cycles at the position where the delta front progrades basinward of the underlying stratigraphic cycle. Analysis of the Ferron gas field reveals that marine mudstones bounding parasequences or delta lobes compartmentalize the reservoir. Favorable sites for stratigraphic entrapment occur where proximal and distal portions of parasequences pinch out into lagoonal and marine shales, respectively.

Marine shales coincident to stratigraphic cycle boundaries vertically subdivide the landward-stepping system tract. Within landward-stepping stratigraphic cycles, parasequences and component mouthbar deposits are amalgamated into a lithologically homogeneous strike-elongate sand body. The absence or poor development of bay-fill successions and marine mudstones coincident to parasequence bounding surfaces reflects the dominance of wave and storm processes. Lithologic variation is minimal and limited to gradual upward shoaling and onshore to offshore facies transition.

Channel sand bodies associated with seaward-stepping units are preserved as lithologically homogeneous ribbonlike sand bodies, encased in and widely separated from adjacent channel sand bodies by mud-rich delta-plain, bay-fill, and lower delta-front strata, providing excellent conditions for reservoir compartmentalization. Because of their scale, the probability of contacting one of these sand-body types by conventional drilling strategies is relatively low. However, the crosscutting nature of distributary channel sand bodies with underlying delta-front deposits indicates that they are likely to have an important impact on fluid flow. Dip-aligned channel belts may act as conduits connecting delta-front strata of separate progradational events, providing no low-permeability flow boundaries are present along the facies contact. These relationships are almost reversed in landward-stepping deltaic successions. Within the delta-plain distributaries are preserved a complex network of broad, tabular sand bodies, elongate parallel to depositional dip, that encase adjacent fine, interdistributary deposits. Internal heterogeneities, related to abandoned channel fill, and mudclast lags and mudstone drapes, formed principally along channel base bounding surfaces, severely disrupt lateral and vertical continuity.

Reservoir volumetrics reflect sediment partitioning trends. Volumetrically, distributary channel deposits make up the principal reservoir facies in landward-stepping stratigraphic cycles, whereas the reversed relationship is true of seaward-stepping stratigraphic cycles where delta-front strata compose the dominant reservoir facies. Reservoir quality and the spatial distribution of reservoir properties are largely determined by environment of deposition. Wave-dominated intervals are better sorted and more quartz-rich than fluvial-dominated intervals and predictably display higher porosity and permeability. The delta-front facies association consists of upward-coarsening successions with fine-grain pelagic sediments at their bases, grading upward into quartz-rich sandstones. Permeability increases from the base to the top of the cycle and displays minimal variation along strike except where mud-rich abandoned channel fills have removed and replaced a portion of the otherwise homogeneous wave-dominated delta front. The best reservoir units occur at the top and near the landward pinchout of each upward-coarsening succession. In seaward-stepping units the proximal and distal portions of the delta-front facies tract are where wave-dominated delta-front sand bodies are most likely to form, whereas in landward-stepping units the delta-front facies tract is mostly wave dominated.

Within distributary channel belts, permeability patterns reflect the geometric arrangement of channel forms. In distributary channel belts coeval to seaward-stepping cycles, permeability patterns are the composite of several trends that reflect the vertical stacking of channel forms within these multistory channel belts. Within landward-stepping cycles, permeability patterns display an upward-fining trend that reflects the strong vertical partitioning of stratal types. Laterally, this trend is disrupted by the presence of thick, mudclast-rich lags deposited along channel base bounding surfaces within these multilateral channel belts.

Project Implications:

This research has characterized a reservoir analog exposed in outcrop. The comparison with the producing Ferron field indicates the role which flow barriers play in creating storage compartments and the scale on which they occur. It is our hope that the sequence stratigraphic definition of the environments within the fluvial-deltaic system will be useful in estimating size and architecture of similar environments elsewhere.

During the next and final year it is very important to relate this characterization study to fluvial-deltaic environments in other locations, specifically the Gulf Coast, and to evaluate how useful an outcrop study can be when projected to reservoir scales.

CONTENTS

Figures

Abstract

In this report, outcrop information is integrated with adjacent subsurface data to examine reservoir heterogeneity within fluvial-deltaic deposits. Sequence stratigraphic and sedimentologic principles are used to divide extensive outcrops of the Ferron Sandstone into a hierarchy of stratal units consisting of stratigraphic cycles and parasequences. Within this framework, lateral facies relationships, barriers to flow, and the distribution of petrophysical properties are documented and mapped in detail. A suite of wells located adjacent to the Ferron outcrop document the expression of stratigraphic cycles, parasequences, and facies characteristics in wireline and core data. A comparative analysis contrasting styles of heterogeneity within the Ferron Sandstone demonstrates that stratal characteristics, bounding element attributes, and petrophysical property structure vary in a predictable fashion between landward- and seaward-stepping stratigraphic cycles. Analysis of the Ferron gas field reveals that marine mudstones bounding parasequences or delta lobes compartmentalize the reservoir. Favorable sites for stratigraphic entrapment exist where proximal and distal portions of parasequences pinch out into lagoonal and marine shales, respectively.

Introduction

This project focuses on the Cretaceous Ferron Sandstone as an outcrop analog to a heterogeneous group of fluvial-deltaic reservoirs having significant potential for reserve growth. Fluvial-deltaic reservoirs are investigated because of the importance of remaining resources in this reservoir type in Gulf Coast, Midcontinent, and Alaska petroleum provinces and because of the potential for incremental recovery through accurate reservoir characterization. The low hydrocarbon recovery efficiencies in Texas fluvial-deltaic reservoirs, which range from only 24 percent to 69 percent (average 40 percent), indicate that substantial reserves remain and highlight the need for predicting the spatial distribution of interwell heterogeneities. Exposures of the Upper Cretaceous Ferron Member of the Mancos Shale provide the opportunity to quantify the three-dimensional architecture and petrophysical attribute structure of fluvial-deltaic sandstones within a sequence stratigraphic framework and to document the expression of such relationships within a subsurface setting. The end product of this analysis is a quantitative image of internal reservoir structure in a form that is based on normally available reservoir data.

Approach

In this report, sedimentology, sequence stratigraphy, petrology, petroleum geology, petroleum engineering, geostatistics, and petrophysics are combined in order to understand geologic controls governing reservoir heterogeneity. The goal is to provide a geological model of reservoir heterogeneity within fluvial-deltaic deposits that can be translated into usable information by well log analysts, development geologists, and production engineers. The integration effort involves three tasks.

In the first task, the geometry, architecture, and distribution of important lithofacies are documented within a sequence stratigraphic framework and integrated with subsurface data to emphasize their relationship to reservoir equivalents. Stratal architecture imaged from extensive outcrops is calibrated with nearby well log and core data. On the basis of such relationships, regional and local cross sections are constructed, differentiating key bounding surfaces and lithofacies associations. This exercise illustrates the use of sequence stratigraphy and sedimentology in constraining reservoir models and provides identification criteria necessary for accurate reservoir characterization.

In the second task, the anatomy and petrophysical property structure of seaward- versus landward-stepping reservoirs are compared and contrasted by linking permeability structure and bounding element architecture to a hierarchy of sedimentologic and stratigraphic elements. Changes in reservoir architecture are related to two stratigraphic processes: accommodation and stratigraphic base level (Jervey, 1988; Gardner and Cross, 1989; van Wagoner and others, 1990; Gardner, 1993). Relating a stratigraphic and sedimentological hierarchy to reservoir description provides the means for importing and calibrating outcrop-derived data to reservoirs from other geologic settings and/or reservoirs of different geologic ages. The Ferron was deposited under conditions of high sediment supply and accommodation. Consequently, the geometric attributes described are characteristics of high subsidence rate margins where base level is generally rising and preservation potential is high.

In the third task, the reservoir architecture of the Ferron gas field is examined. Subsurface data from the Ferron gas field and outcrop information from nearby exposures of the Ferron Sandstone are integrated to construct a geological description. The exercise documents styles of stratigraphic entrapment and compartmentalization within the Ferron Sandstone.

Methods and Data

This study is a synthesis of considerable previous sedimentologic, stratigraphic, and petrophysical analysis. Methods and sources of information for each task are discussed below.

Task I

Over the past 12 years a number of petroleum companies and research groups have conducted a series of shallow subsurface studies on the Ferron Sandstone. A total of 15 stratigraphic test wells have been drilled adjacent to the Ferron outcrop: 7 wells by ARCO in 1982 (ARCO 82-2, 82-3, 82-4, 82-5, 82-6, 82-8, and an ARCO stratigraphic test well [Thompson, 1985]) and the collection of core, wireline, and petrophysical data of the entire Ferron sequence; 1 well by Unocal Oil Company in 1984 (DW-1 [Rex Cole, personal communication, 1990]) that includes core and wireline data of the entire Ferron sequence; 2 wells by University of Utah Research Institute in 1991 (UURI 1 and UURI 2) and the collection of core, wireline, FMS, and dipmeter data of the entire Ferron sequence; and 5 wells by British Petroleum in 1992 (MC 1–5 [Gustason and others, 1993]) and the collection of wireline data of the entire Ferron sequence and core through SC 1 and SC 2. The Utah Geological Survey plans to drill five to seven wells in the Ivie Creek area during the fall of 1994.

In the first task, previous stratigraphic studies by Ryer (1977, 1981, 1982), Ryer and McPhillips (1983), Ryer and Lovekin (1986), and Gardner (1992, 1993) provide a starting point in the construction of a stratigraphic framework. Additional stratigraphic and sedimentological data have been collected in the field and from continuous cliff face photomosiacs along the Molen Reef escarpment between Miller and Short Canyons (18 mi). This outcrop-derived data base has been calibrated with key surfaces and facies associations identified in cores and well logs located adjacent to the outcrop, and the stratigraphic framework has been reconstructed. Wireline, core, and petrophysical data obtained from 12 stratigraphic test wells have been assembled into 2 cross sections differentiating key bounding surfaces and facies associations. The first cross section (fig. 1) consists of eight wells (ARCO St-1, 82-8, 82-6, 82-4, 82-2, Unocal No. 1, UURI No. 1, and British Petroleum MC No. 2) distributed along a 20-mi section that parallels the depositional axis of the Ferron system. The second cross section (fig. 2) consists of six wells (UURI No. 1 and British Petroleum MC No. 1 through MC No. 5) spaced approximately

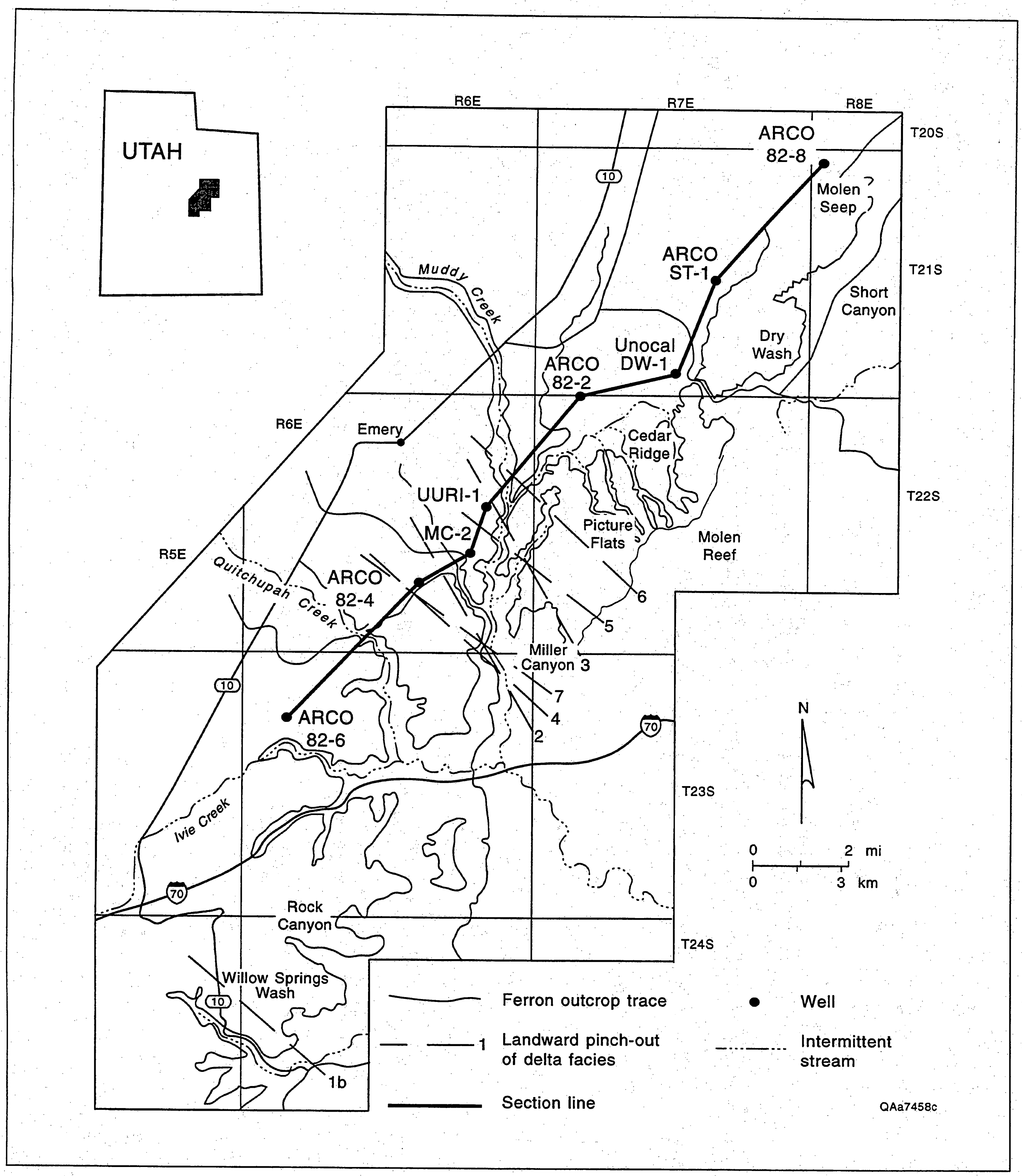


Figure 1. Location of wells used in regional cross section.

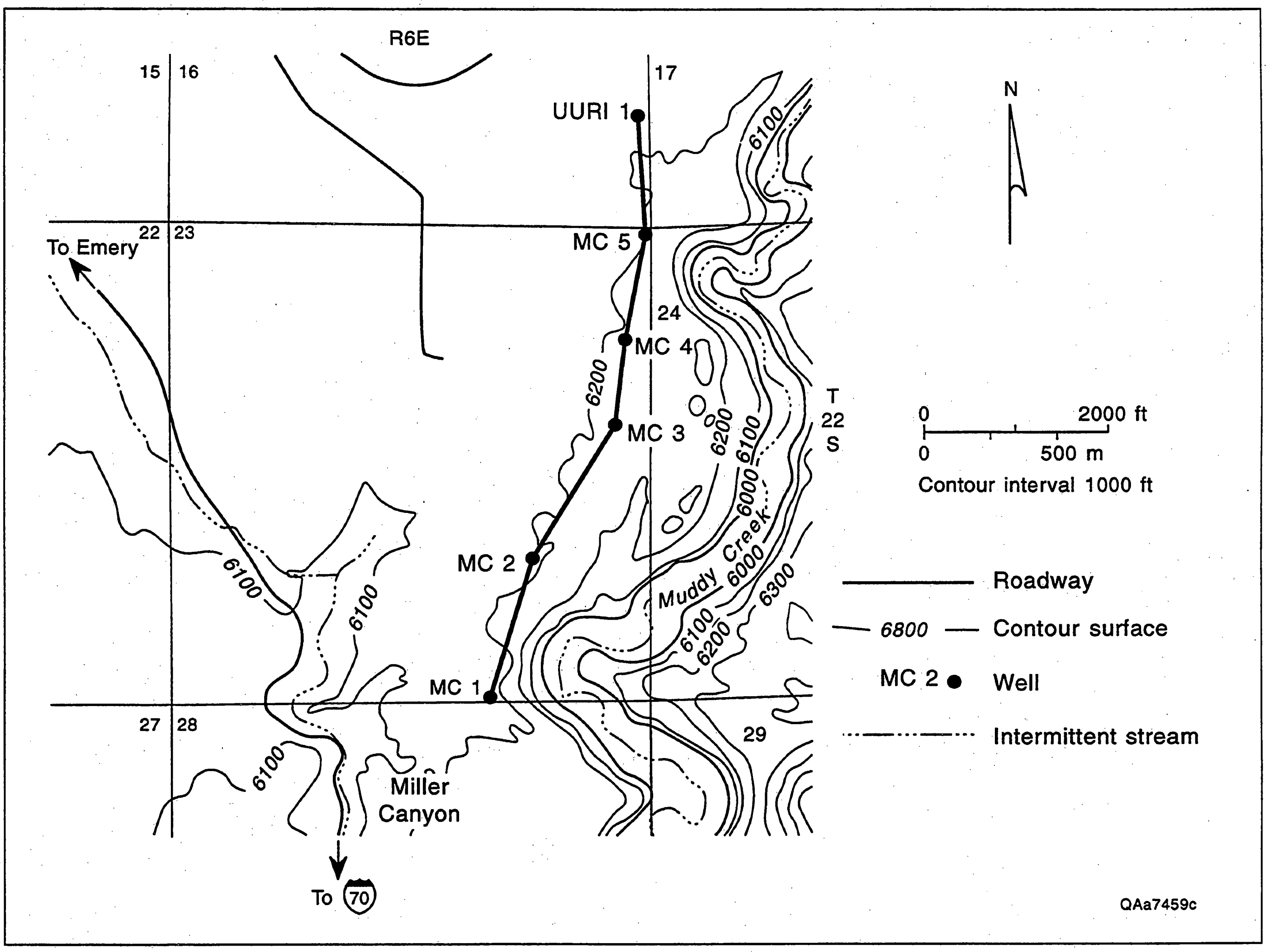


Figure 2. Location of stratigraphic test wells used in local cross section.

1,000 ft apart along a 1-mi-long section that is subparallel to the depositional axis of the Ferron system in the vicinity of Muddy Creek.

Task II

Data for the second task are largely derived from two studies (Gardner, 1993; Barton, 1994). Work by Gardner (1993) established a stratigraphic hierarchy of chronostratigraphic units and related stratigraphic cycle stacking patterns to their sedimentological and facies attributes. Stratigraphic cycle stacking patterns and facies compositions in shallow-marine and coastal-plain facies tracts are shown to vary with stratigraphic position; seaward- and landward-stepping stratigraphic cycles contain fluvial- (SC 2) and wave-dominated (SC 5) deltaic facies, respectively. Stratigraphic changes in facies associations are interpreted to record systematic changes in accommodation, volumetric partitioning of sediments in time and space, and facies differentiation during stratigraphic cycles. Within this chronostratigraphic framework, Barton (1994) quantified changes in facies architecture and permeability structure. Two deltaic cycles of contrasting depositional style were selected for study: a strongly fluvial-dominated, seaward-stepping deltaic unit, referred to as stratigraphic cycle no. 2 (SC 2), and a wave-modified, landward-stepping unit, referred to as stratigraphic cycle no. 5 (SC 5). Within each of these units, representative areas were selected for detailed analysis, including field-scale characterization of sandstone architecture and quantification of permeability variation by use of a field minipermeameter from representative outcrops.

Figure 3 is an index map of the Ferron study area showing the location of detailed case study areas.

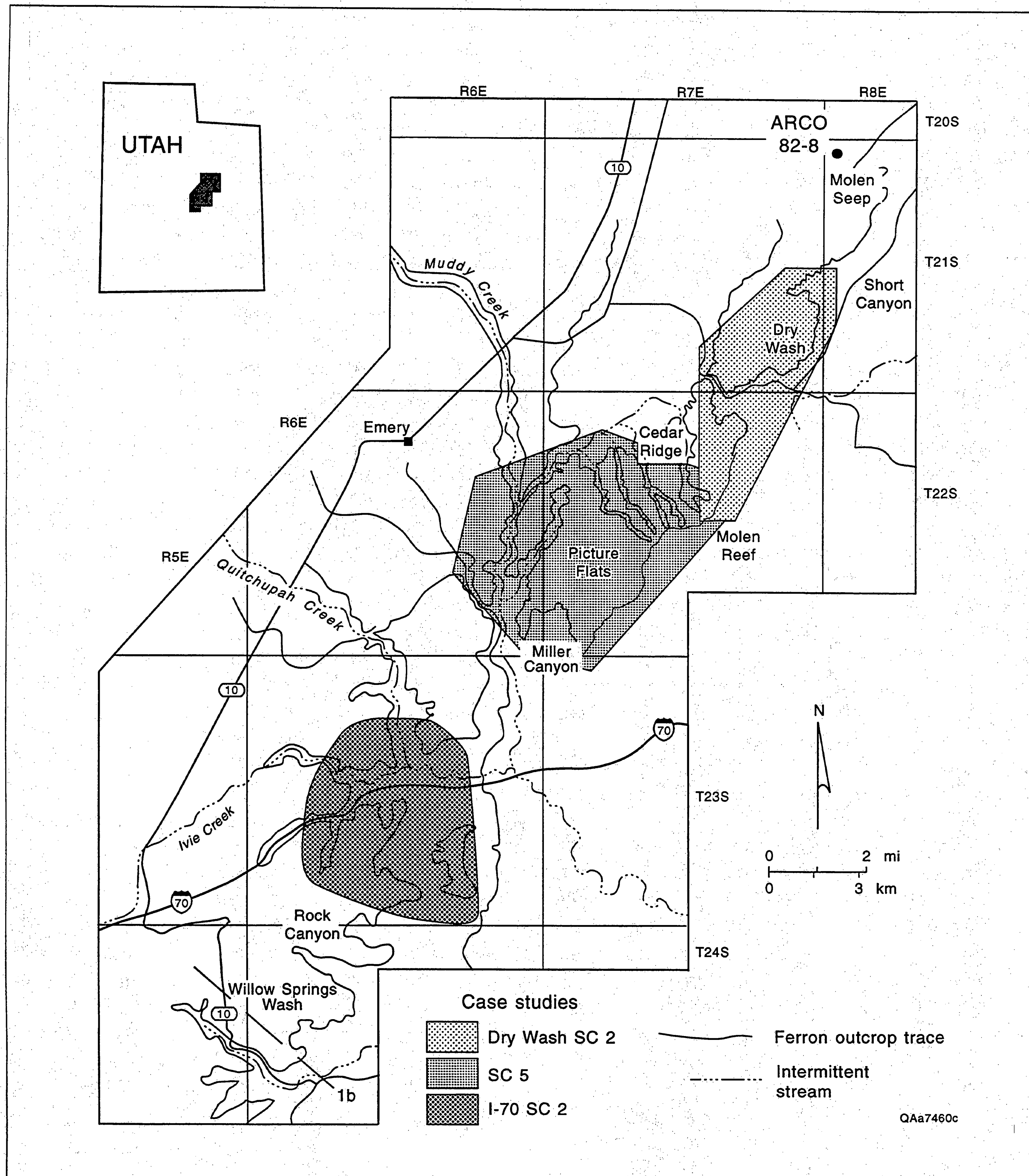


Figure 3. Index map of BEG–Ferron case study.

Within the seaward-stepping stratigraphic cycles, stratigraphic and permeability data were collected at two sites. The first site is located near Ivie Creek Canyon and the Interstate 70 (I-70) road cut, a position approximately 15 mi landward from the Dry Wash locality. At this site the investigation focused on channel belt architecture and permeability variation within a large distributary channel sand body.

The second site is located where Dry Wash canyon intersects the Molen Reef escarpment, a position near the seaward extent of the delta-plain facies tract within SC 2 (fig. 4). At this locality, the investigation examined permeability variation and delta-front architecture. Additional stratigraphic data documenting parasequence relationships were gathered primarily along the Molen Reef escarpment between Miller Canyon and Short Canyon. The outcrop provides a continuous cross-sectional view subparallel to the depositional profile of the Ferron system for a distance of approximately 10 mi.

Within the landward-stepping stratigraphic cycles, outcrop characterization concentrated on four localities positioned along the depositional profile of SC 5 (fig. 5); these include, from southwest to northeast: (1) Muddy Creek Canyon, near the landward pinchout of marine sandstone, (2) Picture Flats Canyon, about 1 mi seaward of Muddy Creek, (3) Cedar Ridge I, about 1 mi seaward of Picture Flats, at the seaward extent of SC 5 distributary channels, and (4) Cedar Ridge II, approximately 0.5 mi seaward of Cedar Ridge I.

During the geologic investigation of permeability variation funded during phase I of the GRI Ferron Project, over 12,000 outcrop-derived minipermeameter measurements were obtained from SC 2 and SC 5. An additional 5,000 permeability measurements have been collected from core samples obtained from 6 stratigraphic test wells drilled adjacent to the Ferron outcrop.

Sources of additional outcrop-derived architectural and permeability data include Lowry and Rabeim (1991), who gathered data on sand-body dimensions within seaward-stepping stratigraphic cycles. Ryer and others (1993) examined facies relationships of seaward-stepping stratigraphic cycles south of I-70. Stalkup and Ebanks (1986) examined the effects of weathering on outcrop-derived permeability measurements and examined the relationship of permeability to lithofacies characteristics within shallow marine strata of SC 3 near Dry Wash. Garrison and Smallwood (1993) collected permeability data from a distributary channel sand body within SC 1 near Willow Springs Wash. Lowry and Jacobsen (1993) modeled the effects of lithofacies variation from outcrop-derived permeability within a wave-dominated shoreline sand body from SC 2 near Short Canyon.

Petrographic and petrophysical studies completed by Fisher and others (1993) of the Bureau of Economic Geology and by Dr. John Holder (*in* Miller and others, 1993) of the Earth Sciences and Engineering Laboratory of The University of Texas have augmented the BEG field studies by resolving the relative importance of depositional and diagenetic processes on porosity and permeability. They also established petrophysical relations for a suite of select field and core samples (UURI No. 1 and 2) of contrasting permeability character. In addition, petrophysical data available from the ARCO cores have been used to supplement the existing data set.

Task III

The third task involved reservoir characterization of the Ferron gas field using principles developed during the first two tasks. The Ferron gas field lies 5 mi south and 3 mi east of the town of Ferron in east-central Utah. Data from the field consist of 40 geophysical logs (fig. 6) in a 20-mi^2 area, as well as production data and perforated zones for each well. Additional information was provided by core obtained from two nearby stratigraphic test wells (ARCO 82-2 and ARCO Stratigraphic Test Well No. 1) and outcrop exposures of the Ferron Sandstone located 3 mi to the east of Ferron field.

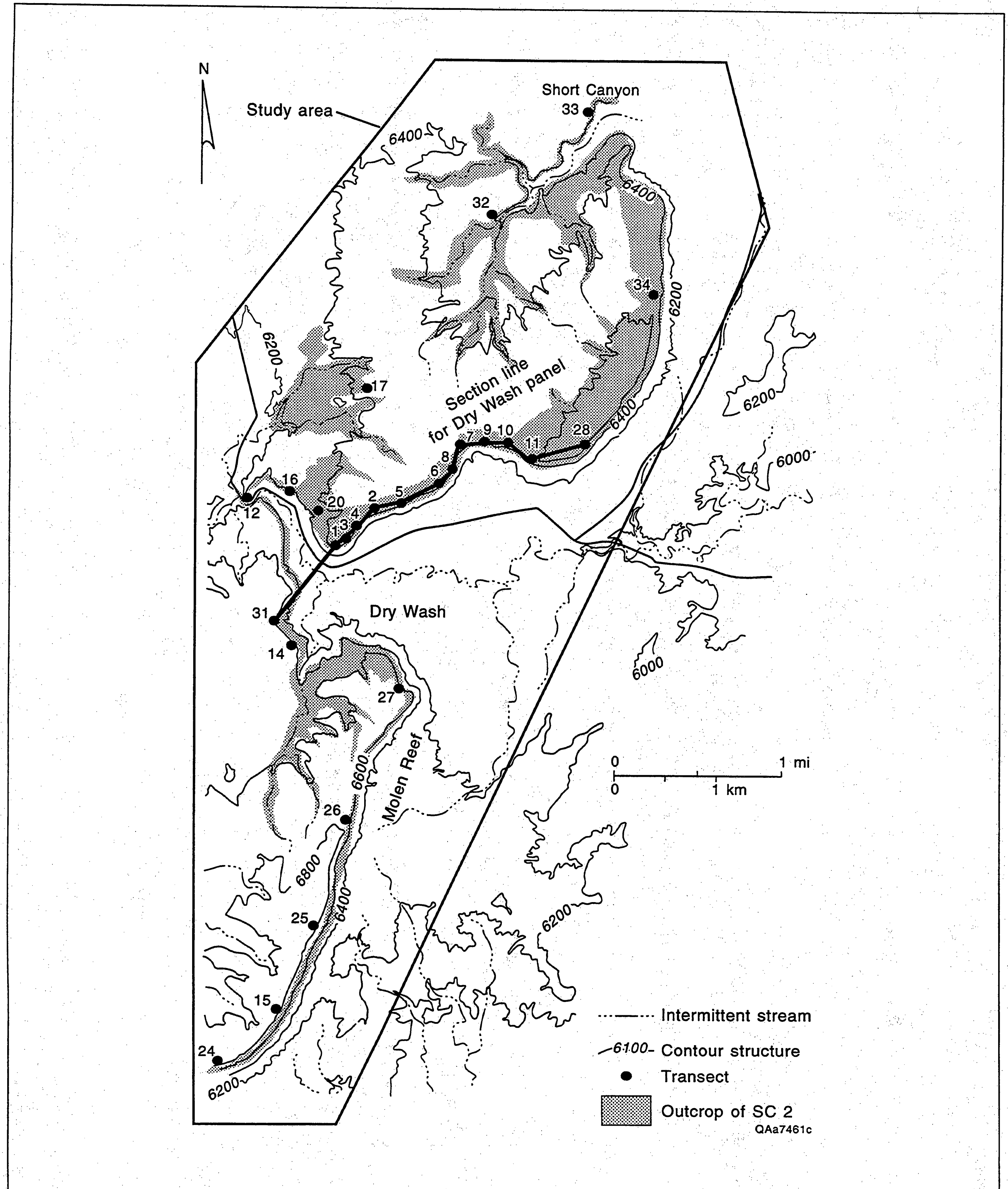


Figure 4. Index map of stratigraphic and permeability studies within Ferron SC 2.

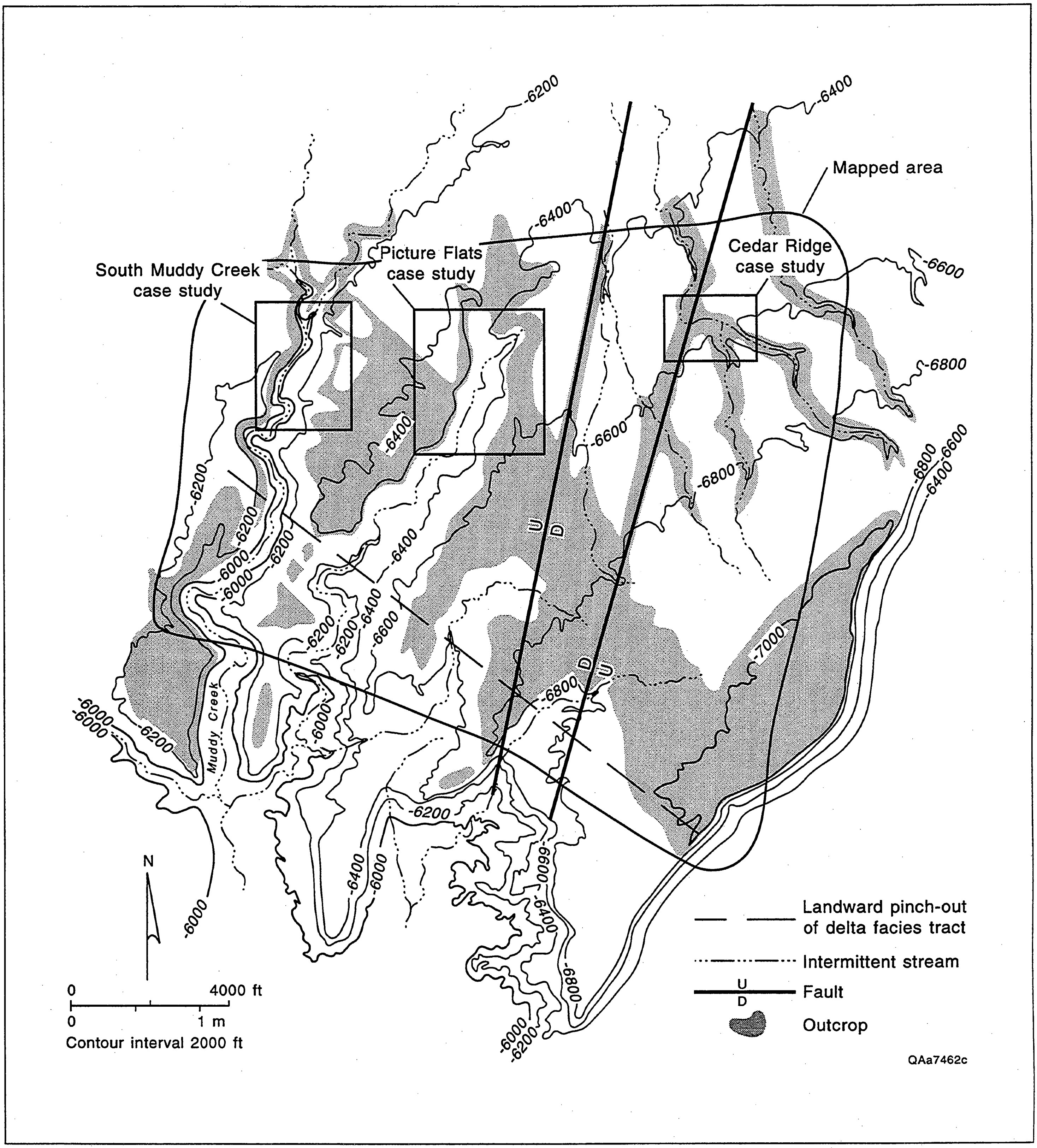


Figure 5. Index map of stratigraphic and permeability studies within Ferron SC 5.

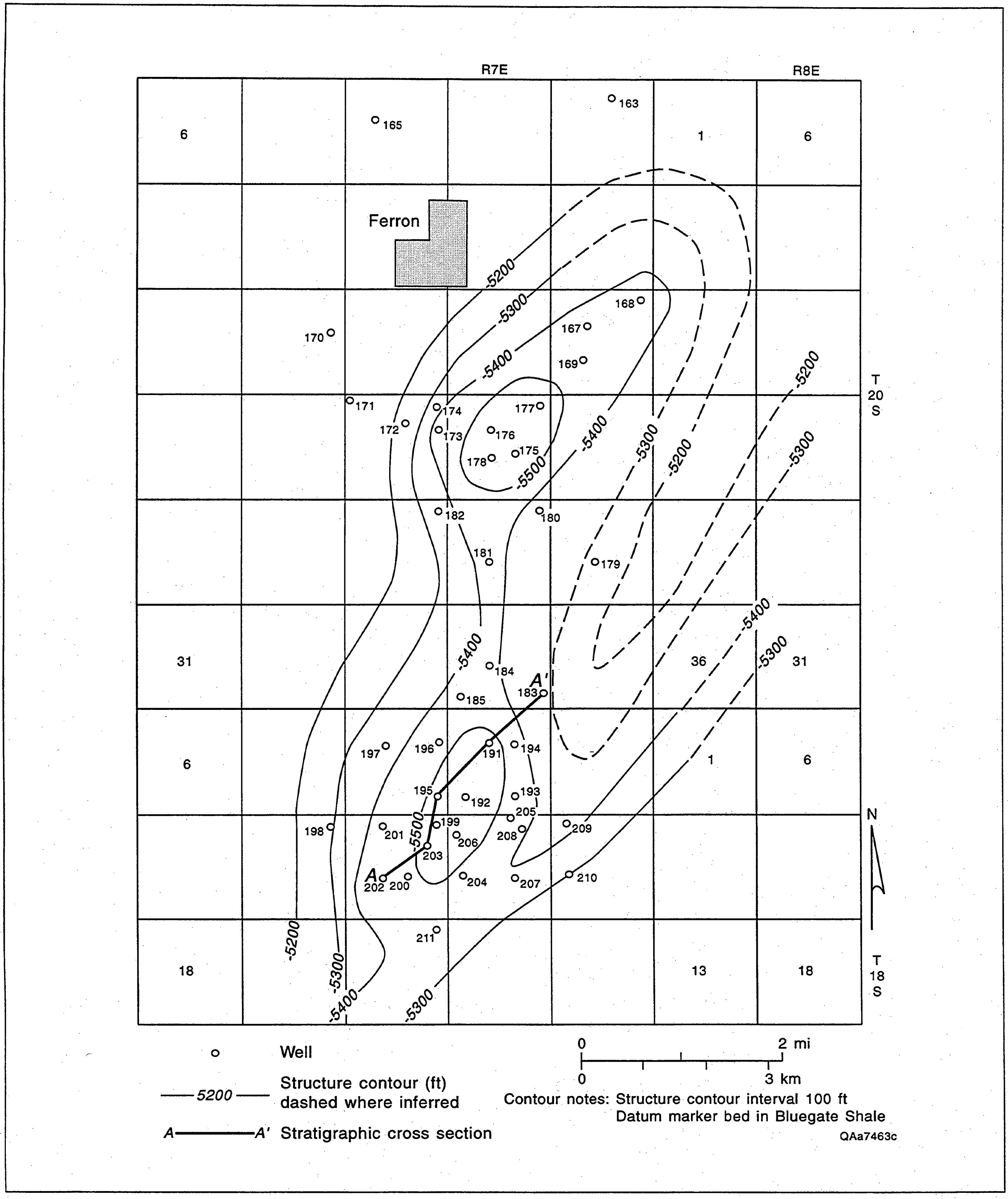


Figure 6. Structural contour map of Ferron gas field (after Tripp, 1991).

Outcrop Analog: The Ferron Sandstone, Utah

Location

Exposures of the Cretaceous (Turonian) fluvial-deltaic Ferron Sandstone form a succession of northwestward-dipping, northeast-trending ridges that outcrop for a distance of 60 mi along the eastern margin of Castle Valley in east-central Utah (fig. 7). Paleocurrent analysis of marine sandstones indicates that Ferron ridges are oriented subparallel to the northeasterly progradation of the upper Turonian shoreline (Davis, 1954; Katich, 1954; Gardner, 1993). Small side canyons (Ivie Creek, Miller Canyon, and Dry Wash) that crosscut the escarpment provide limited views parallel to depositional strike.

Geological Setting

The Upper Cretaceous Ferron Sandstone is a member of the Mancos Shale and consists of cyclically interbedded successions of mudstone, siltstone, sandstone, and coal that form an eastward-thinning clastic wedge bounded by marine mudstones and siltstones of the underlying and overlying Tununk and Bluegate Shale members of the Mancos Shale, respectively (fig. 8). The Ferron Sandstone and contemporaneous strata (Frontier Formation) in the Western Interior record a widespread regression of the Western Interior shoreline as thrust belt sediments were shed eastward and accumulated within a rapidly evolving foreland basin during a highstand in sea level. Biostratigraphy and argon-argon-dated volcanic ashes within the Ferron sequence indicate that it accumulated over a period of 1.5 to 2 m.y. during Turonian through early Coniacian time (Gardner and Cross, 1989). The Ferron exposes a complete deltaic systems tract of coastal-plain through marine strata. Investigators have interpreted the Ferron sequence to have been deposited by a system of small lobate deltas that formed along the western margin of the Cretaceous seaway (Ryer and McPhillips, 1983) or alternatively by longitudinal axial drainage from a large fluvial system flowing parallel to the thrust belt from southern to central Utah (Gardner, 1993).

Early workers separated the Ferron Sandstone Member into two distinct depositional systems (Davis, 1954; Katich, 1954; Hale and van de Graaf, 1964; Hale, 1972). In the study area, the lower system, informally called the Vernal Delta (Hale and van de Graaf, 1964), consists of shelf sediments from an older northerly derived clastic wedge that contains the ammonite *P. hyatti* and therefore is referred to as the Hyatti sequence (Gardner, 1993). The younger depositional system, informally called the Last Chance delta (Hale, 1972), consists of coal-bearing deltaic sediments and is from a southerly derived, westward-thickening clastic wedge called the Ferron sequence (Gardner, 1993).

On the basis of outcrop exposures, Ryer (1981) divided the upper Ferron sequence into seven discrete and mappable deltaic cycles (designated no. 1 through 7 in ascending stratigraphic order) that range in thickness from 40 to 120 ft and extend several miles to tens of miles along depositional profile. Each cycle consists of a delta-front sand body and associated coal bed (designations originally assigned by Lupton, 1916) that record a regressive-transgressive cycle of sedimentation. Deltaic cycles that compose the Ferron sequence are characterized by initial forward- or seaward-stepping arrangements (no. 1 through 3, followed by vertical- to back- or landward-stepping arrangements (no. 4 through 7), as illustrated by comparing geographic positions of each shallow-marine facies tract. Utilizing stratigraphic, sedimentologic, and biostratigraphic evidence, Gardner (1993) extended Ryer's work by erecting a chronostratigraphic framework of the Ferron system that physically and temporally relates nonmarine- through marine-shelf strata. The methodology used is based on vertical and lateral changes in facies architecture of shallow-marine and coastal-plain strata that correspond to cycles of increasing and decreasing accommodation and sediment supply rates in different facies tracts.

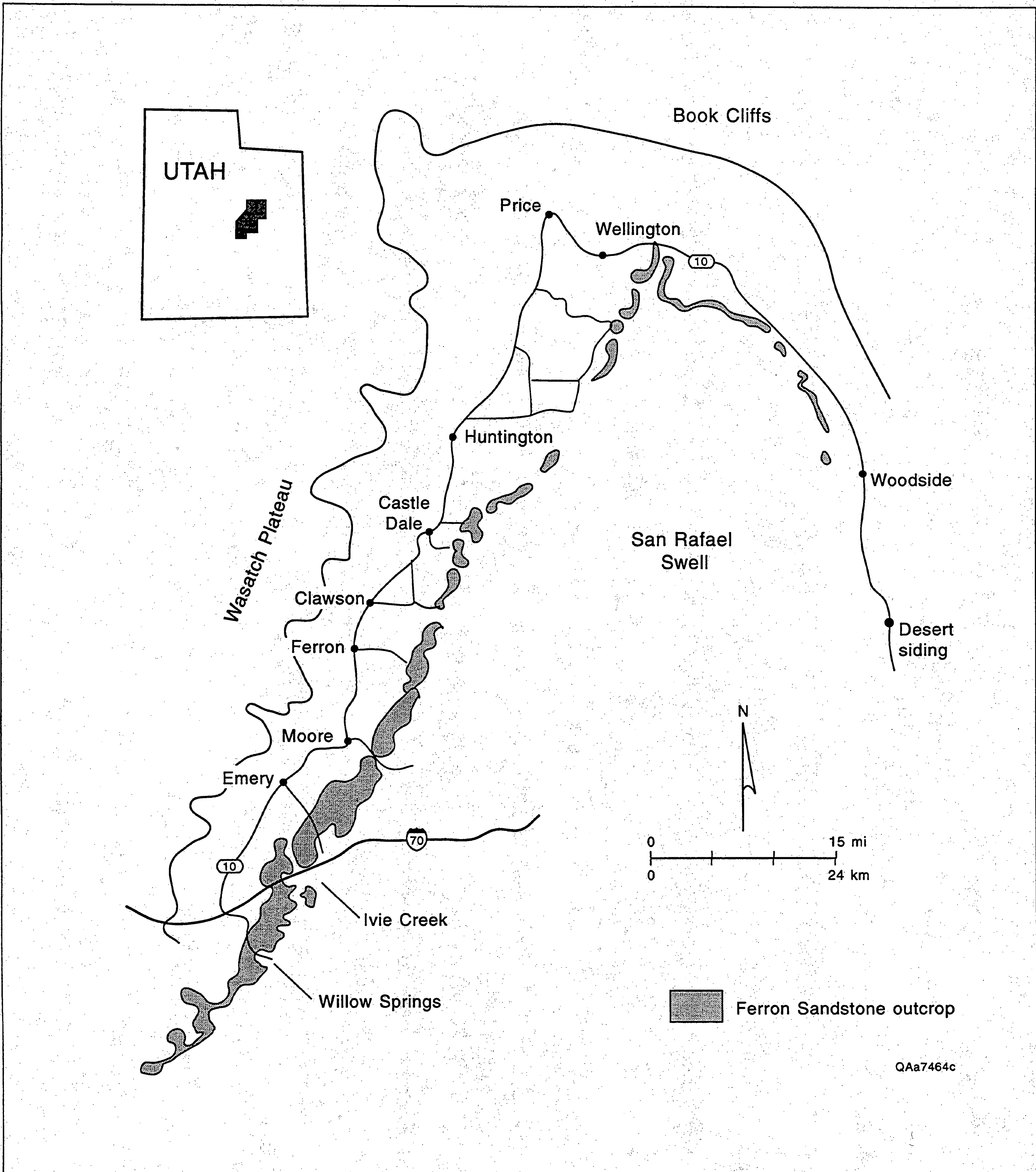


Figure 7. Location of the Ferron Sandstone outcrop in Castle Valley, Utah.

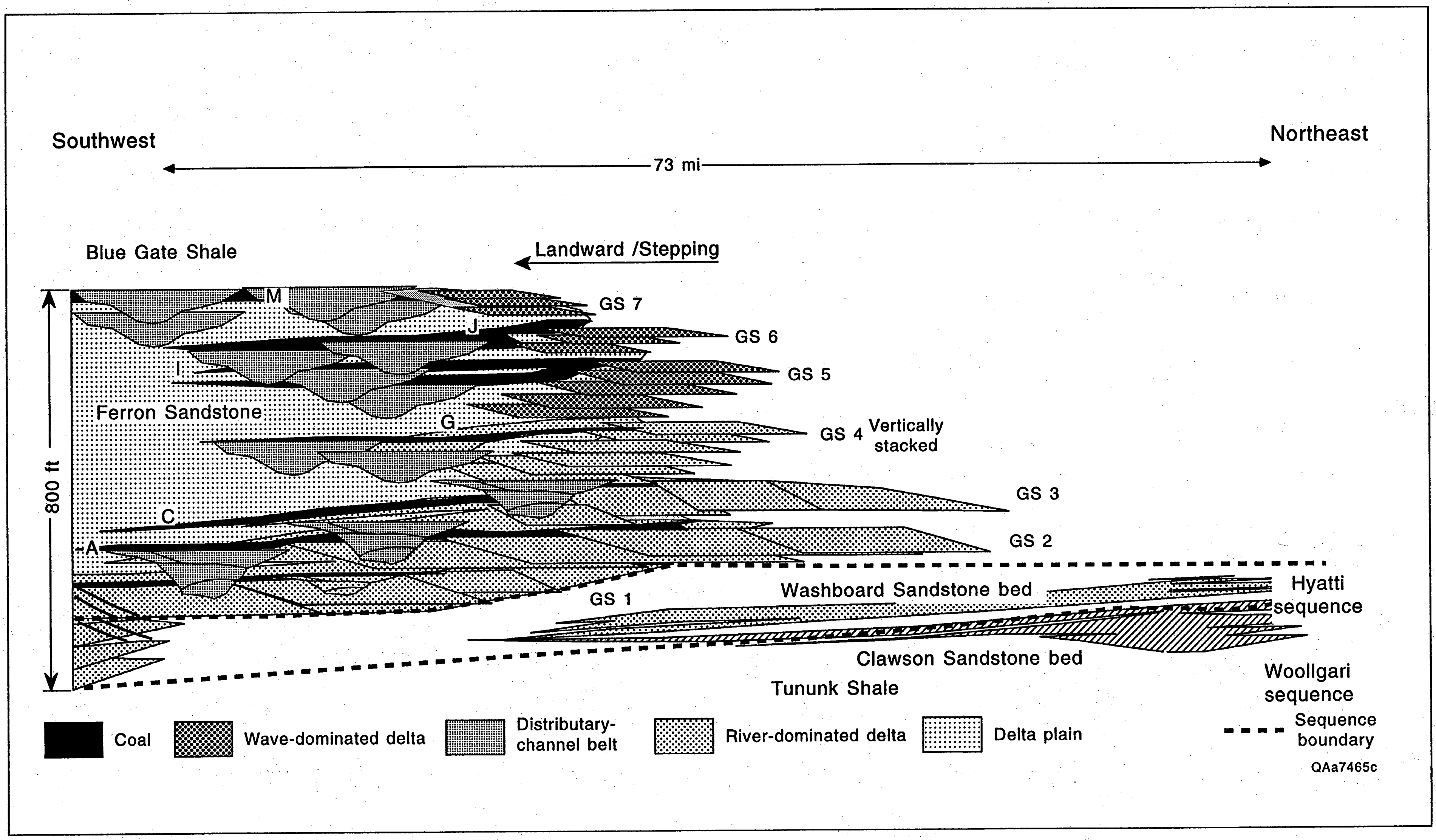


Figure 8. Schematic cross section depicting sequence stratigraphic relationships of Ferron Sandstone in central Utah (after Ryer, 1981; Gardner, 1993).

Stratigraphic and Sedimentologic Concepts

Sequence stratigraphy is the study of genetically related facies within time-significant surfaces. Fundamental to sequence stratigraphy is the recognition that sedimentary rocks are composed of a hierarchy of stratal units (Campbell, 1967; van Wagoner and others, 1990). Within the Ferron system, stratigraphic surfaces and/or correlative strata define a threefold hierarchy of stratigraphic elements bounded by marine flooding events. Each stratigraphic element records an episode of regression and transgression under conditions of rising relative sea level. From smallest to largest, this hierarchy consists of parasequences, stratigraphic cycles, and composite sequences.

A parasequence is defined as a relatively conformable succession of beds and bedsets that record a seaward migration of sedimentary environments bounded by marine flooding surfaces or their correlative surfaces (van Wagoner and others, 1990). A stratigraphic cycle is defined as a conformable set of parasequences recording a seaward to vertical migration of sedimentary environments. A sequence is defined as a succession of stratigraphic cycles recording a seaward, vertical, and landward migration of sedimentary environments. Within sequences, distinctive stacking patterns described geometrically as seaward-stepping, vertically stacked, and landward stepping (Cross, 1988) are grouped into system tracts. System tracts define a linkage of contemporaneous depositional systems and provide a high degree of facies predictability within the framework of sequence boundaries (Cross and others, 1993). Regardless of scale, each stratigraphic element is a chronostratigraphic rock unit bounded by surfaces that separate younger from older strata.

Each stratigraphic element contains a complete spectrum of marine-shelf, shallow-marine, and coastal-plain facies tracts. The marine-shelf facies tract records deposition on a storm-dominated shelf below storm wave base. Deposits consist of outer-shelf mudstones and inner-shelf, thin, interbedded sandstones and mudstones, which are capped by condensed sections of fossiliferous, organic-rich siltstone, muddy bioturbated sandstone, or concretionary calcarenite. The shallow-marine facies tract records deposition in a shoreline setting between storm wave base and the swash zone. Facies associations include prodelta, lower through upper delta-front, foreshore, and bay-fill successions. The delta-plain facies tract records nearshore to nonmarine conditions landward of the shore zone. Facies associations include distributary channel belt, crevasse splay, levee, overbank, swamp, marsh, and lagoonal successions.

Accommodation, Base Level, and Stratal Architecture

The Ferron sequence, component stratigraphic cycles, and boundaries are interpreted as the product of two stratigraphic processes: accommodation and stratigraphic base level (Jervey, 1988; Gardner and Cross, 1989; van Wagoner and others, 1990; Gardner, 1993). Accommodation regulates the volume of sediment preserved in different facies tracts. Base level reflects the transfer of sediment mass across the Earth by processes that erode, transport, and deposit sediment. During a base-level cycle, a progradational/aggradational unit is deposited within available accommodation space and is positioned according to sediment flux. Changes in progradational geometry and sediment volume partitioning of shallow-marine and coastal-plain facies tracts reflect geographic and temporal shifts in the site of maximum effective accommodation space (Gardner, 1993). In seaward-stepping progradational units, the position of maximum effective accommodation space is shifted seaward, reducing effective accommodation space in proximal regions of the fluvial and coastal-plain tract. The volume of sediment exceeds available accommodation space, and lateral progradation dominates over vertical aggradation. By contrast, in landward-stepping progradational units, the position of maximum effective accommodation space is shifted landward, increasing effective accommodation space in proximal regions of the fluvial and coastal-plain facies tract. The volume of sediment accumulating in shoreface settings is proportionally reduced, and vertical aggradation dominates over lateral progradation.

The progressive changes from fluvial- to wave-dominated delta-front facies in seaward- to landward-stepping short-term cycles reflect the sensitivity of delta-front profiles to the balance between ocean waves and currents and sediment discharge from feeding distributary channels (Gardner, 1993). In seaward-stepping cycles, negligible sediment is stored in the coastal-plain facies tract. Proportionally greater sediment volume accumulates in shallow-marine facies tracts that step seaward, recording higher progradation/aggradation ratios. Higher progradation rates allow waves and currents proportionally less time to rework sediment delivered to the shoreface. Increased accommodation landward increases storage capacity in coastal-plain facies tracts, causing shallow-marine facies tracts to step landward. These changes produce different facies mosaics and facies proportions within the same facies tracts of different stratigraphic cycles.

Stratigraphic Correlation and Recognition

The Ferron sequence and component stratigraphic cycles, parasequences, bedsets, and facies associations are illustrated in outcrop-based well log and core cross sections. In the first cross section (fig. 9), the stratal expression of stratigraphic cycle, parasequence, and facies attributes are illustrated in well log response and core descriptions. The cross section parallels the depositional axis of the Ferron system between Ivie Creek Canyon and Short Canyon, a distance of approximately 20 mi. Complex lateral and vertical facies changes in delta-front and coastal-plain strata within seaward-stepping cycles SC 1b and SC 2 are documented in a second cross section that extends approximately 1 mi subparallel to the depositional axis of the Ferron system near Muddy Creek (fig. 10). A volcanic ash bed present within the C coal was used as a datum to construct both cross sections. The datum approximates the boundary between the regressive and transgressive facies tracts.

Ferron Stratigraphic Framework

Marine strata of the underlying Tununk Shale and overlying Bluegate Shale bound the Ferron sequence, which forms a northeastward-thinning clastic wedge ranging in thickness from 450 ft near Ivie Creek Canyon to less than 200 ft near Short Canyon. Eight stratigraphic cycles (listed from oldest to youngest as SC 1a, SC 1b, SC 2, SC 3, SC 4, SC 5, SC 6, and SC 7) compose the system. The stratigraphic framework documented in this investigation differs slightly from previous studies (Ryer, 1981; Ryer and others, 1993; Gardner, 1993), which recognized seven stratigraphic cycles. Stratigraphic cycles previously identified as SC 1 and SC 2 have been subdivided into three cycles, labeled SC 1b, SC 1a, and SC 2. Landward and seaward pinchouts of each stratigraphic cycle are shown in figure 9, along with each well location. The lack of significant unconformities, the subequal ratio of seaward- to landward-stepping cycles, and the stratigraphic rise between cycles indicate that both sediment supply and accommodation were high and relative sea level was continually rising.

All Ferron stratigraphic cycles, with the possible exception of No. 7, can be subdivided into parasequences bounded by localized transgressive surfaces (Gardner, 1993; Ryer and others, 1993; Barton, 1994). Parasequences are 20 to 60 ft thick and rarely extend more than a few miles, dipping seaward at a few degrees. Parasequences are named following methodology proposed by Ryer and others (1993). Parasequence names are based on the stratigraphic cycle in which they occur (SC 2), their locality (for example, Molen Reef–MR), and relative age within the stratigraphic cycle (for example, 1, 2, and 3). The oldest SC 1b parasequence identified in the Muddy Creek (fig. 10) panel, for example, is referred to as SC 1b–MC 1. Parasequences are interpreted to record episodic progradation within the delta system related to distributary channel avulsion and delta lobe abandonment. In turn, parasequences are composed of numerous bedsets bounded by seaward-dipping clinoform surfaces (fig. 10). Clinoforms are several feet to 20 ft in thickness and extend several hundred to several thousand feet along depositional profile. Clinoforms are interpreted to record episodic progradation of the delta front related to variable sediment discharge at distributary mouths.

Recognition and Correlation Criteria

Criteria useful in the analysis of reservoir architecture from wireline and core data are based on the recognition of (1) time-significant surfaces and (2) distinctive vertical stratal successions or patterns.

In the Ferron system, the most recognizable and correlatable surfaces on outcrop, core, and well logs are those associated with marine flooding events. Surfaces coincident with stratigraphic cycles and parasequences form correlatable horizons over the distance of tens of miles and several miles, respectively. Marine flooding events record reduced rates of sedimentation in all facies tracts and may be preserved as surfaces recording sediment starvation within paraconformable strata or stratigraphic discontinuities marked by facies offset. On the shelf (offshore marine facies tract), marine flooding events occur at the top of condensed section deposits in marine-shelf strata. Deposits are characterized by a thin interval of organic-rich mudstones and volcanic ashes that display a very high gamma-ray response. In the delta front, marine flooding events are recognizable by facies offset recording an increase in water depth. Deposits consist of marine shales that overlie a surface of erosion or interval marked by intense burrowing. Within the coastal plain, correlative surfaces occur at the change from sandstone-poor, organic-rich to sandstone-rich, organic-poor deposits in coastal-plain strata (Gardner, 1993).

Marine shales bounding stratigraphic cycles and parasequences show up as radioactive highs on the gamma-ray log at the base of an upward-coarsening, bed-thickening delta-front succession. Marine shales bounding stratigraphic cycles range in thickness from 0.5 to 40 ft and extend laterally several miles to tens of miles. Marine shales bounding parasequences display similar characteristics but generally lack a well-developed transgressive facies. Marine shales range in thickness from 0.5 to 15 ft and may extend laterally several thousand feet to tens of thousands of feet. Laminated mudstones and bioturbated siltstones bounding delta-front clinoforms are often not resolvable on the gamma log but may show up as a thin radioactive spike within an upward-coarsening, bed-thickening delta-front succession (fig. 10). Mudstones and siltstones range in thickness from 0.1 to 2 ft and extend laterally several hundred to several thousand feet. Delta-front clinoforms are resolvable with core and dipmeter data (UURI Well No. 1 [fig. 10]). Abrupt changes in azimuth and inclination correspond to clinoform boundaries.

Patterns useful in the correlation of stratal elements include stratigraphic thickening and thinning, sand-rich and sand-poor facies associations, conformable facies successions, and degree of burrowing. For example, seaward-stepping stratigraphic cycles deposit a greater proportion of sediment within the shallow-marine facies tract, whereas landward-stepping stratigraphic cycles deposit a greater proportion of sediment in coastal-plain environments. The turnaround between seaward-stepping stratigraphic cycles to vertically stacked or landward-stepping stratigraphic cycles is marked by a trend of thinning and deepening within the delta front. In the coastal-plain facies tract, the turnaround is expressed as an increase in cycle thickness and a change from sand-poor facies associations to sand-rich facies associations.

Stratal elements are composed of conformable successions of strata. In vertical successions of strata composing the stratigraphic cycles and parasequences, lateral changes are expressed as increased asymmetry in log response in both seaward and landward directions. On the shelf (offshore marine facies tract), marine flooding events are characterized by aggradational pelagic or hemipelagic deposits that indicate sediment starvation. Within the delta-front facies tract, correlative surfaces are bounded by asymmetrical stratal successions displaying vertical patterns of upward bed thickening and coarsening associated with delta-front progradation and shoaling. Within the coastal-plain facies tract, correlative surfaces are bounded by asymmetrical upward-fining packages of sandstone, siltstone, and mudstone capped by a carbonaceous shale or coal associated with delta lobe abandonment. In a similar fashion, clinoforms display a change from upper delta-front to lower delta-front deposits over the distance of several thousand feet from proximal to distal regions. The degree of burrowing is also an extremely useful tool in the correlation of stratigraphic cycles, parasequences, and even clinoforms through a succession of depositional facies. Although the absolute degree of burrowing varies from one environment to another, stratigraphic elements at several scales display an overall trend of decreased bioturbation from the base to the top (see fig. 10).

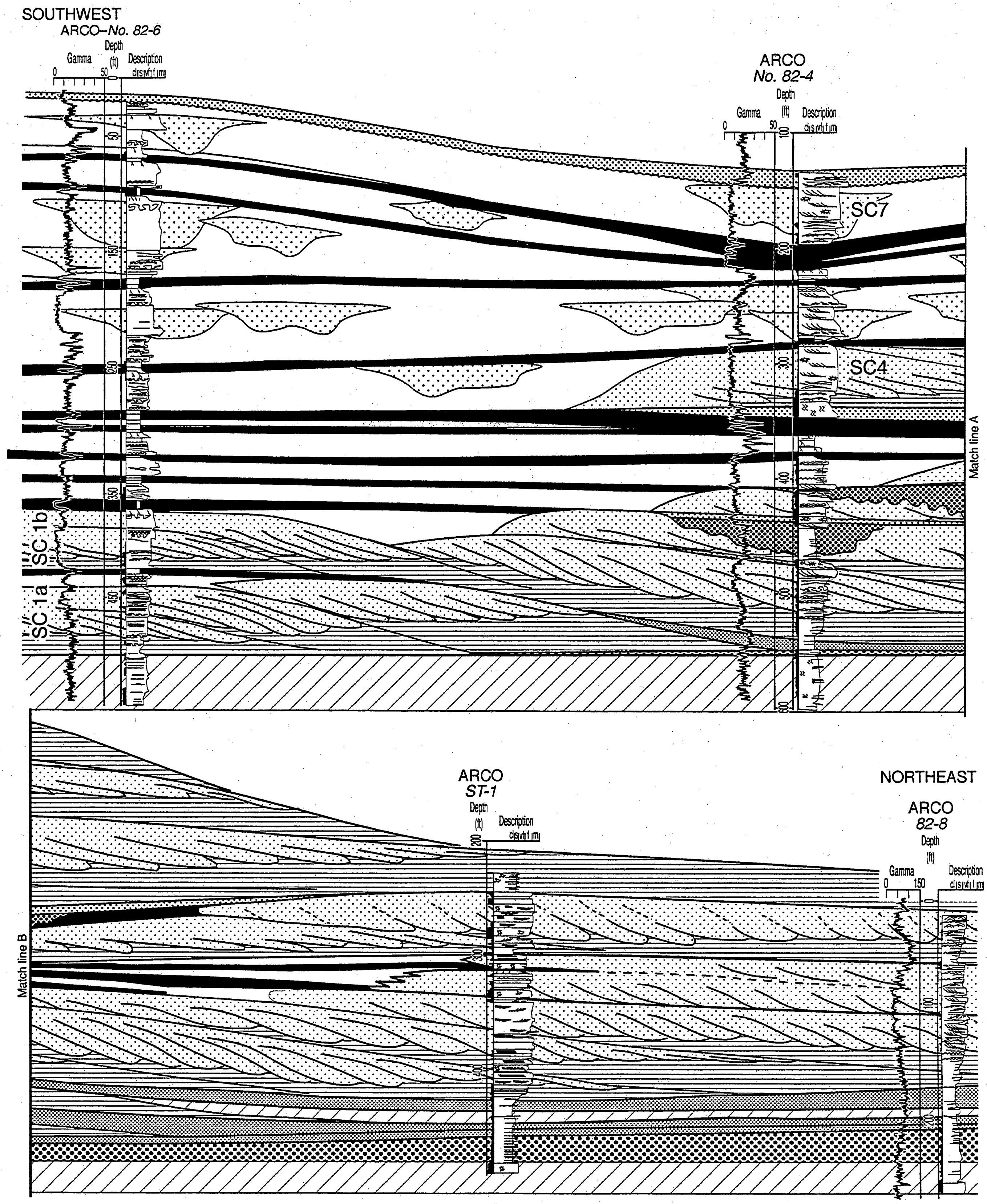
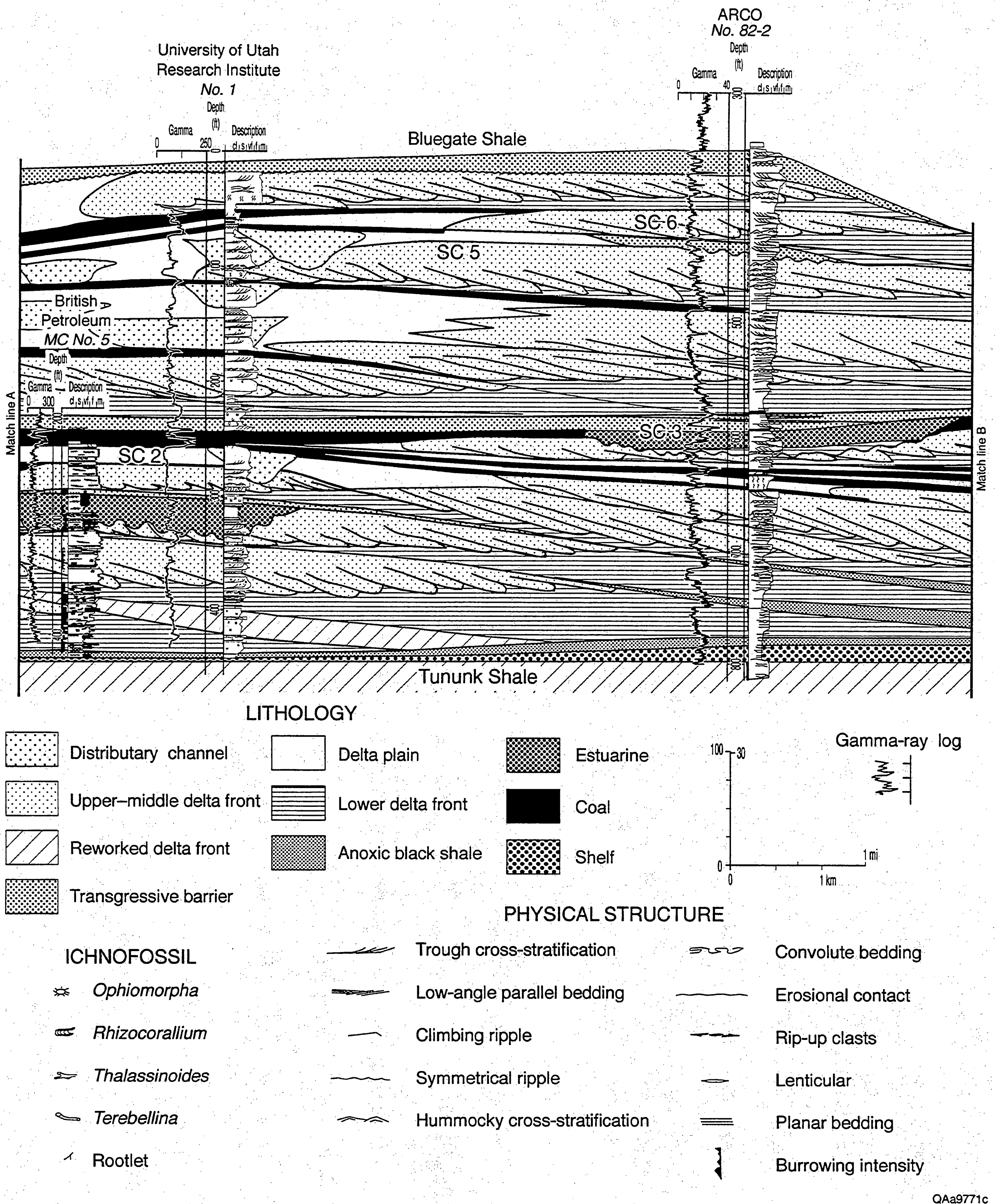


Figure 9. Regional well log and core cross section illustrating sequence stratigraphic relationships and facies characteristics of Ferron Sandstone, Utah.



ARCO
No. 82-2
University of Utah
Research Institute
No. 1
Gamma
Depth (ft)
Description
Bluegate Shale
SC 6
SC 5
British
Petroleum
MC No. 5
SC 3
SC 2
Match line A
Match line B
Tununk Shale
LITHOLOGY
Distributary channel
Upper–middle delta front
Reworked delta front
Transgressive barrier
Delta plain
Lower delta front
Anoxic black shale
Estuarine
Coal
Shelf
Gamma-ray log
1 mi
1 km
PHYSICAL STRUCTURE
Trough cross-stratification
Low-angle parallel bedding
Climbing ripple
Symmetrical ripple
Hummocky cross-stratification
Convolute bedding
Erosional contact
Rip-up clasts
Lenticular
Planar bedding
Burrowing intensity
ICHNOFOSSIL
Ophiomorpha
Rhizocorallium
Thalassinoides
Terebellina
Rootlet
QAa9771c

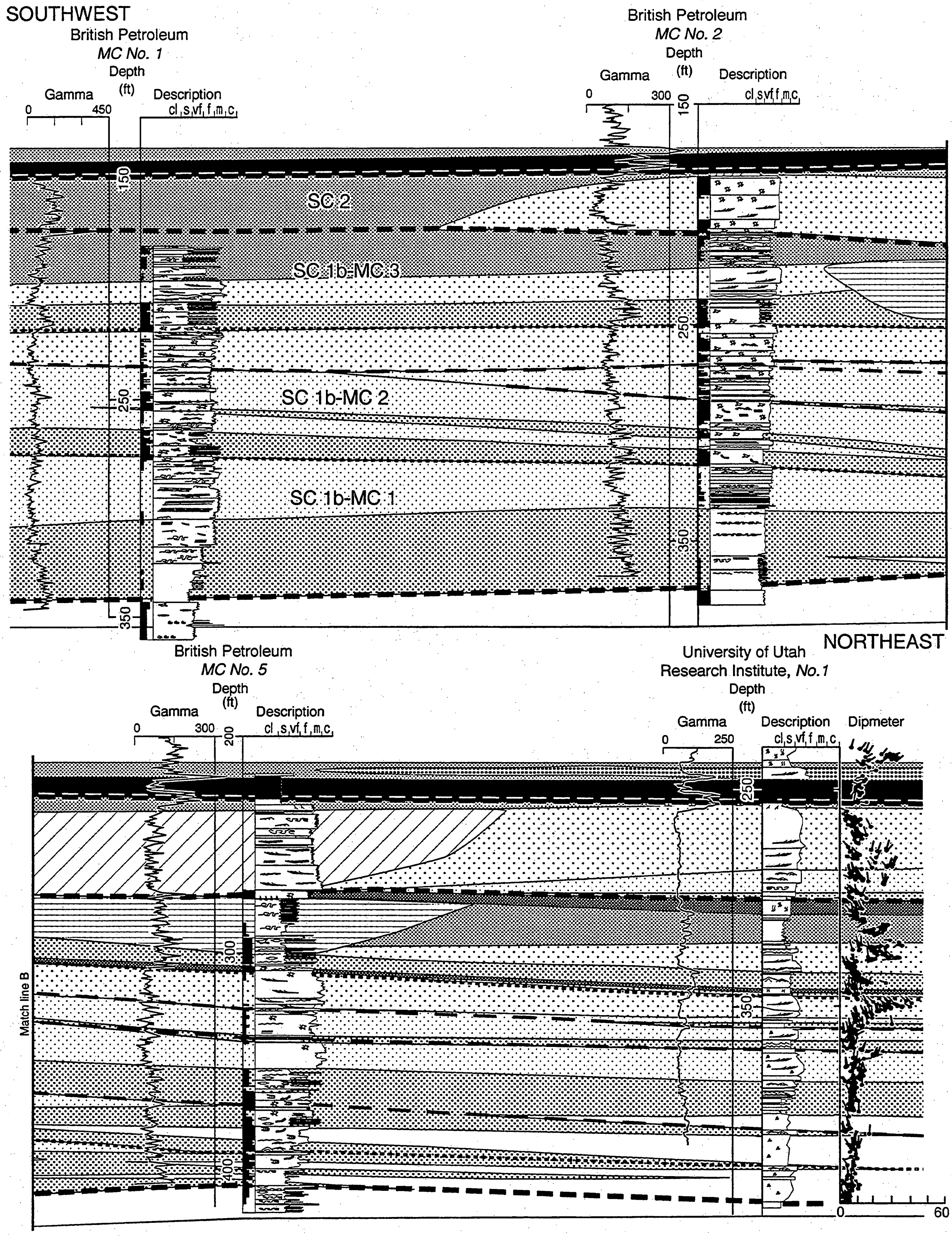
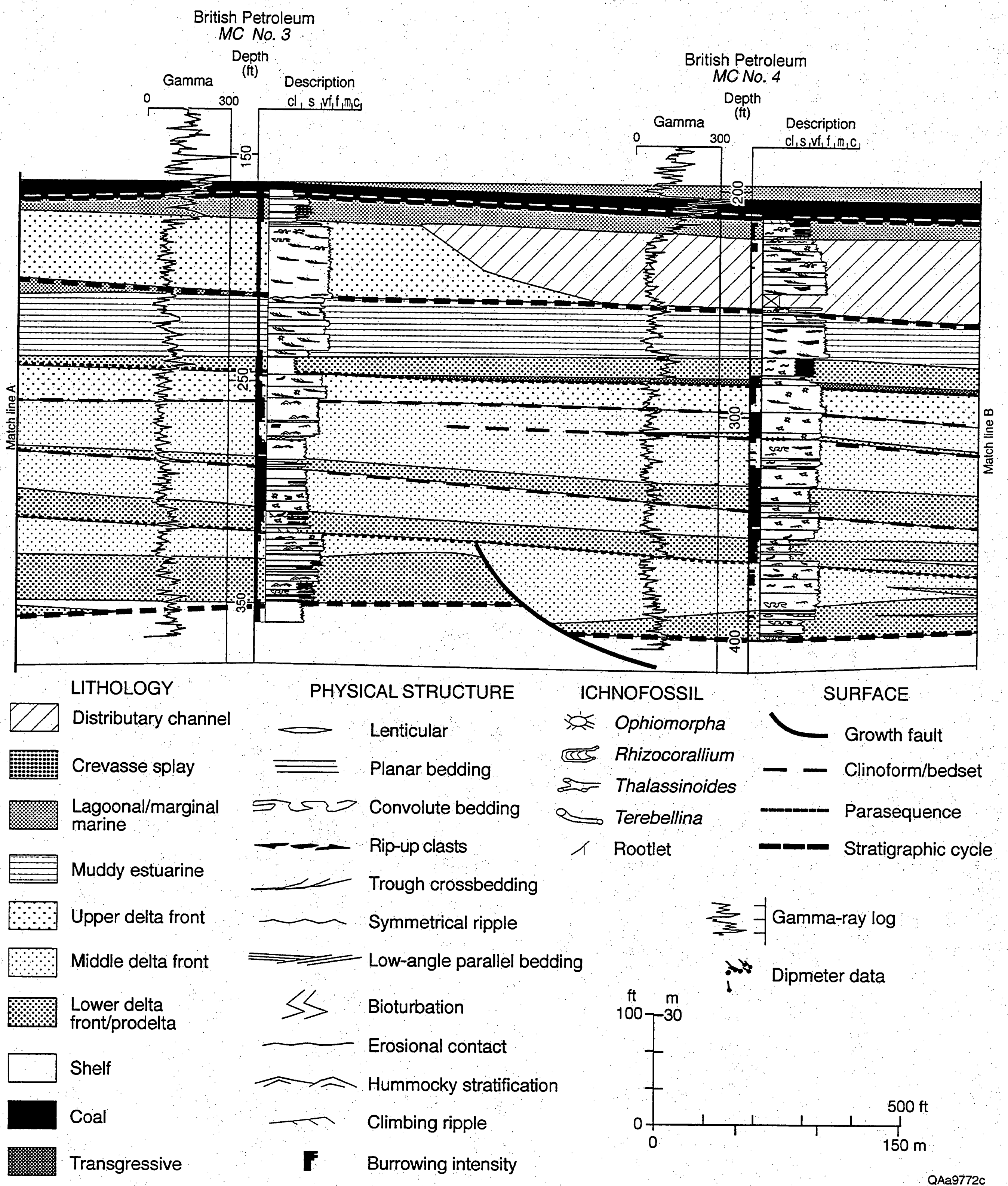


Figure 10. Local well log and core cross section illustrating sequence stratigraphic relationships and facies characteristics of Ferron Sandstone, Muddy Creek, Emery County, Utah.


British Petroleum
MC No. 3
Depth (ft)
Gamma
0
300
Description
cl s vf f m c
150
250
300
350
British Petroleum
MC No. 4
Depth (ft)
Gamma
0
300
Description
cl s vf f m c
200
300
400
Match line A
Match line B
LITHOLOGY
Distributary channel
Crevasse splay
Lagoonal/marginal marine
Muddy estuarine
Upper delta front
Middle delta front
Lower delta front/prodelta
Shelf
Coal
Transgressive
PHYSICAL STRUCTURE
Lenticular
Planar bedding
Convolute bedding
Rip-up clasts
Trough crossbedding
Symmetrical ripple
Low-angle parallel bedding
Bioturbation
Erosional contact
Hummocky stratification
Climbing ripple
Burrowing intensity
ICHNOFOSSIL
Ophiomorpha
Rhizocorallium
Thalassinoides
Terebellina
Rootlet
SURFACE
Growth fault
Clinoform/bedset
Parasequence
Stratigraphic cycle
Gamma-ray log
Dipmeter data
ft
m
100
30
0
0
500 ft
150 m
QAa9772c

Correlative surfaces and cycles may become obscure because of facies substitution, the lack of facies offset, depositional topography, and differential compaction. Examples of facies substitution include replacement of delta-front and coastal-plain deposits by distributary channel deposits, or substitution of mud-rich interdistributary bay deposits for sand-rich shoreface deposits within the delta front. The lack of facies offset occurs where identical but noncontemporaneous facies are adjacent to one another. Such relationships are typically not separated by a distinct lithology. For example, within the upper delta front, finer grained facies separating noncontemporaneous shoreline sands are not preserved, and stratal units of similar characteristics are instead separated by a surface of erosion (in this situation the maximum flooding surface corresponds to ravinement surface). This is often the case near the landward pinchout of the delta-front facies tract or within a wave-dominated delta-front succession. Landward of the delta-front facies tract, the persistence of long-lived bays, lagoons, or swamps may result in peat horizons coeval to separate stratigraphic cycles amalgamating into a single zone.

Sequence stratigraphic correlations follow the inclination and orientation of original depositional surfaces and downlap the underlying sequence, stratigraphic cycle, or parasequence. In landward-stepping units, delta-front strata are deposited across an essentially horizontal surface with little depositional topography. Correlations parallel the depositional surfaces and are approximately horizontal. In seaward-stepping units significantly greater depositional topography exists. Delta-front strata prograde across the underlying delta-front platform. As a result, correlations follow the dip of inclined surfaces of the original topographic profile and are more steeply inclined than the boundaries of landward-stepping units. Shortly after burial, however, original depositional topography may be distorted by differential compaction of sands, silts, muds, and peat. This is best expressed where delta-front (note SC 7) and distributary channel sand bodies overlie thick successions of organic-rich lagoonal, bay-fill, and delta-plain deposits.

Major facies associations are resolvable on logs to various degrees. Delta-front strata are easily recognizable by a well-developed, upward-decreasing gamma log response. Dip inclination progressively increases from the base to the top of the interval and displays dips that parallel the direction of progradation (northwest to northeast). However, near the landward pinchout of the delta-front facies tract, the gamma log may display a blocky pattern, because upper delta-front strata directly overlie the erosional ravinement surface. Overlying foreshore sandstones display shallow-dip inclination. Associated washover and lagoonal deposits display a high proportion of landward-directed dips. Criteria useful in distinguishing river-dominated from wave-dominated delta fronts include proportion of mud-rich lithologies, lithologic diversity, proportion of gravity resedimentation features, and degree of bioturbation. River-dominated delta fronts may display an erratic upward-decreasing gamma log response that is extremely unpredictable from well to well relative to wave-dominated delta fronts. Distributary channel deposits tend to display an upward-fining to blocky well log response that may extend laterally up to several thousand feet. Channel base bounding surfaces are often recognizable as a thin spike on the gamma-ray log.

Comparative Analysis of Landward- and Seaward-Stepping Reservoirs

In this section the sequence framework will be used in a comparative analysis to contrast styles of heterogeneity within landward- and seaward-stepping stratigraphic cycles. The purpose is to illustrate how a stratigraphic hierarchy provides a context for understanding complex vertical and lateral changes in facies architecture, bounding elements, and permeability structure of delta-front, coastal-plain, and delta-abandonment facies. Changes are documented in a case study comparison of a strongly seaward-stepping stratigraphic cycle (SC 2) and of a vertically to landward-stepping stratigraphic cycle (SC 5).

Stacking Pattern and Sediment Volume Partitioning

The overall regressive, then transgressive, character of the Ferron sequence is defined by the stacking pattern of the stratigraphic cycles. The regressive portion of the sequence, referred to as the seaward-stepping system tract, consists of four strongly seaward-stepping stratigraphic cycles (SC 1a, SC 1b, SC 2, and SC 3) that extend over 60 mi into the basin. Individual stratigraphic cycles of the regressive system tract build out over a distance of 10 to 30 mi and downlap the sequence boundary. Seaward-stepping stratigraphic cycles are imbricated in a basinward direction and display a sigmoidal geometry that thickens dramatically basinward of the seaward pinchout of the underlying stratigraphic cycle. The imbricated geometry results from delta-front progradation and sediment accumulation on the inclined depositional surface of the previous stratigraphic cycle. The seaward-stepping system tract is bounded above by a transgressive surface that marks the turnaround between seaward-stepping stratigraphic cycles and landward-stepping stratigraphic cycles. The overlying transgressive portion, referred to as the landward-stepping system tract, consists of four stratigraphic cycles arranged in a vertically stacked to landward-stepping fashion (SC 4, SC 5, SC 6, and SC 7). By comparison, the landward-stepping system tract is compressed, with individual stratigraphic cycles extending 5 to 10 mi into the basin. Landward-stepping stratigraphic cycles gradually thin seaward into marine shales and thicken landward into coastal-plain and fluvial strata. Expressed as a ratio of length to thickness (measured along depositional profile), the progradational geometry of seaward-stepping stratigraphic cycles is approximately 1200:1 and landward-stepping stratigraphic cycles approximately 350:1.

Changes in parasequence stacking patterns follow changes in stratigraphic cycle stacking relationships. Within seaward-stepping stratigraphic cycles, parasequences are arranged in a strongly forward-stepping fashion compared to stratigraphic cycles of the landward-stepping system tract, where parasequences are arranged in an aggradational fashion. Furthermore, parasequence stacking patterns change as a function of stratigraphic position within the stratigraphic cycle. Initial parasequences of the regressive phase are strongly progradational, displaying a large degree of facies offset and a small amount of stratigraphic climb (5 to 10 ft). By comparison, late-stage parasequences tend to be aggradational, displaying a low degree of facies offset and a high degree of stratigraphic climb (15 to 30 ft).

Accompanying shifts in stacking pattern and progradational geometry are shifts in the partitioning of sediment into comparable depositional systems (Gardner, 1993). In the Ferron sequence, the shallow-marine facies tract of seaward-stepping cycles and the coastal-plain facies tract of landward-stepping cycles are sites where proportionally more sediment is stored. Sediment volumes expressed as a ratio of nonmarine to marine sandstone volumes and sand content expressed as a percentage of net sand to gross sediment volume within all facies tracts proportionally increase from seaward- to landward-stepping stratigraphic cycles. In a similar fashion, transgressive pulses separating progradational from aggradational parasequences are coeval to an aggradational wedge of marginal marine and coastal sediments landward of the shoreline. As a result, most of the coastal-plain sediments within the seaward-stepping stratigraphic cycles are time equivalent with an aggradational parasequence. The stratigraphic relationship implies a relative rise in sea level that produced vertically stacked delta-front deposits and made accommodation space available landward for the aggradation of coastal-plain deposits.

Stacking Patterns and Facies Architecture

Although a complete spectrum exists, the Ferron delta complex records an upward change from fluvial- to wave- and storm-dominated facies successions. Shoreline characteristics of seaward-stepping stratigraphic cycles indicate delta-front sediments accumulated on a fluvial-dominated coast line. Delta-front strata consist of subequal amounts of wave- and fluvial-dominated deposits. Changes in depositional style are abrupt between the two end members (Gustason, 1993). Sand-rich homogeneous wave-dominated delta lobes alternate with mud-rich bay-fill successions and heterolithic fluvial-dominated delta lobes. Although variation exists, wave-dominated delta lobes are best developed where delta-front environments have prograded across a stable platform (landward pinchout) or at the turnaround from progradational to aggradational parasequence configurations (seaward pinchout). By contrast, fluvial-dominated delta lobes are best developed basinward of the underlying delta lobe or stratigraphic cycle. Large bay-fill successions often occur at this transition point and act to physically separate wave- and fluvial-dominated delta-front deposits within the same stratigraphic cycle.

The delta front of seaward-stepping cycles is capped by a thin veneer of marginal marine (lagoonal) and lower delta-plain sediments (15 to 40 ft). Marginal marine deposits achieve maximum thickness (up to 40 ft) immediately landward of the shoreline, where sand-rich washover deposits are replaced in a landward direction by relatively thick mud-rich successions of lagoonal and marsh deposits. Locally, isolated distributary channel belt sand bodies may remove and replace the underlying coastal-plain and delta-front succession.

By contrast, the shallow-marine facies tract of landward-stepping stratigraphic cycles consists largely of wave- to storm-dominated facies associations. Delta-front deposits are thinner, more lithologically homogeneous, and sand rich than in seaward-stepping stratigraphic cycles. The delta-front succession consists largely of an upward-coarsening, bed-thickening succession of laminated mudstones, bioturbated siltstones, and hummocky cross-stratified sandstones. The absence of mud-rich bay-fill successions and marine mudstones coincident to parasequence and mouth-bar bounding surfaces reflects the dominance of wave and storm processes associated with reduced rates of progradation and increased rates of vertical aggradation. Component parasequence and distributary mouth-bar deposits are amalgamated into a lithologically homogeneous strike-elongate sand body, with lithologic variation limited to gradual upward shoaling and onshore to offshore facies transition. Landward of the shoreline, channel sand bodies are laterally expanded and composed of a high diversity of facies in heterogeneous and lithologically diverse facies successions, which may extensively replace underlying delta-front deposits. The succession is truncated by a broad, low-relief surface that records marine flooding and reworking of the abandoned delta lobe. Transgressive facies capping landward-stepping cycles are well developed and include bioturbated sandstones, tidal-channel sandstones, and tidal-sandwave sandstones.

Case Study Comparison of SC 2 and SC 5

Ferron SC 2, a strongly progradational or seaward-stepping deltaic unit, is characterized by a relatively high volume of delta-front sandstones, siltstones, and shales that form a thick, laterally extensive platform (120 ft thick and extending 25 mi along depositional dip) over which a thin veneer of delta-plain and abandonment facies are deposited. Facies architecture is illustrated in figure 11 for a portion of this interval between Miller Canyon and Short Canyon.

Shallow-marine facies tracts of seaward-stepping cycles consist of offlapping, gently seaward dipping, upward-shoaling successions bounded by laterally extensive bioturbated mudstones of deeper water origin. Within SC 2, parasequences are 20 to 60 ft thick, dip seaward at a few degrees, and rarely extend more than a few miles. Between Miller and Short Canyons (10 mi), 10 east-northeast-dipping (northeast) para-

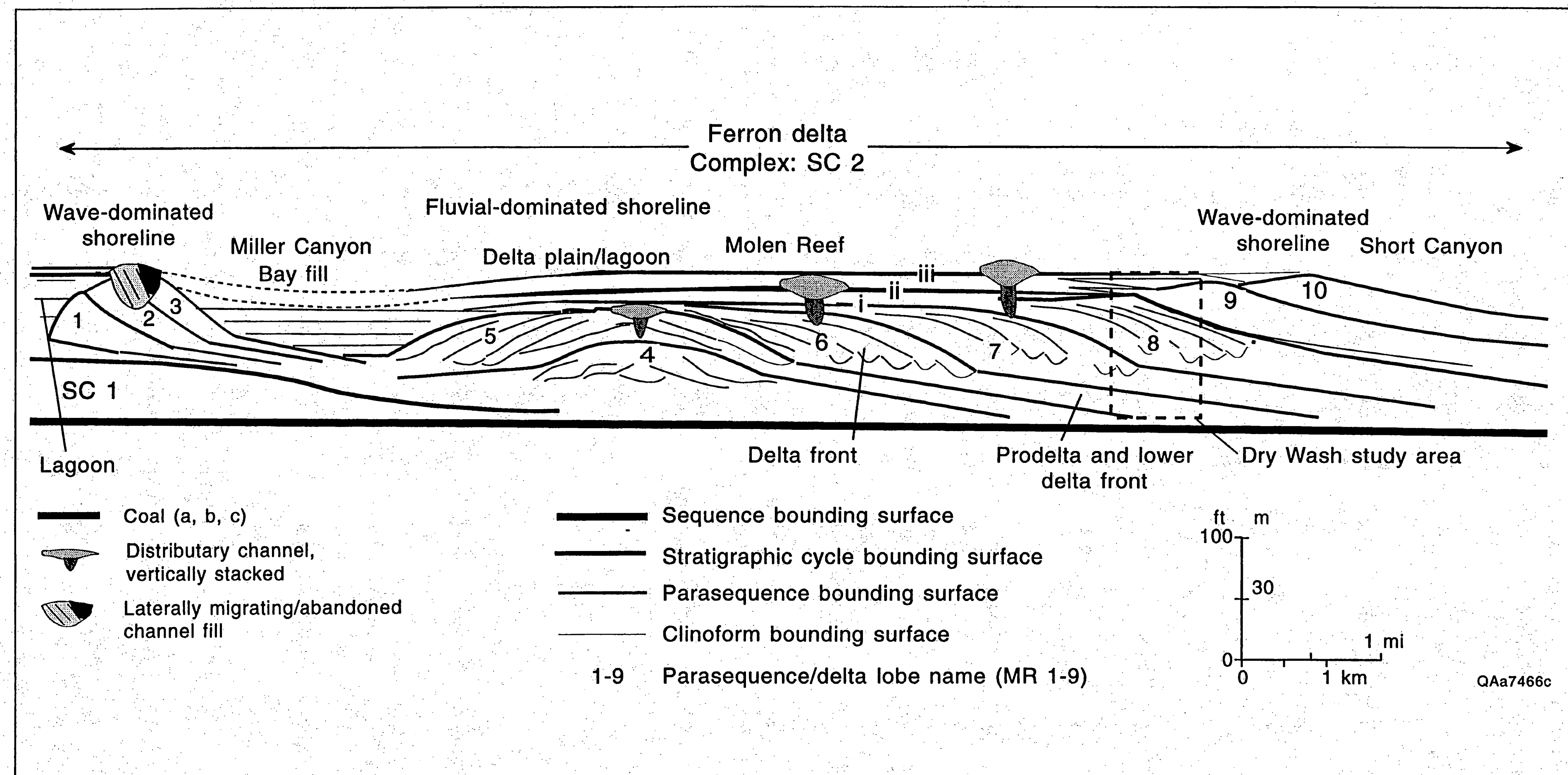


Figure 11. Regional stratigraphy of SC 2.

sequences have been identified that form a progradational parasequence set numbered SC 2 MR 1–MR 10.

Each delta-front sandstone comprising a parasequence is contemporaneous with a thin, landward- (SW) thickening wedge of lagoonal and lower delta-plain deposits consisting of an upward-fining succession of sandstone, siltstone, mudstone, and coal. Recurrent upward-fining successions of sandstone, siltstone, mudstone, and coal record repeated episodes of delta-front progradation. For example, coals i, ii, and iii cap lagoon/bay-fill cycles that are coeval to parasequences 7, 8, and 9, respectively. The thickest lagoonal, marsh, and lower delta-plain facies association is coeval to the youngest parasequence (MR 9). In a seaward direction, these coals or carbonaceous shales correlate to bioturbated marine mudstones and siltstones capping distal delta-front sandstones. Multiple episodes of progradation are recorded in alternating upward-fining successions within the coastal-plain facies tract of SC 2.

These relationships are almost reversed in Ferron SC 5, a landward-stepping or retrogradational unit. Figure 12 illustrates facies architecture for an interval of GS 5 between Muddy Creek and Dry Wash. In Ferron SC 5, the entire facies tract is compressed; thickness is as much as 60 ft, and total length from landward (Muddy Creek) to seaward extent (Dry Wash) is only approximately 5 mi. The basal delta front is expressed as an extremely regular, upward-shoaling, sand-rich succession that is extensively replaced by distributary channel and associated delta-plain deposits. Regionally, the succession is truncated by a broad, low-relief surface that records marine flooding and extensive reworking of the abandoned delta lobe. Overlying transgressive deposits consist of a thin, intensely bioturbated sand sheet or tabular, strike-elongate sand bodies composed of trough and hummocky cross-stratified sandstones.

In contrast to SC 2, in which the delta front was composed largely of strongly seaward-stepping parasequences, SC 5 is composed of a set of five aggradational parasequences. Parasequences are thinner than observed in SC 2, ranging in thickness from 15 to 20 ft and extending 1-2 mi in a lateral distance along depositional profile.

In contrast to SC 2, internal seaward-dipping clinoform and parasequence bounding surfaces are indistinct, reflecting lithologic homogeneity. Bounding elements consist of thin, discontinuous bioturbated mudstones, siltstones, and very fine grained sandstones. In a landward direction, parasequence correlations cannot be extended into coeval coastal-plain strata, as with SC 2. However, geographic and stratigraphic changes in channel-belt architecture from early-stage, deeply incised channel forms to laterally expanded channel forms may reflect a cycle of base-level rise and fall (Barton and Gardner, 1992).

Facies Architecture

Shallow-Marine Facies Tract

Delta-front sand bodies are the principal reservoir facies within SC 2, and depositional characteristics range in style from fluvial to wave dominated. Interpreted wave-dominated intervals include the following characteristics: a relatively thin (less than 10 ft) lower shoreface zone distinguished by layers of storm-deposited sandstone interbedded with fair-weather mudstones; a lack of mudstone interbeds throughout the succession; an abundance of burrowing (with the most abundant trace fossils being *Ophiomorpha* and *Thalassinodes*); multidirectional trough cross-stratification within the upper delta front; and a well-developed foreshore zone that is often overlain by a coal instead of a carbonaceous shale. By contrast, fluvial-dominated delta fronts display the following characteristics: a relatively thick (20 to 40 ft) lower delta front characterized by soft sediment deformation and gravity remobilization features, including sediment gravity flows, rotated slump blocks, and growth faults; a weakly developed or often unrecognizable middle delta-front zone; an upper delta-front zone that may display large-scale, unidirectional cross-strata with abundant clasts of clay and organic matter; numerous mudstone interbeds throughout the succession; and a general lack of burrowing.

Wave-dominated delta lobes range in thickness from 30 to 60 ft and may extend thousands of feet along depositional profile. Laterally adjacent wave-dominated delta lobes amalgamate to produce a single homogeneous, lobate to strike-elongate sand body that is tens of thousands of feet in width and length. By contrast, fluvial-dominated delta-front successions are subdivided at multiple scales by seaward-dipping clinoform surfaces. Large-scale clinoform surfaces downlap the cycle boundary and are draped by fine-grained successions of bay-fill and lower delta-front deposits (2 to 20 ft thick and thousands to ten thousands of feet in length) that separate adjacent delta lobes or

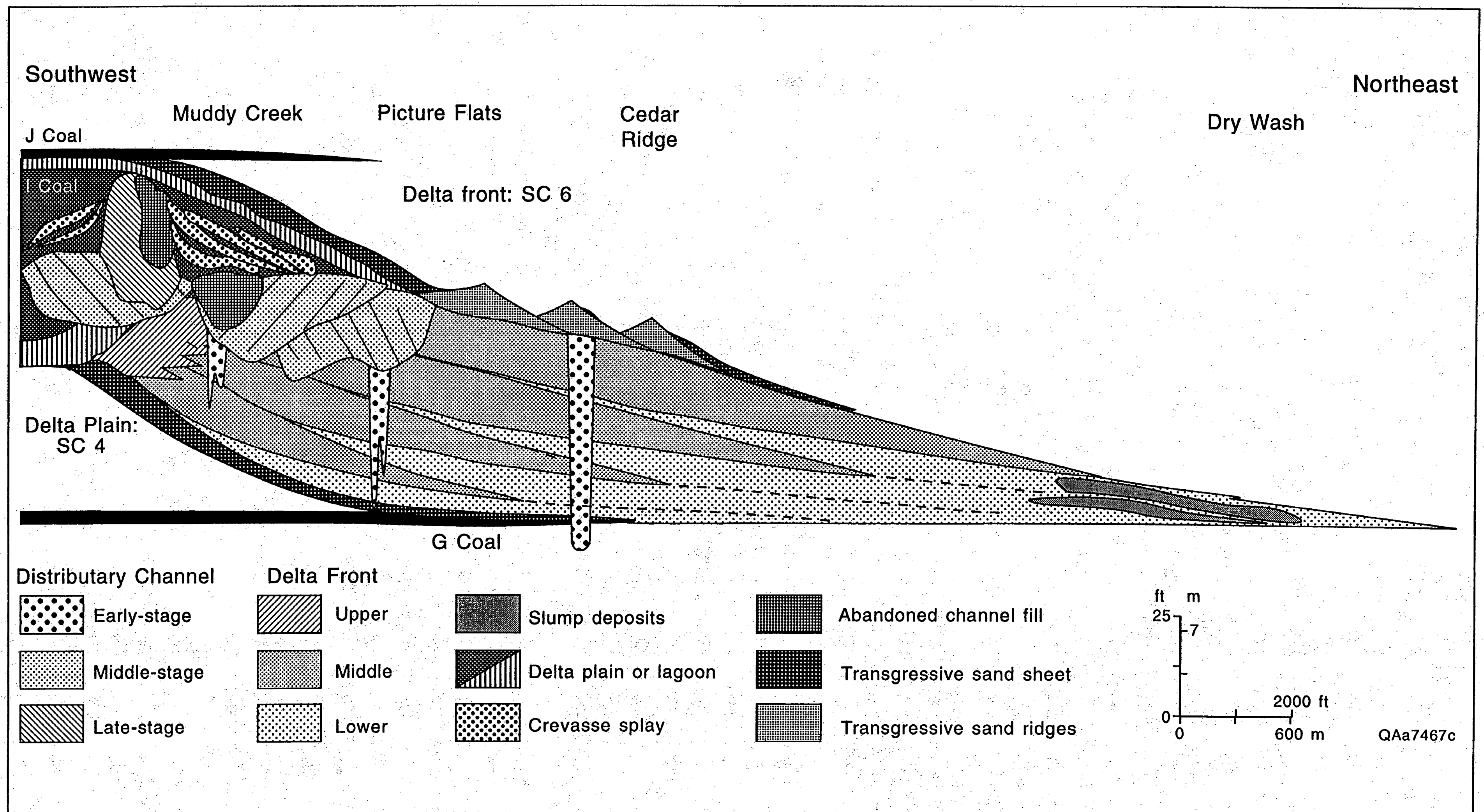


Figure 12. Schematic diagram illustrating facies architecture of SC 5 along depositional profile.

parasequences. Smaller scale clinoform surfaces downlap the parasequence boundary and are draped by thin (0.25 to 2 ft), laterally extensive (hundreds to thousands of feet) mudstone drapes that act to separate individual mouth-bar deposits. Fluvial-dominated parasequences are generally thinner than wave-dominated delta lobes ranging between 20 and 40 ft, but they are more laterally extensive, extending 0.5 to 3 mi along depositional profile. Large-scale low-angle clinoforms record episodic progradation associated with distributary channel avulsion and delta-lobe abandonment. Locally, complexes of delta-lobes are separated by large bay-fill successions (30 to 60 ft thick and ten thousands of feet in length). Lateral facies changes from delta-front sandstone to interdistributary-bay mudstone reflect point-source sediment dispersal in the shallow-marine facies tract related to the seaward extension of distributary channels.

As previously discussed, abrupt shifts in depositional style are recorded along the depositional profile (fig. 11). Near the landward pinchout of SC 2, the shallow-marine facies tract consists of sand-rich, homogeneous, wave-dominated delta-front deposits. Laterally, in a seaward direction where the underlying SC 1 cycle thins and begins to pinch out into marine shales, these deposits are abruptly replaced by a thick succession of fine-grained bay-fill deposits that are approximately 65 ft thick and 1.2 mi in width. Further seaward, these deposits are replaced by heterolithic, fluvial-dominated delta-front successions.

Variations in facies association are in part attributed to along-strike shifts of an active delta complex that result in large-scale alterations of shoreline characteristics between strandplain, interdistributary bay, and active delta complex. River-dominated shorelines originate near the mouth of major distributaries or within protected embayments of the delta complex, whereas wave-dominated shorelines form along an open coast line or portions of the delta lobe that receive a low rate of sediment input. However, stratigraphic relationships previously discussed suggest that systematic changes in facies characteristics are also modified by basin floor topography and relative sea level and sediment supply. Fluvial-dominated parasequences are best expressed basinward of the transition point between delta platform and delta slope of the underlying stratigraphic cycle (SC 2 MR 4–MR 8). Consequently, proximal portions of each stratigraphic cycle consist largely of wave-dominated facies associations (SC 2 MR 1–MR 3). Alternatively, wave-dominated parasequences are also developed near the seaward extent of each stratigraphic cycle where parasequences change from highly progradational to aggradational (SC 2 MR 9–MR 10).

Because of its proximity to the Ferron gas field and its importance in resolving the scale-dependent nature of reservoir architecture, the parasequence architecture is documented in detail within SC 2 near Dry Wash (fig. 4). Paleogeographically, Dry Wash is located near the mouth of active distributaries during the deposition of SC 2. The shallow-marine facies tract of SC 2 consists of three offlapping, gently seaward-dipping parasequences (SC 2 MR 7–MR 9). Exposures of MR 7 and MR 8 show distal and proximal portions of two strongly progradational, river-dominated parasequences, respectively. By contrast, MR 9 displays the marginal marine and proximal portions of an aggradational, wave-dominated parasequence (fig. 13).

Parasequence MR 7 (fig. 14) is exposed on the extreme south side of Dry Wash, where it is about 20 ft thick, but it thins and fines to the northeast and is absent on the north side of Dry Wash. Facies change upward from mudstone and nodular siltstone to very fine grained, planar to hummocky stratified sandstone beds from 0.5 to 2 ft thick and sparsely burrowed, thin laminated mudstone and siltstone interbeds. The succession is capped by deeper water marine mudstones, and the basal contact is gradational with SC 1. Locally, the upward-coarsening succession is replaced by thick, lenticular sand bodies containing large-scale trough crossbedding and massive or deformed bedding showing evidence of slumping and growth faulting. Lower to middle delta-front deposits are arranged in a series of seaward-dipping, offlapping shingles. Thickness trends show a northeastward-progradation direction. Lower to middle delta-front sandstones thin to the northeast and are replaced by a thick lower delta-front succession. To the south, MR 7 thickens and overlies the distal portion of an older delta lobe. In this area, marine mudstones form the lower contact, with the upper contact consisting of a flat erosional surface separating upper delta-front sandstones of the two delta lobes. Farther south, near its landward pinchout, the upper contact is traced into delta-plain deposits recording an upward change from organic-rich to organic-poor sediments.

Parasequence MR 8 (fig. 15) is a fluvial-dominated delta lobe 45 to 50 ft thick forming the first prominent sandstone ledge along the Molen Reef escarpment at the mouth of Dry Wash. Facies shoal upward from

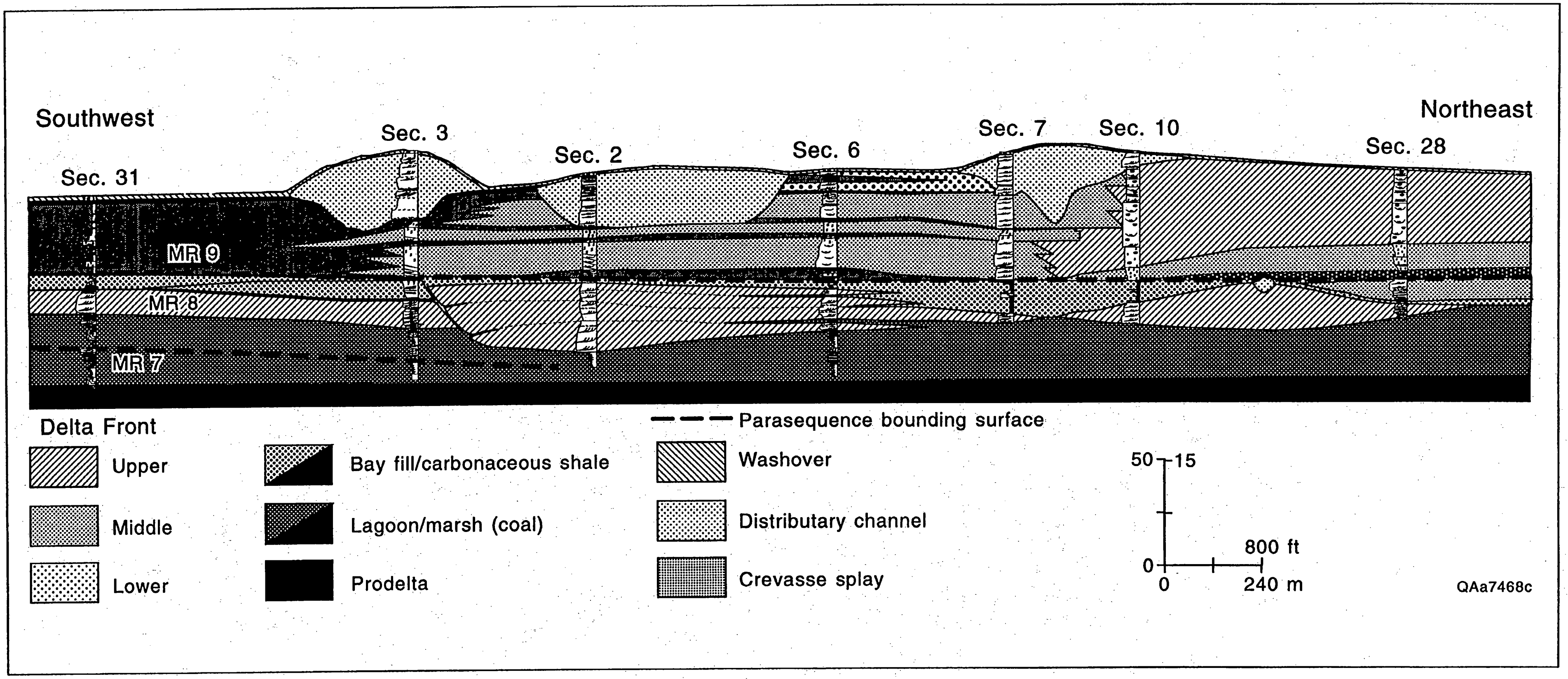


Figure 13. Stratigraphy and facies architecture of Ferron SC 2: Dry Wash.

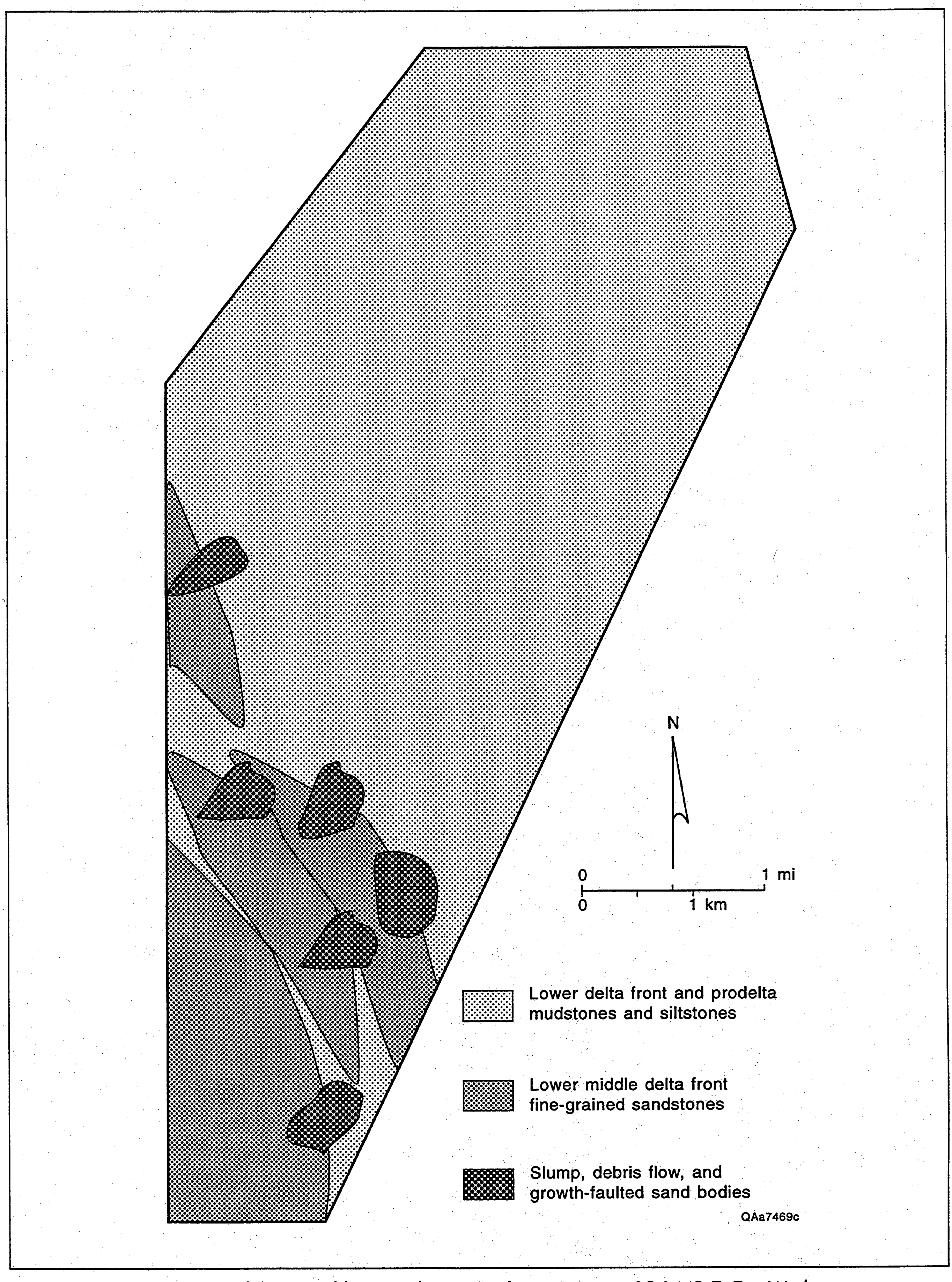


Figure 14. Plan view of facies architecture of parasequence SC 2 MR 7: Dry Wash.

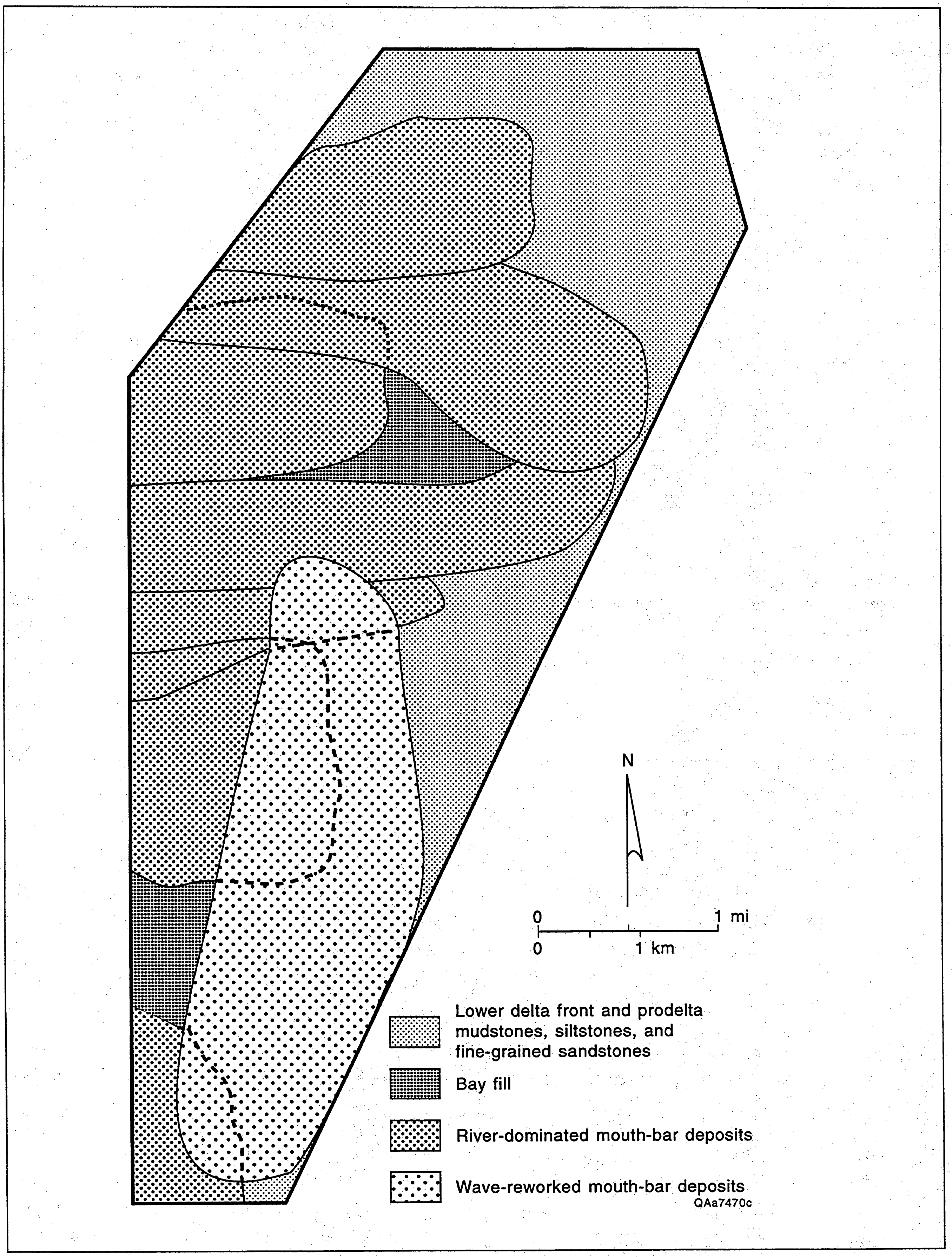


Figure 15. Plan view of facies architecture of parasequence SC 2 MR 8: Dry Wash.

sparsely burrowed shale, siltstone, nodular mudstone, and very fine grained sandstone to be sharply overlain by medium- to coarse-grained, unidirectional trough cross-stratified sandstone (up to 30 ft thick) or fine-grained interdistributary-bay mudstone, siltstone, and carbonaceous shale. On the south side of Dry Wash, this succession is capped by a thin coal not present to the northeast, where the coal may have been removed by marine reworking during delta abandonment. Paleoflow analysis and thickness trends record an east to northeast progradation in the Dry Wash area. Distributary mouth-bar sand bodies are elongate to lobate, 10 to 30 ft thick, several thousand feet wide, and several thousand to tens of thousands of feet long. Mouth-bar sands display truncating, sidelapping and offlapping relationships with adjacent mouth-bar sands. Numerous inclined and lenticular mudstone interbeds (several inches to several feet in thickness and tens to hundreds of feet in length) as well as thicker bay-fill successions form bounding elements encasing mouth-bar sand bodies. To the south of Dry Wash, a margin of the delta lobe has been reworked by wave processes into a thin, homogeneous north-trending shoreline sand that overlies distal mouth-bar deposits. To the north of the Dry Wash area near Short Canyon, upper delta-front deposits progressively thin and are replaced by mud-rich, lower delta-front deposits.

Overlying a transgressive disconformity capping MR 8 in northeastern parts of Dry Wash, MR 9 (fig. 16) consists of an upward-shoaling, sand-rich shoreface succession that is about 60 ft thick, is massive in appearance, and forms a prominent cliff. Lower delta-front sandstones and mudstones change upward to middle delta-front, bioturbated and amalgamated hummocky cross-stratified sandstone beds, sharply overlain by upper delta-front, multidirectional, trough crossbedded sandstones. Burrowing is moderate and dominated by *Ophiomorpha*. To the southwest, delta-front sandstones interfinger and are replaced by heterolithic interdistributary-bay or perhaps lagoonal successions (35 to 45 ft thick). Back-barrier or washover sandstones flank the landward margin of the delta-front facies association. The deposits rapidly thin and pinch out in a landward (southwest) direction and display a sharp basal contact, a gradational burrowed upper contact, and a landward-directed cross-strata. In a landward direction, exposed in a road cut near the entrance to Dry Wash, each washover sandstone body (three total) is replaced by an upward-fining cycle of bioturbated siltstone, carbonaceous mudstone, and coal.

Facies characteristics indicate that MR 9 accumulated near the landward pinchout of a wave-dominated delta lobe, with thickness trends and facies relationships indicating the parasequence prograded to the northeast. Upper delta-front sandstones form a northwest-elongate sand body (60 ft thick), flanked on the landward side by a succession of fine-grained lagoonal mudstone and back-barrier and washover sandstone, and on the seaward side by lower delta-front and marine-shelf mudstone and siltstone. A laterally continuous coal incised by a series of lenticular distributary channel deposits caps MR 9. Distributaries are preserved as narrow, elongate (ribbon) sand bodies (40 to 60 ft thick and 500 to 1,000 ft wide) displaying northwest to northeast paleoflow. Distributary channel sand bodies are occasionally flanked by crevasse-channel and splay sand bodies that interfinger with lagoonal mudstones.

In contrast, the entire delta front of SC 5 is characterized by an extremely regular, sand-rich, large-scale, upward-coarsening and bed-thickening sequence consisting of interbedded hummocky cross-stratified sandstone and bioturbated mudstone that record deltaic progradation in a wave- to storm-modified shallow-marine setting. Regionally, the delta front forms a strike-aligned deposit, elongated northwestward. In cross section, the deposit displays a broadly asymmetrical lenticular shape that abruptly thickens near the landward pinchout (up to 40 ft) and gradually thins to a feather edge at its seaward extent (fig. 12). Internally, the interval is composed of lithologically homogeneous, offlapping subunits that dip gently seaward and that range from several feet to 20 ft in thickness. Discontinuous fine-grained sediments bound the progradational sigmoids that extend downdip for several miles and along strike for many miles. The absence of fine-grained bay-fill successions and the amalgamation of distributary-mouth-bar sandstones into laterally continuous sand sheets indicate complete reworking of sediment by storm and wave processes shortly after deposition. The extreme lateral continuity of individual beds, both normal and parallel to depositional dip, suggests that progradation involved the entire delta front rather than particular points.

The facies architecture of delta-front strata in SC 5 was investigated at Cedar Ridge (fig. 17). The delta front consists largely of a single upward-coarsening trend composed of an amalgamation of three minor upward-increasing trends. Each minor upward-increasing trend

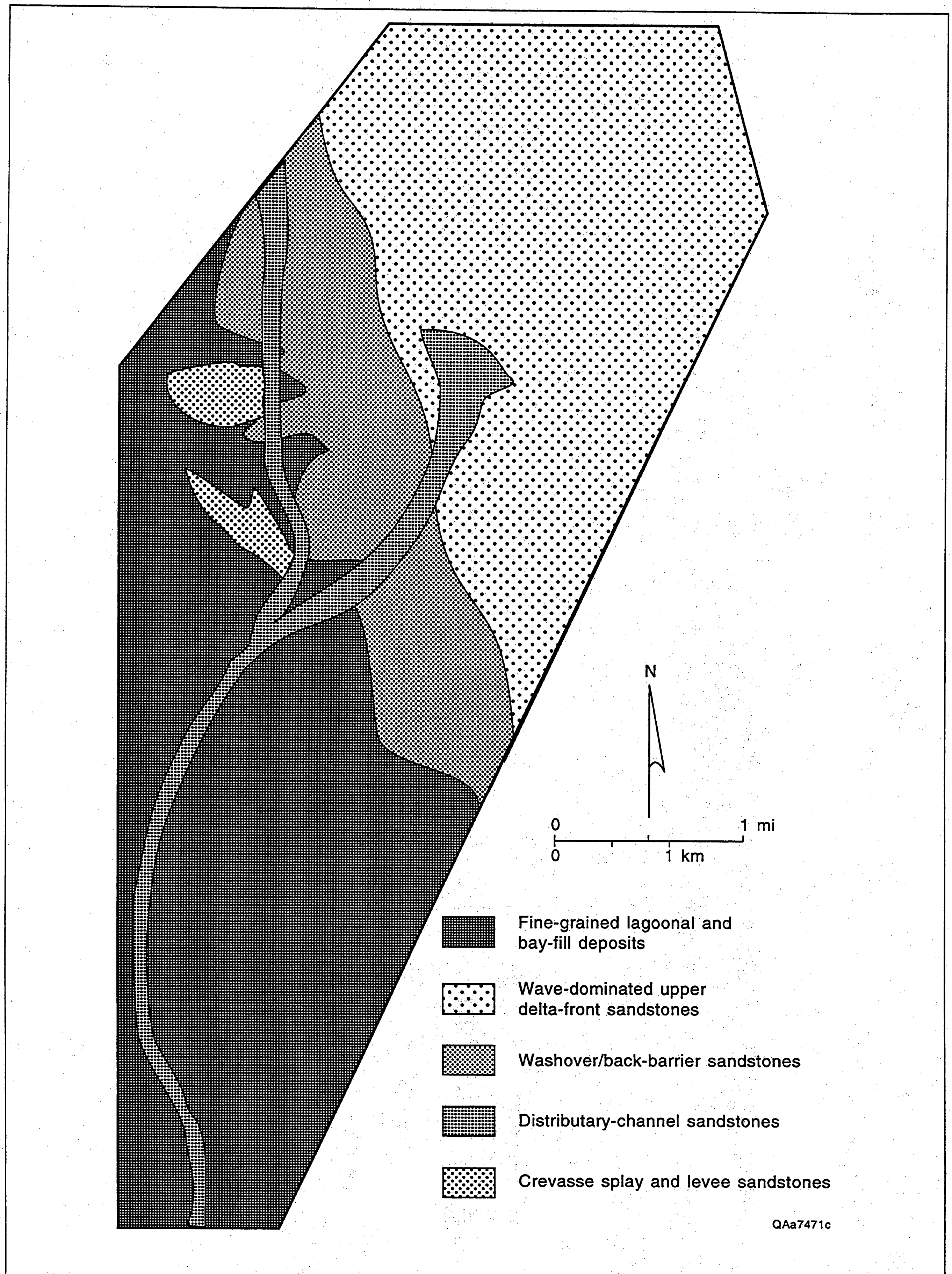


Figure 16. Plan view of facies architecture of parasequence SC 2 MR 9: Dry Wash.

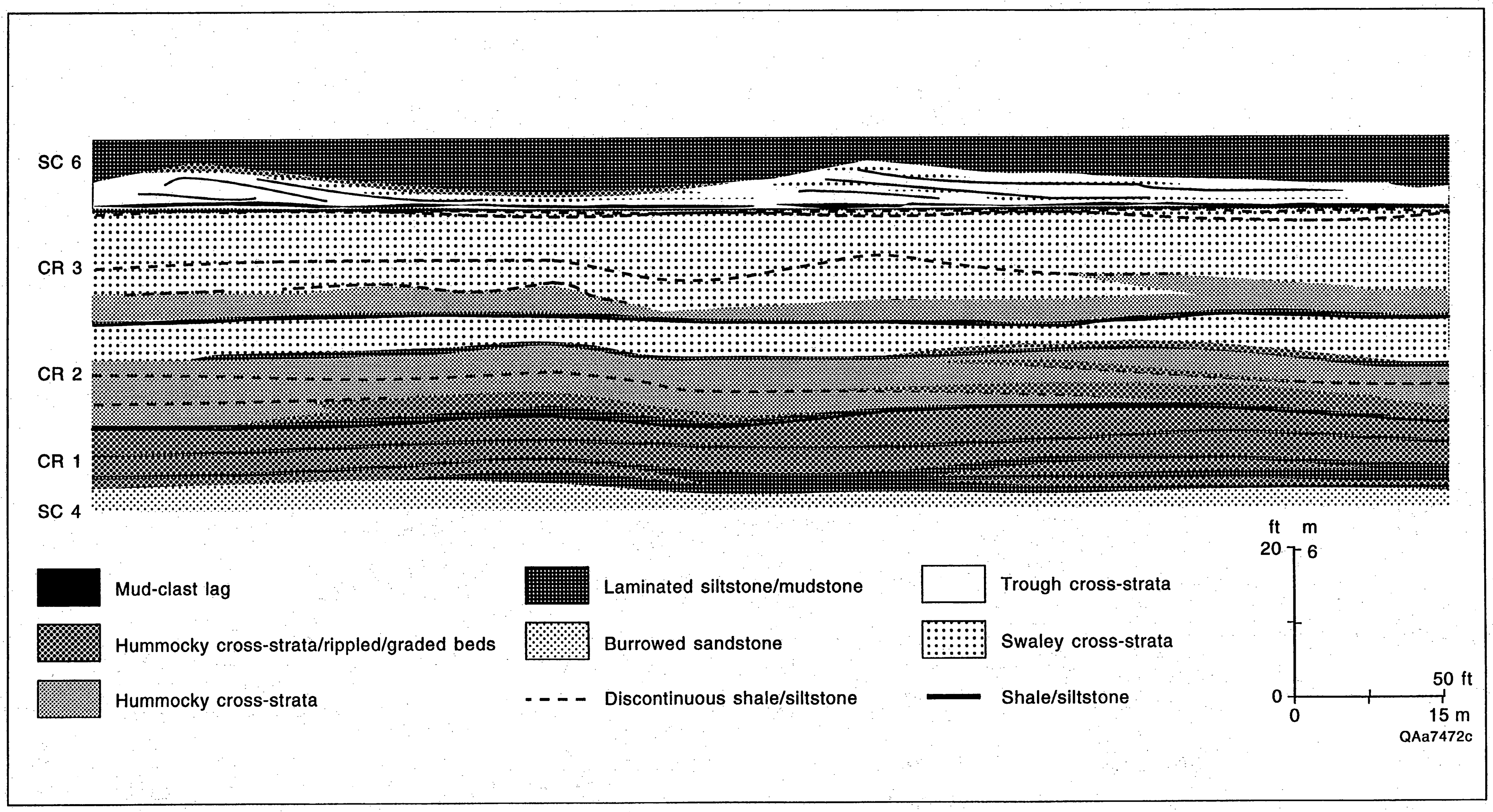


Figure 17. Stratal architecture of Ferron SC 5: Cedar Ridge canyon II.

corresponds to a single upward-coarsening parasequence. In contrast to Dry Wash, parasequences in SC 5 are thin and have amalgamated into a single upward-shoaling trend that displays a high degree of lithologic homogeneity and extreme lateral continuity. The succession is truncated by a low-relief surface and overlain by a set of beds that display an upward-deepening trend. The succession is interpreted to record reworking of the delta front by wave processes during delta-lobe abandonment. Variations in a dip direction are associated with a systematic onshore to offshore facies transition.

Coastal-Plain Facies Tract

In contrast to delta-front deposits of SC 2, the delta plain displays a relatively low degree of facies complexity. The delta front is capped by a thin veneer of marginal marine lagoonal and lower delta-plain deposits (15 to 20 ft). However, immediately landward of the shoreline, relatively thick mud-rich successions of lagoonal and marsh deposits may accumulate (40 ft). Narrow, elongate, sand-rich channel belts locally incise and crosscut preexisting mouth-bar, delta-front, bay-fill, and lagoonal deposits (fig. 18). Laterally extensive interchannel areas consisting of fine-grained levee, marsh, and overbank deposits separate the widely spaced, lenticular, channel sand bodies. In cross section, channel belts typically display a narrow funnel-shaped geometry as much as 80 ft thick and 2,000 ft wide. Erosional surfaces subdivide the channel fill into a number of vertically stacked channel forms (fig. 19). Unidirectional trough cross-strata and thin sand-rich lag deposits separating channel forms compose most of the channel fill. The amalgamated nature of sand bodies within widely spaced, narrow, elongate channel belts is attributed to repeated erosion of vertically aggrading barforms within fixed, low-sinuosity channels. The fixed nature of the channel belts may reflect that distributaries were incised into and bounded by cohesive, mud-rich delta-front, bay-fill, and delta-plain deposits. Although the dimensions of individual distributary channel belts are substantial, volumetrically they are a minor component, constituting less than 5 percent of the total net sand within the SC 2 interval.

In contrast to SC 2, distributaries are the dominant sand body type within SC 5. Distributary complexes remove and replace almost the entire delta front and are preserved as a network of lenticular sandstone bodies elongated parallel to depositional dip, interdigitate with overbank, crevasse splay, and abandoned channel fill (fig. 20). In that cross section, distributaries display a broad tabular geometry as much as 60 ft thick and 3,000 ft wide (average width to thickness ratio of 25) and composed of numerous multilateral to multistory, poorly amalgamated macroforms (fig. 21). A variety of stratal types are present within the channel fill, with thick mud-clast-bearing lag deposits or fine-grained sediments separating individual macroforms. These attributes indicate distributaries were highly mobile, repeatedly

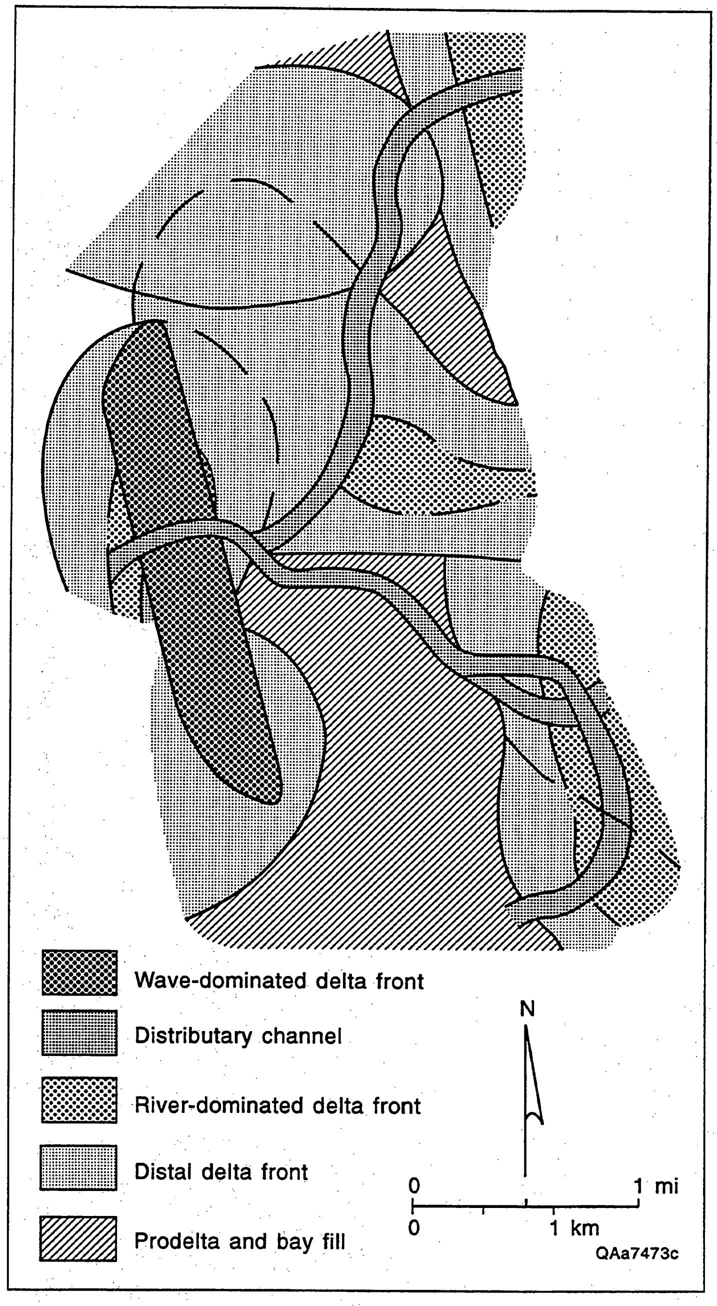


Figure 18. Plan view of composite facies architecture within Ferron SC 2 between Rock Creek and Miller Canyon.

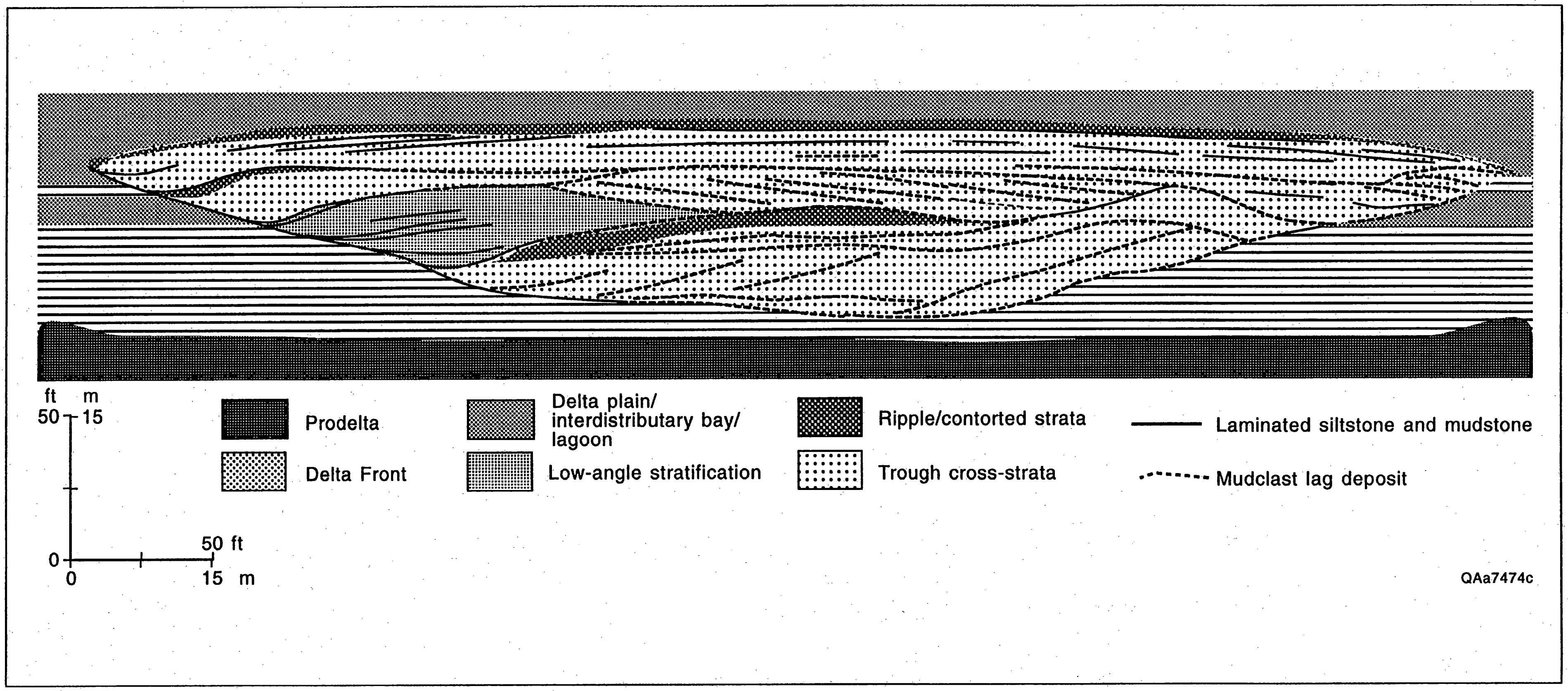


Figure 19. Distributary channel architecture of Ferron SC 2: I-70.

eroding laterally adjacent delta-front and delta-plain sediments.

Characteristics of distributary channel deposits vary markedly from proximal to distal portions of the facies tract. Distal deposits are encased in delta-front strata and display significant evidence of marine modification, whereas proximal deposits form laterally expansive sand bodies, up to 3,000 ft wide and flanked by crevasse splay and abandoned channel fill facies. Near the seaward extent of distributary channel influence, channel belts are composed of several laterally inclined and offset sigmoidal sand bodies deeply incised into coeval delta-front deposits. Mudstone layers bounding sand bodies display a low bedform diversity, are bioturbated, and contain shell debris as well as sharks' teeth. The interbedded nature of these deposits reflects a strong interaction between marine and fluvial processes. Sand bodies formed during high-stage events and bioturbated mudstone layers developed during intervening low-stage events as a marine salt water wedge occupied distal portions of the channel. In a landward direction, these deposits are partially to completely eroded by laterally expansive belt deposits. Channel sand bodies consist of poorly interconnected multilateral sand bodies segregated by thick mud-clast lag deposits. Channel belts display a high diversity of stratal types, contain well-developed mudstone and siltstone drapes along accretion surfaces, and are closely associated with crevasse splay deposits and abandoned channel fill.

A comparison between channel belt geometries of seaward- and landward-stepping units is provided in figure 22. The average width-to-thickness ratio of seaward-stepping channel belts is approximately 12:1; in landward-stepping units the ratio increases to approximately 24:1. The proportion and distribution of lithofacies within distributary channel belts associated with seaward- and landward-stepping units are compared in figure 23. Distributary channel belts associated with seaward-stepping units consist largely of trough cross-strata and thin, sand-rich lag deposits. Other lithologies, such as ripple cross-stratification and fine-grained laminated sediments, are restricted largely to the uppermost portion of the channel fill. This trend is interpreted to reflect the high degree of amalgamation between channel forms within these multistoried channel belts, with the upward-fining succession of strata preserved only during the final channel fill event. By contrast, within distributary channel belts of landward-stepping units, lithofacies are partitioned more evenly throughout the channel fill. The trend is attributed to the greater overall preservation of the channel forms within these multilateral channel belts.

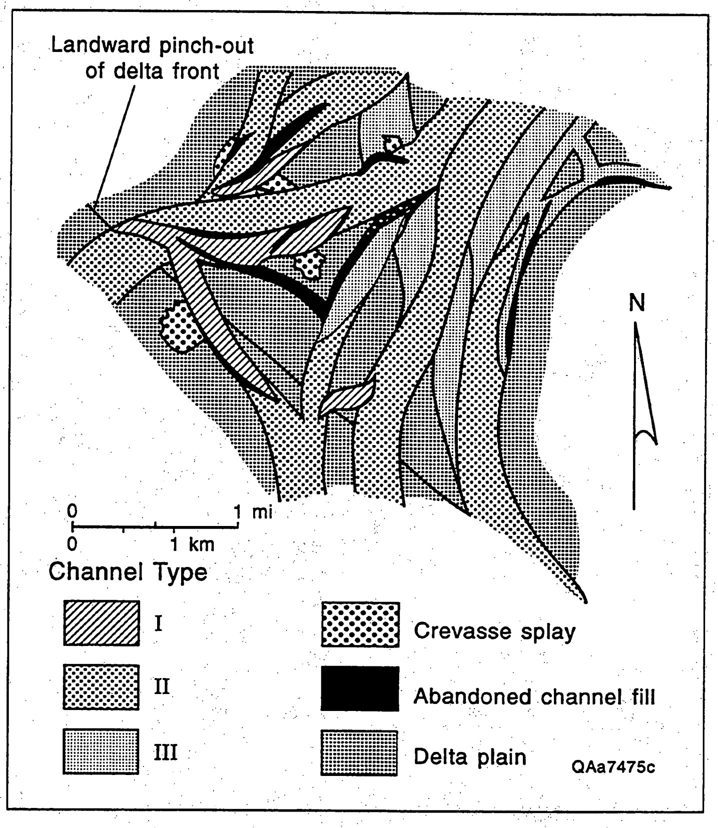


Figure 20. Plan view of regional facies architecture within Ferron SC 5 between Muddy Creek and Cedar Ridge canyon.

Transgressive Facies Tract

The delta-abandonment facies association comprises those facies that accumulate following the abandonment of a delta and is initiated by channel avulsion and a reduction in the amount of sediment supplied to the delta. Deposits are characterized by a thin, laterally persistent unit that is the product of reworking of the underlying abandoned delta for sediment supply.

In Ferron SC 5, wave reworking of the abandoned delta lobe is appreciable. Much of the foreshore and upper delta-front facies have been removed, resulting in a predominance of incomplete, attenuated delta-front sequences, with local preservation of distributary channel sandstones (Cedar Ridge) entirely encased within marine strata. The facies succession is marked by a sharp, low-relief erosion surface overlain by upper shoreface to shelf deposits. Redistributed sand is deposited as a thin, intensely bioturbated sand sheet

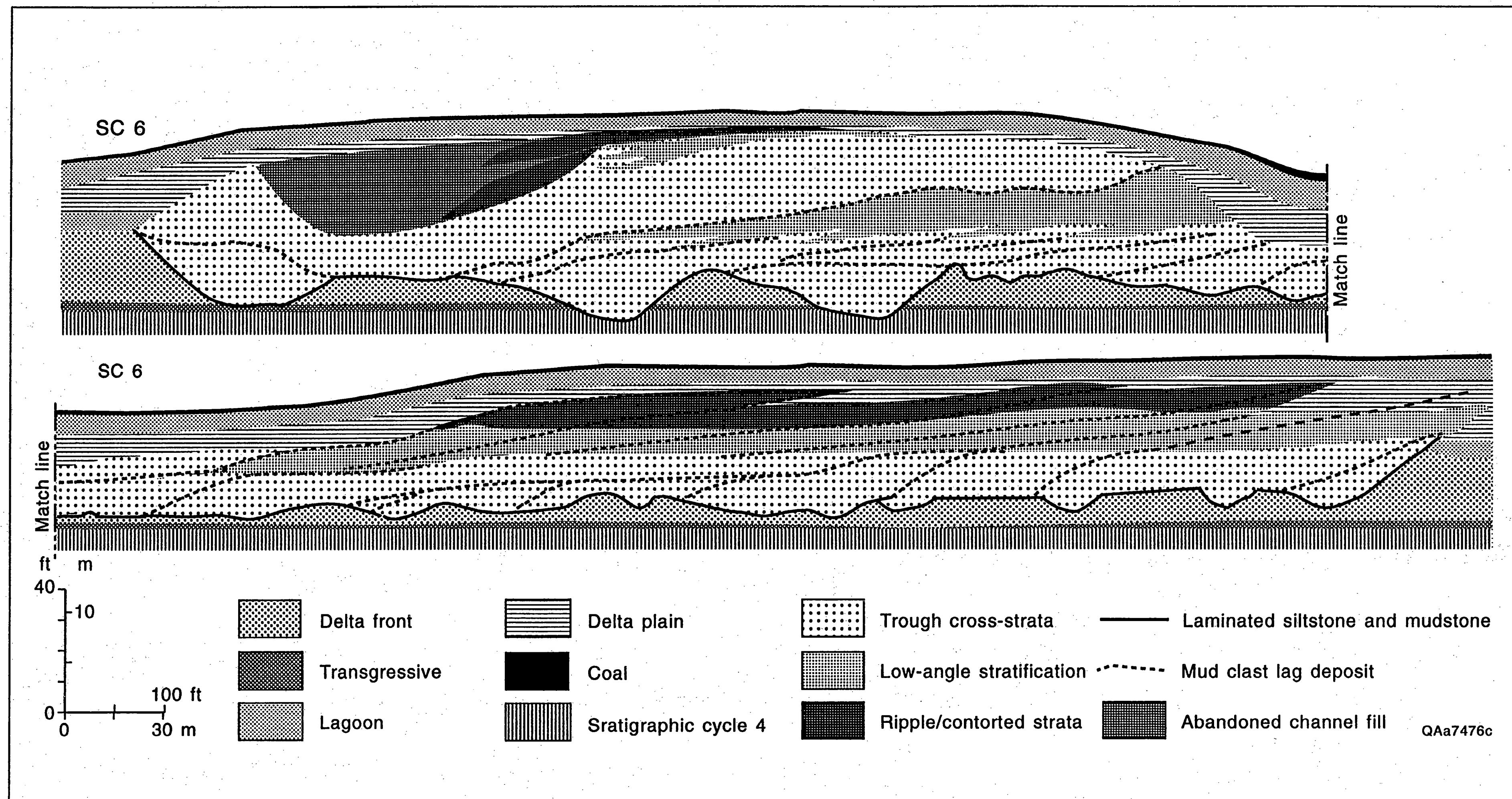


Figure 21. Distributary channel architecture of Ferron SC 5: South Muddy Creek.

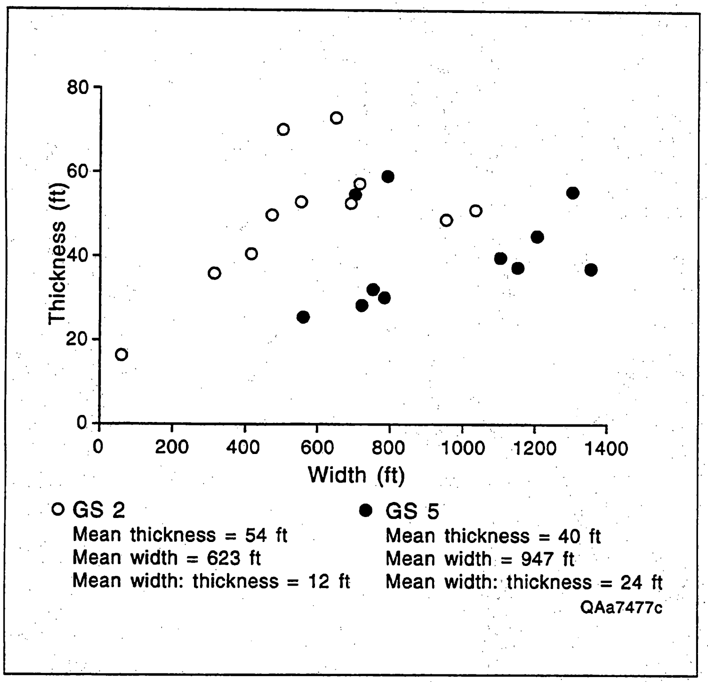


Figure 22. Comparison of SC 2 and SC 5 distributary channel belt dimensions.

or a series of lenticular trough cross-stratified sand bodies that are up to 15 ft thick. Areas landward of the transgressive shoreline are covered with relatively thick lagoon, marsh, washover, and abandoned channel fill or estuarine deposits.

In Ferron SC 2, reworking of sediment by wave processes is not as significant as in SC 5. Transgressive deposits form a thin, locally discontinuous but laterally extensive unit (up to several feet) in which internal stratification is obscured by intense burrowing, locally overlain by a thin bed of hummocky cross-stratified sandstone. While these modifications are taking place, areas landward of the migrating shoreline are covered with thick, extensive marsh deposits.

Bounding Element Architecture

The sequence stratigraphic approach provides a framework for accurate facies analysis and interpolation

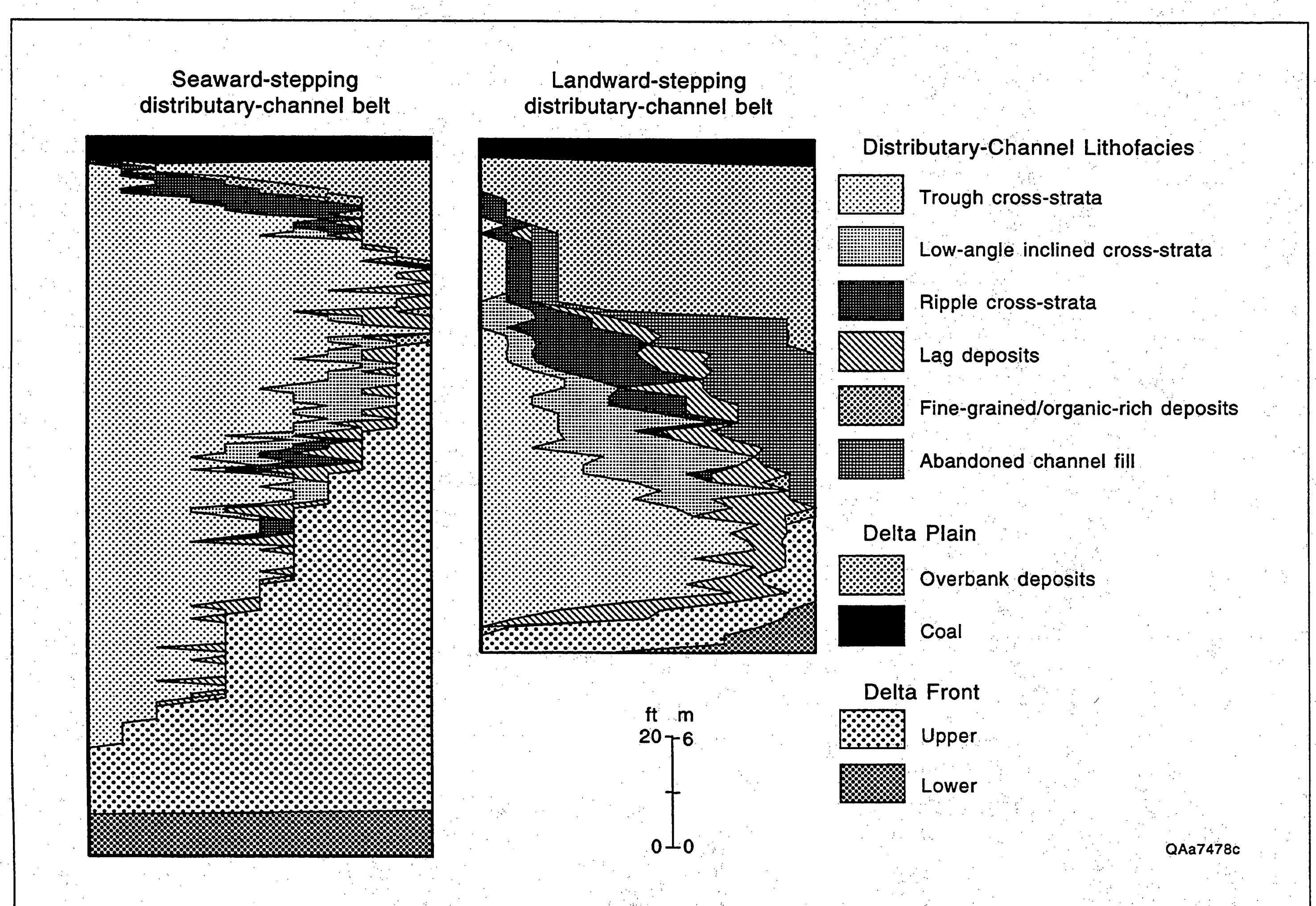


Figure 23. Comparison of lithofacies distribution in seaward- and landward-stepping distributary channel belts.

that is relevant to reservoir development and description. Many types of petrophysical boundaries are coincident with stratigraphic bounding surfaces, and correlation techniques using principles of sequence stratigraphy allow identification of heterogeneities that divide the reservoir into compartments.

Lithologically, shales form the most important type of barriers or bounding elements in the Ferron system. Shale barriers occur over a wide range of scales and display diverse characteristics. Types of shale barriers include (1) seaward-thickening wedges of shallow-marine strata, (2) laterally extensive coastal-plain and marginal marine mudstones, (3) lenticular bay-fill successions, (4) shoestring-like mudstone plugs, and (5) thin intermouthbar and interchannel mudstones. Nonshale bounding elements include laterally extensive coals, intensely carbonate-cemented transgressive sandstones, and mud-clast lag deposits formed along channel base bounding surfaces. Changes in accommodation and base level lead to variable preservation of these features.

A hierarchy of bounding elements exists that display both coincident and discordant relationships with chronostratigraphically significant surfaces. Bounding elements coincident with chronostratigraphically significant surfaces are best developed in the delta-front facies tract; bounding elements that display discordant relationships to chronostratigraphically significant surfaces are best expressed in the coastal-plain facies tract. The combination of different barrier types leads to complex bounding element structures that vary in systematic fashion between seaward- and landward-stepping stratigraphic cycles.

Delta Front

In the delta front, the most laterally extensive barriers are coincident with marine flooding or abandonment surfaces. A hierarchy exists in which mudstones bounding stratigraphic cycles (0 to 40 ft in thickness and 5 to 30 mi in length) display greater thickness and lateral continuity than do mudstones bounding parasequences (0 to 20 ft thick and 0.5 to 5 mi in length). Bounding elements consist of a seaward-thickening wedge of marine strata composed of progradational lower delta-front, prodelta, and marine-shelf mudstones. The base of the bounding element conforms to the underlying topography, but the top interfingers with middle to upper delta-front deposits. Landward, these bounding elements are replaced by a surface of erosion (typically in the upper shoreface zone) and a paraconformable succession of lagoonal mudstones and marsh deposits within the coastal plain. In seaward-stepping cycles, these bounding elements are steeply inclined in a seaward direction and act to severely compartmentalize the prograding wedge into a series of shingled compartments (parasequences). In the transgressive phase these bounding elements are less steeply inclined and are poorly preserved between parasequences.

Within seaward-stepping delta fronts, delta lobes may be replaced laterally by vertically accreted, fine-grained bay-fill successions that are 30 to 60 ft thick and 1 to 5 mi in width. Bay fills are best developed within the seaward-stepping cycles where the delta front progrades basinward of the underlying stratigraphic cycle. Fluvial-dominated delta fronts also contain numerous inclined and lenticular mudstone interbeds displaying truncating, sidelapping, and offlapping relationships (several inches to several feet in thickness and tens to hundreds of feet in length), as well as thicker bay-fill successions that form bounding elements encasing mouth-bar sand bodies. At the distal portion of the delta lobe, fine-grained lower delta front deposits encase thin, discontinuous fine-grained storm beds or alternately thick, discontinuous fault-, slide-, and slump-block sandstones.

Marine shales coincident to stratigraphic cycle boundaries vertically subdivide the landward-stepping system tract. Within landward-stepping stratigraphic cycles, parasequences and component mouth-bar deposits are amalgamated into a lithologically homogeneous strike-elongate sand body. The absence or poor development of bay-fill successions and marine mudstones coincident to parasequence bounding surfaces reflects the dominance of wave and storm processes. Wave erosion during marine flooding events may result in the complete removal of upper delta-front deposits. Overlying transgressive deposits are often intensely calcite cemented, further enhancing reservoir discontinuity between stratigraphic cycles.

Coastal Plain

Bounding elements within the coastal-plain facies tract consist of lagoonal mudstones, floodplain mudstones, organic-rich marsh deposits, abandoned channel fill mudstones, and channel base bounding mudstones and mud-clast lag deposits. Predictably, mudstones in floodplains and lagoonal environments display greater lateral continuity than do mudstones deposited in abandoned channel fills or along channel base bounding surfaces.

Mud-rich lagoonal deposits overlie and replace delta-front lobes in a landward direction. Lagoonal mudstones interfinger with washover and tidal delta/channel sandstones. In seaward-stepping cycles, these deposits are generally relatively thin (10 to 20 ft) but laterally extensive (1 to 5 mi in width and 5 to 20 mi in length). However, immediately landward of the shoreline, relatively thick successions of lagoonal mudstones may accumulate (up to 45 ft). In landward-stepping stratigraphic cycles, lagoonal deposits display similar lateral facies relations but are relatively restricted laterally (0.5 to 1 mi in width).

In a landward direction, lagoonal mudstones are replaced by coastal-plain mudstones. Coastal-plain mudstones bound channel and crevasse-splay sandstones and are between 1 and 30 ft thick, but successions up to 100 ft are preserved where floodplain deposits of successive stratigraphic cycles vertically stack. In seaward-stepping stratigraphic cycles, coastal-plain mudstones are preserved as thin, laterally extensive deposits that bound widely spaced distributary channel sand bodies, constituting over 90 percent of the coastal-plain deposits. In landward-stepping cycles, coastal-plain mudstones are preserved as erosional remnants within or between channel sand bodies, constituting between 30 and 50 percent of the coastal-plain deposits. However, although channel belt amalgamation has created lateral continuity between channel belts, the internal connectivity is severely disrupted by numerous abandoned channel fills, shale drapes, and mud-clast lag deposits.

Bounding elements can be mapped with different degrees of certainty. In landward-stepping cycles, only bounding elements corresponding to marine flooding events that bound stratigraphic cycles can be mapped with a high degree of certainty. By contrast, in seaward-stepping cycles, marine shales coincident with flooding events, bay-fill successions, lagoonal mudstones, and floodplain mudstones can be mapped with a moderate to high degree of certainty. Other bounding elements, such as abandoned channel fills, channel base bounding elements, and interbar mudstones, are mapped with a very low degree of confidence.

Reservoir Quality

Petrography and Reservoir Quality

Petrologic investigations were conducted in conjunction with petrophysical measurements to determine what mineralogical, textural, and diagenetic properties characterize reservoir and nonreservoir rock.

Petrography: texture, composition and cement

Sequence stratigraphic and geologic studies integrated with petrographic determinations (petrographic characterization conducted by Fisher and others [1993a, b]) reveal variations in detrital and authigenic mineralogy that correlate with differences in depositional environment, sequence stratigraphy, and position within the facies tract.

Although compositionally different, equivalent facies in Ferron SC 5 and SC 2 show similar relationships. In both the seaward-stepping SC 2 and landward-stepping SC 5, transgressive, delta-front, and mouth-bar sandstones are more quartz rich than are distributary channel sandstones (figs. 24 and 25). For example, distributary sandstones associated with wave-modified deltaic sequences (SC 5) have a mean composition of Q:F:R = 77:11:12, whereas coeval delta-front deposits have a mean composition of Q:F:R = 88:9:3. In contrast, distributary channel sandstones associated with fluvial-dominated, seaward-stepping deltaic sequences (SC 2) have a mean composition of Q:F:R = 68:25:7, and coeval delta-front deposits have an average Q:F:R composition of 82:13:5. Pseudomatrix is more abundant in distributary channel sandstones than in transgressive and delta-front sediments, 2.4 percent and 0.7 percent, respectively. Cement volumes vary from 7.1 percent in distributary channel sandstones to a mean of 10.5 percent in delta-front deposits. Distributary channel sandstones have approximately equal amounts of authigenic quartz and kaolinite, whereas quartz and carbonates are the predominant authigenic phases in delta-front deposits. Within SC 5, marked mineralogical differences occur between distal and proximal portions of the distributary system. Proximal distributary sandstones display a mean composition of Q:F:R = 77:13:10, compared with Q:F:R = 80:15:5 for distal portions. In a similar fashion, pseudomatrix also decreases from proximal to distal

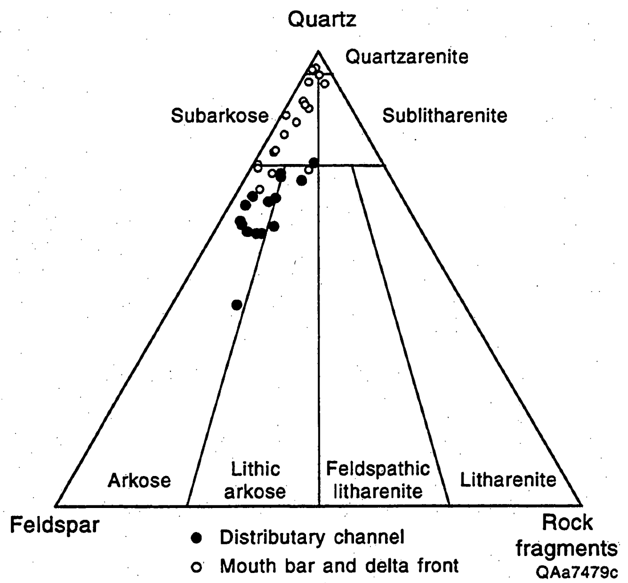


Figure 24. Petrographic composition of distributary channel and delta-front sandstones, Ferron SC 2 (after Fisher and others, 1993).

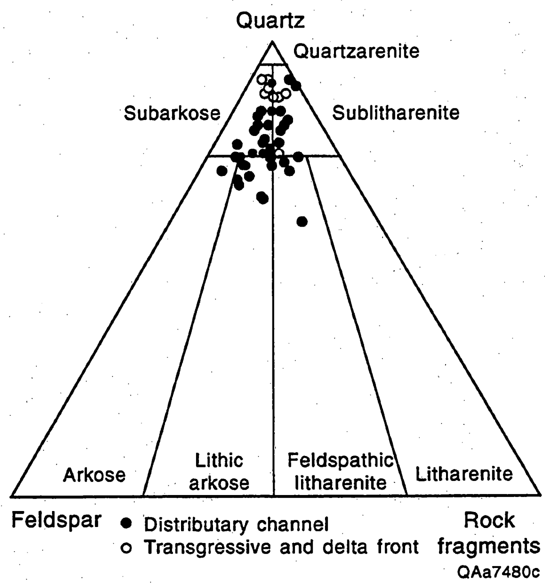


Figure 25. Petrographic composition of delta and distributary channel strata, Ferron SC 5 (after Fisher and others, 1993).

portions, ranging from a high of 3.9 percent to a low of 1.0 percent. Because Ferron SC 2 was sampled at only one location, near the center of the facies tract, landward-to-seaward compositional comparisons were not presented.

Differences in mineralogy between depositional facies as well as in position in the facies tract are consistent with variations in the type and intensity of depositional processes. Quartz-rich compositions of the delta-front and transgressive sandstones are attributed to physical reworking associated with wave and tidal processes. Also, within the distributary system of SC 5, increased transport distances, as well as a seaward increase in reworking effectiveness, probably reduced the amount of ductile rock fragments and locally derived pseudomatrix. Mineralogical differences between landward- and seaward-stepping sequences may reflect sequence stratigraphic controls that result from variations in the location of accommodation space. Alternatively, the mineralogical change may reflect a change in hinterland characteristics, such as source terrain and climate.

Porosity, sorting, and grain size

Porosity is influenced by sorting and grain size. Surprisingly, the highest porosities corresponded to the coarser grained sandstones and the poorest porosities to the finer grained samples (fig. 26). However, for a given grain size, the highest porosities are with the best sorted samples and the lowest porosities with the poorest.

Permeability, grain size, sorting, and detrital composition

Textural and detrital characteristics correlate predictably to permeability. Shifts in grain size, sorting, and detrital composition correspond to marked changes in permeability.

Over a limited scale, increases in grain size corresponded to increases in permeability. From very fine through medium-grained sandstone, permeability shows a predictable increase with increasing grain size (fig. 27). However, as grain size increases beyond

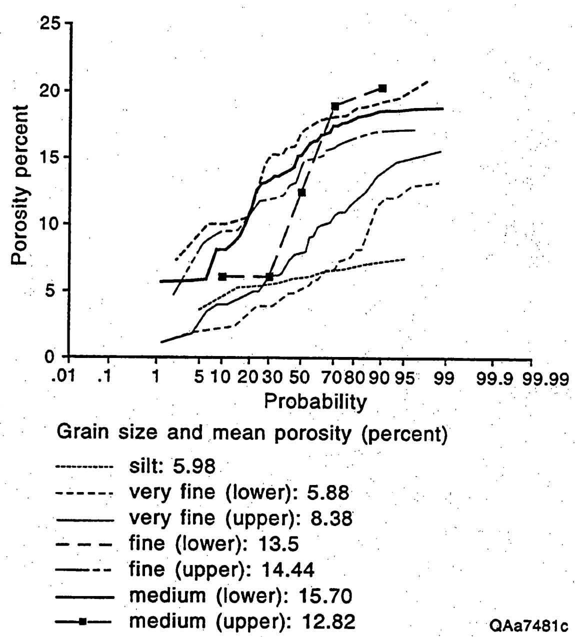


Figure 26. Porosity versus grain size (data from ARCO cores).

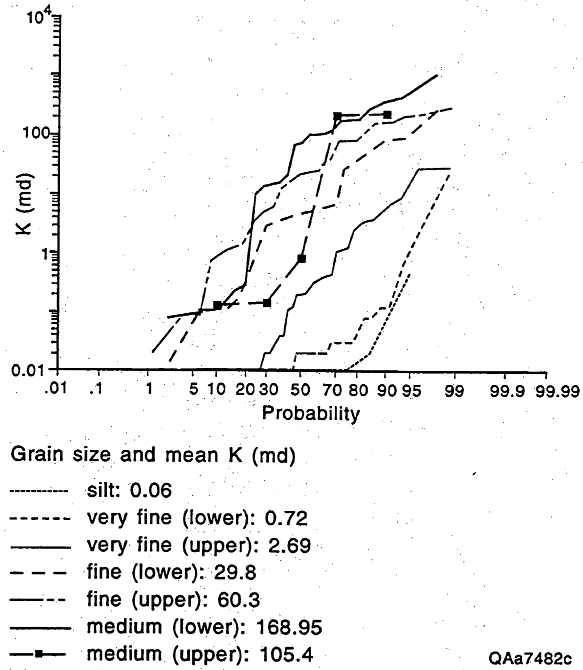


Figure 27. Permeability versus grain size (data from ARCO cores).

medium-grained sandstone, average permeability tends to decrease slightly. The decrease may be related to poorer sorting or the presence of mud clasts, distorted into pseudomatrix within these sandstones. A comparison of sandstones with equivalent grain size and sedimentary structures reveals permeabilities of well-sorted deposits to be more uniform and higher than permeabilities of moderate and poorly sorted sandstones (fig. 28). Within the distributary system, the mineralogical shift to a composition with lower rock-fragment content corresponds to a marked increase in average permeability. Predictably, quartz-rich sandstones display higher and more uniform permeabilities than relatively quartz-poor sandstones (Fisher and others, 1993).

Permeability was related to various petrologic attributes (19 total), such as grain size, sorting, shape, porosity, composition, and cement. Multiple linear regression analyses performed on distributary-channel sandstones quantify petrologic influences on permeability (Miller and others, 1993). In Ferron sandstones, four variables describe 90 percent of the permeability variation. In order of importance these are grain size, sorting, composition, and porosity. These results suggest that unless obliterated by advanced diagenesis, sandstone petrology and permeability can be directly related to depositional processes recorded by lithofacies.

Permeability and porosity

Porosity determined from the cores within the equivalent reservoir interval varies from a low of 1 percent to a maximum of 21 percent. Over the same interval, permeability ranges from .01 md to more than 1,200 md. As might be expected, because porosity and permeability both correlate with grain size and sorting, there is a good overall linear relation between the two variables, such that permeability increases with porosity (fig. 29). In some cases, however, porous units have very low permeabilities.

Porosity and permeability measurements were made under unstressed conditions. Comparison of stress versus unstressed measurements were conducted

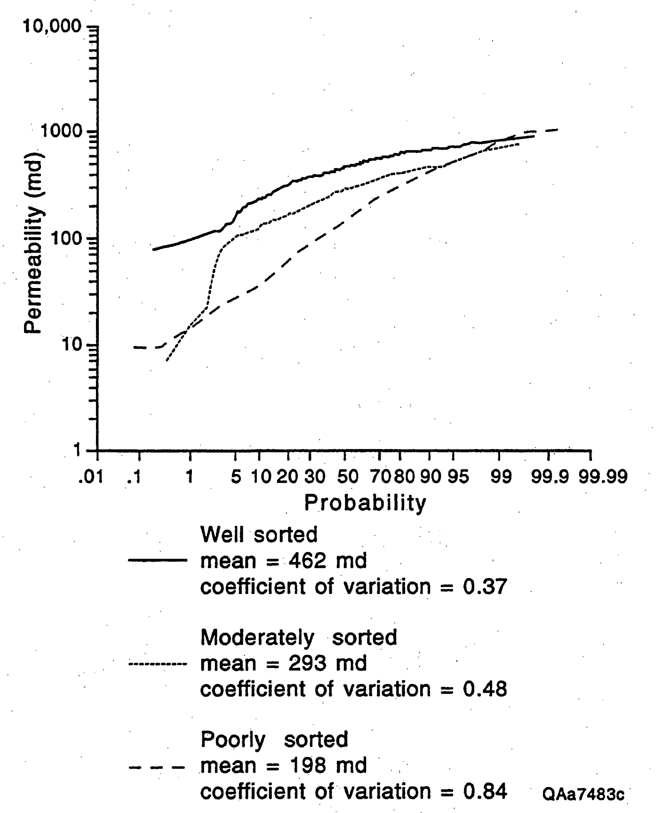


Figure 28. Probability plot of log permeability for poorly, moderately, and well-sorted medium-grain trough cross-stratified sandstone.

by Miller and others (1993) over a range of 200 to 6,000 psi. Results showed that application of overburden stress diminishes average porosity by about 4 percent and permeability by a factor of 2 to 3. The relationship is not linear, however, and most of the reduction occurs during the initial 1,000 psi of added stress.

Facies, Sequence Stratigraphy, and Reservoir Quality

Texture and detrital composition largely control porosity and permeability (reservoir quality) of Ferron sandstones. In turn, texture and mineralogy of the sedimentary rocks of the Ferron Sandstone are determined by sedimentary facies and general depositional setting. The relationship between facies and reservoir quality is largely a manifestation of grain size, sorting, and compositional variations that result

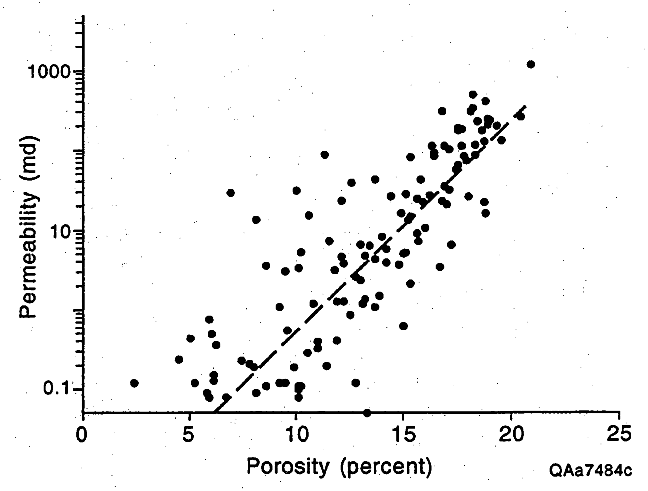


Figure 29. Porosity versus permeability (data from ARCO cores).

from depositional processes. As a result, discrete permeability groups can be established on the basis of lithologic characteristics within distributary channel and delta-front sandstones. Permeability measurements of landward- and seaward-stepping distributary channel and delta-front sandstones were divided into subsets and compared according to depositional and lithologic characteristics.

Permeability and lithofacies

In the field, permeability was classified according to grain size, sorting, and stratification type. A probability plot shows that in general a close relationship exists between permeability and lithofacies. Within the distributary channel facies, five lithofacies related to permeability groups were recognized. Medium- to coarse-grained trough cross-strata formed a high-permeability group, fine- to medium-grained low-angle and planar strata formed an intermediate-permeability group, and very fine to fine-grained ripple cross-strata, coarse-grained lag deposits, and silty to very fine grained laminated sediments formed a low-permeability group (Barton, 1994). A similar relationship was observed within delta-front strata; fine- to medium-grained swash and trough cross-stratified sandstones formed a high-permeability group, very fine to fine-grained swaley and hummocky cross-stratified

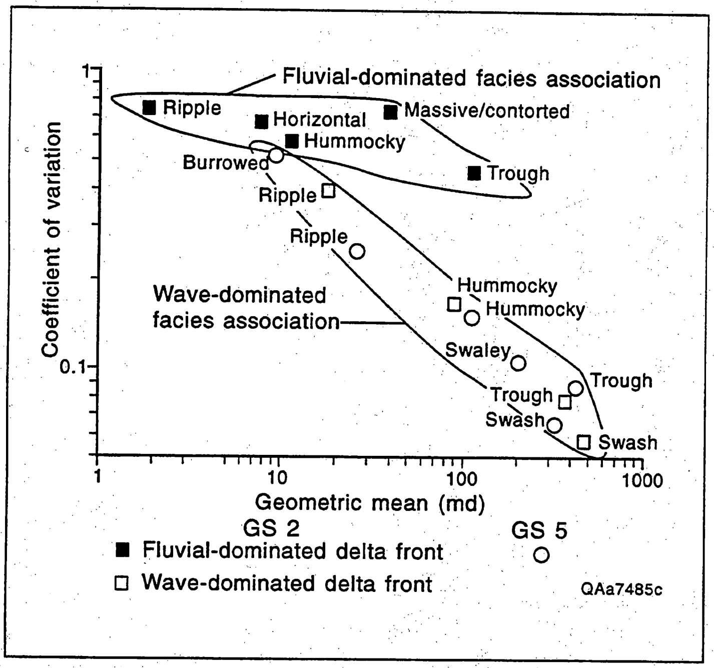


Figure 30. Comparison of permeability characteristics of Ferron delta-front lithofacies.

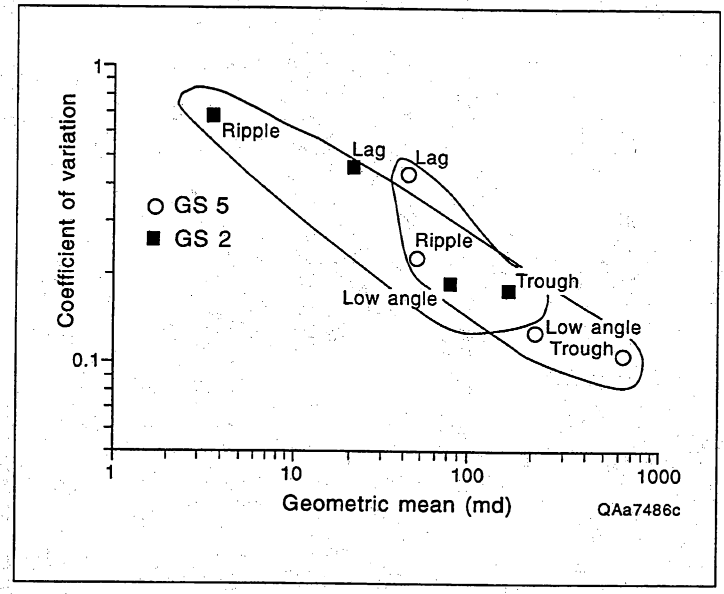


Figure 31. Comparison of permeability characteristics of Ferron distributary channel lithofacies.

sandstones formed an intermediate-permeability group, and very fine to fine-grained rippled and pervasively bioturbated sandstones formed a low-permeability group (Barton, 1994). For a given stratification type, the highest, most uniform permeabilities were found to be in the best sorted and coarsest grained samples, and the lowest, most variable permeabilities were found to be in the poorest sorted and finest grained samples.

Bedform attributes are not a direct indicator of permeability characteristics. Although relative differences are similar, absolute values among bedform groups are not directly transferable between dissimilar depositional or stratigraphic settings. Differences in permeability characteristics among similar bedform groups occur between wave- and fluvial delta-front associations (fig. 30) and between distributary channel deposits of SC 2 and SC 5 (fig. 31). Dissimilarities in permeability characteristics among bedform groups largely reflect variability in sorting and composition rather than grain size. Well-sorted, wave-dominated delta-front lithofacies display uniformly high permeabilities, in comparison with the moderately sorted, fluvial-dominated delta-front lithofacies. In a similar fashion, distributary channel lithofacies of SC 5 display higher permeabilities than comparable lithofacies in SC 2.

Permeability and facies

Lithofacies are grouped into predictable associations. Comparison of permeability values (fig. 32) indicates wave-dominated facies associations display the best reservoir quality. Wave-dominated upper delta-front and washover fan sandstones displayed the highest permeabilities, with mean permeabilities of 605 md and 361 md, respectively. Distributary channel, river-dominated mouth-bar, wave-dominated middle delta-front, and crevasse-splay sandstones form intermediate permeability classes averaging 212 md, 159 md, 99 md, and 66 md, respectively. Wave-dominated lower delta-front, lagoonal, bay-fill, and river-dominated delta-front sandstones displayed low permeabilities averaging 16 md, 12 md, 6 md, and 1 md, respectively. The trend largely reflects the fact that permeabilities of well-sorted, quartz-rich sandstones (from sediment reworking in wave-dominated environments [upper delta front, washover]) tend to be more uniform and higher than permeabilities from poorly sorted sandstones containing abundant feldspar or rock fragments (distributary channel, distributary mouth bar). The lower than expected permeabilities of the fine-grain, quartz-rich transgressive sandstones may reflect a higher concentration of mud matrix because of intense burrowing or preferential calcite cementation.

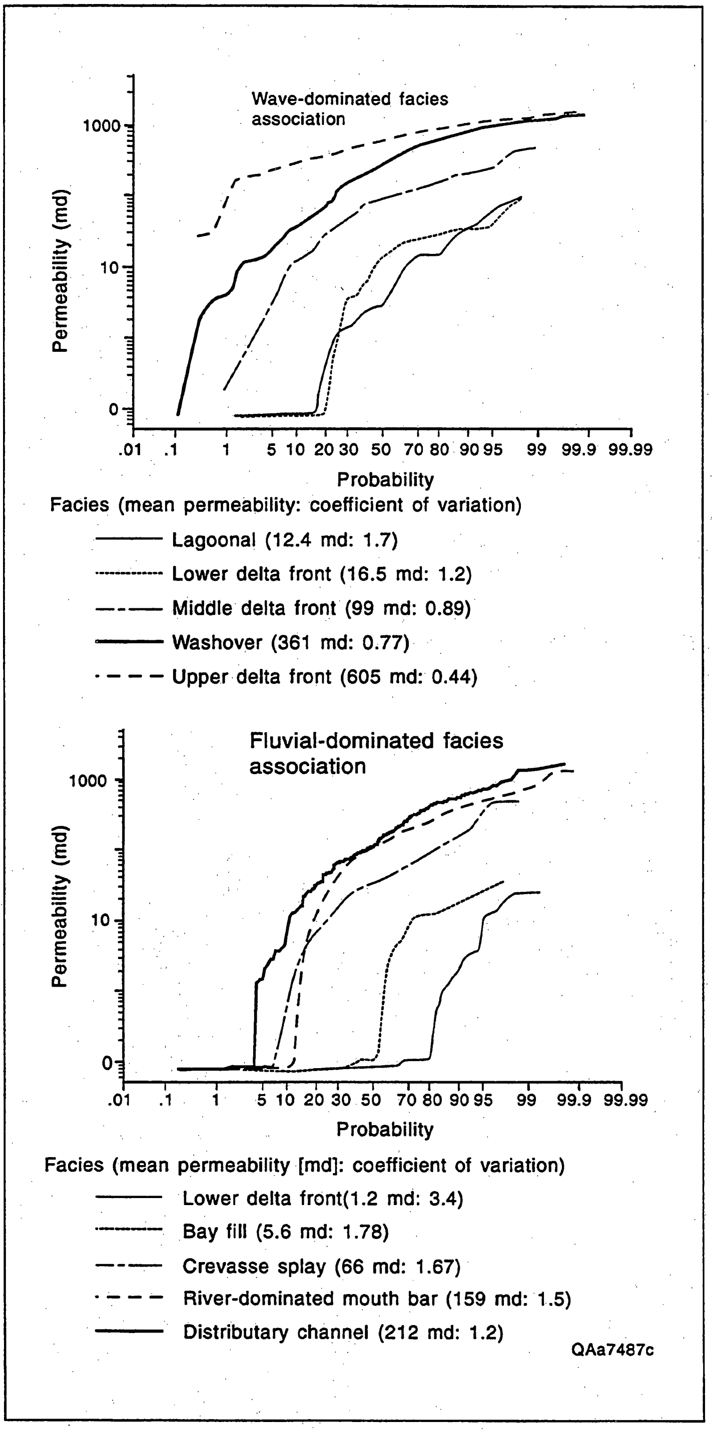


Figure 32. Comparison of permeability characteristics from delta-front facies associations.

In a similar fashion, lithologically diverse, quartz-rich, distributary channel lithofacies associated with landward-stepping SC 5 display higher but more variable permeabilities than do lithologically homogeneous but quartz-poor (feldspathic-rich), distributary lithofacies associated with more fluvially dominated, seaward-stepping SC 2. Results indicate that bedform and grain size characteristics alone cannot be used as a direct indicator of permeability variation. Permeability characteristics of stratal types must be calibrated at the depositional facies scale with regard to sorting and mineralogical characteristics.

Permeability characteristics of seaward- and landward-stepping deltaic units displayed a number of similarities because textural and detrital characteristics of Ferron sandstones fundamentally control permeability and porosity. In both SC 2 and SC 5 sandstones, increases in grain size, sorting, and detrital quartz composition correspond to marked increases in permeability. As a result, permeability displayed a predictable relationship to sedimentary facies type. Because SC 5 has more quartz-rich, well-sorted sandstones in both distributary channel and wave-dominated delta-front strata, it displays higher overall permeabilities than SC 2.

Facies, Sequence Stratigraphy, and Permeability Structure

A comparison is made between the permeability structure of landward- versus seaward-stepping delta fronts and distributary channel sand bodies. Spatial variations in permeability were examined by visual comparison of permeability profiles across the outcrop (Stalkup and Ebanks, 1986) and correlation of permeability trends using the semivariogram technique. The vertical and lateral correlation structure was compared and contrasted within four important reservoir facies: distributary channel, washover, mouth bar, and upper delta front.

Delta front

Figures 33 and 34 show the relationship of permeability to facies architecture at Dry Wash and Cedar Ridge for delta-front deposits of SC 2 and SC 5, respectively. Permeability patterns within the delta front of SC 2 are extremely variable both vertically and laterally (fig. 33). At the largest scale, two distinct upward-increasing permeability trends reflect the presence of two upward-coarsening parasequences. Laterally, the trends persist for several hundred to several thousand feet. Permeability profiles within the

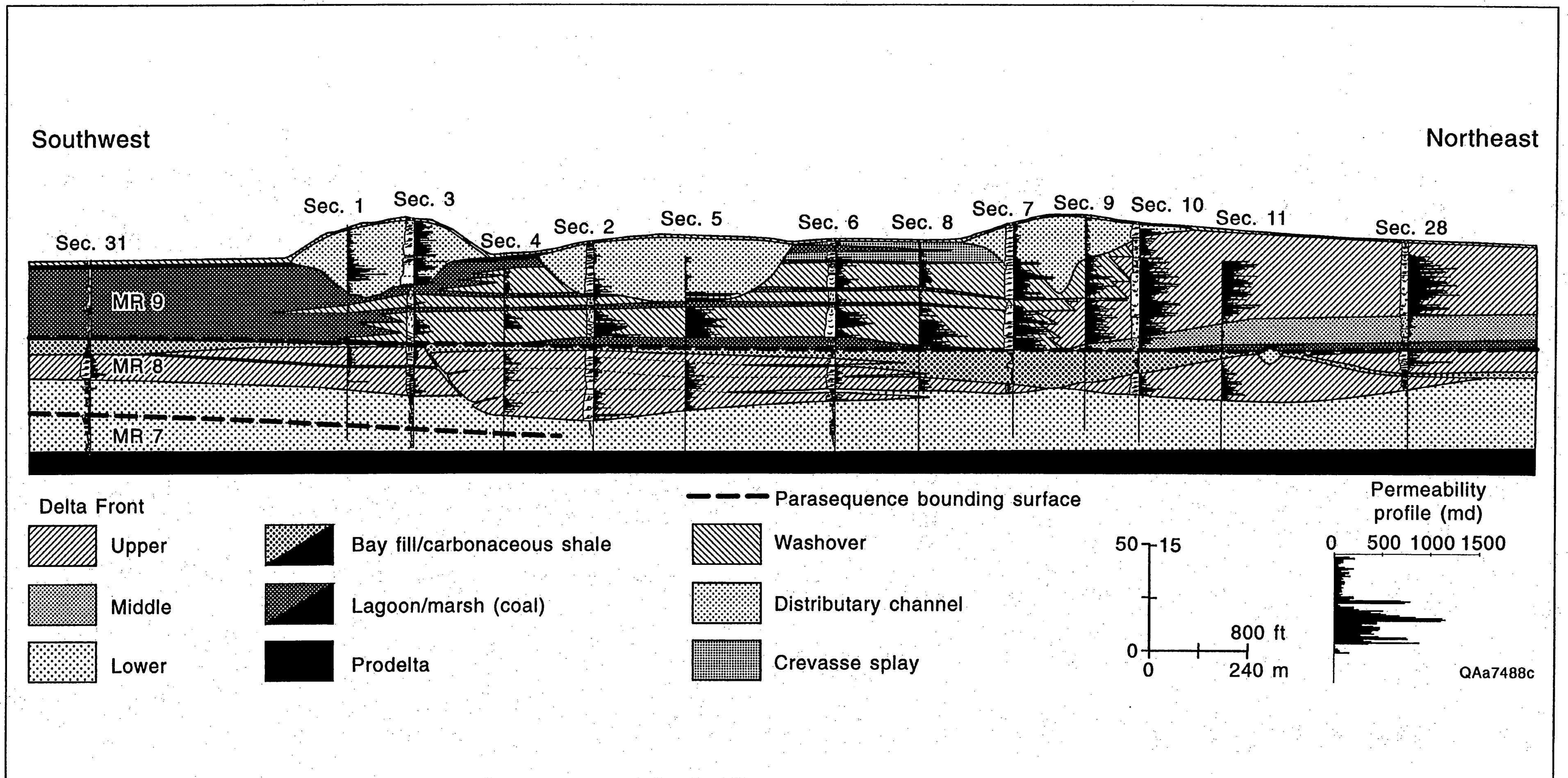


Figure 33. Permeability profiles and facies architecture of Ferron SC 2: Dry Wash.

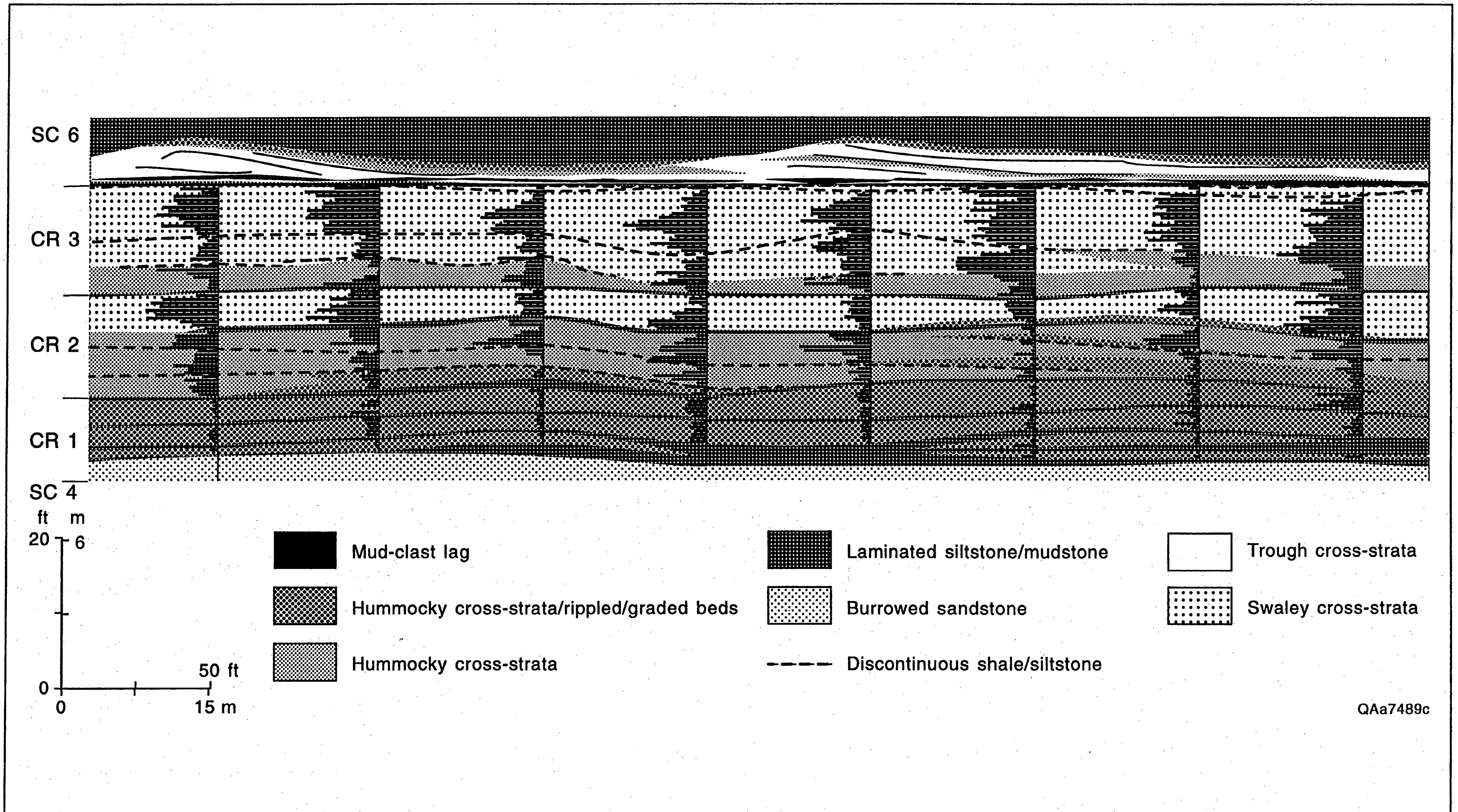


Figure 34. Permeability profiles and delta front stratal architectures of Ferron SC 5: Cedar Ridge canyon II.

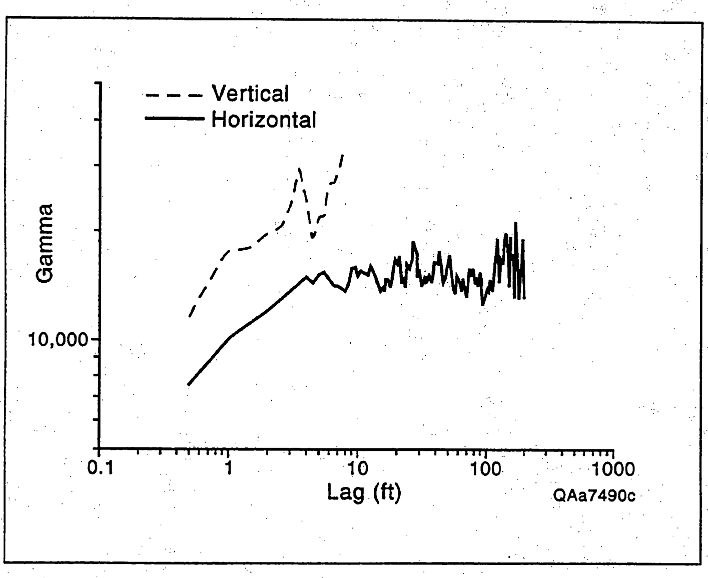


Figure 35. Semivariogram of permeability of wave-dominated upper delta-front deposits of SC 2.

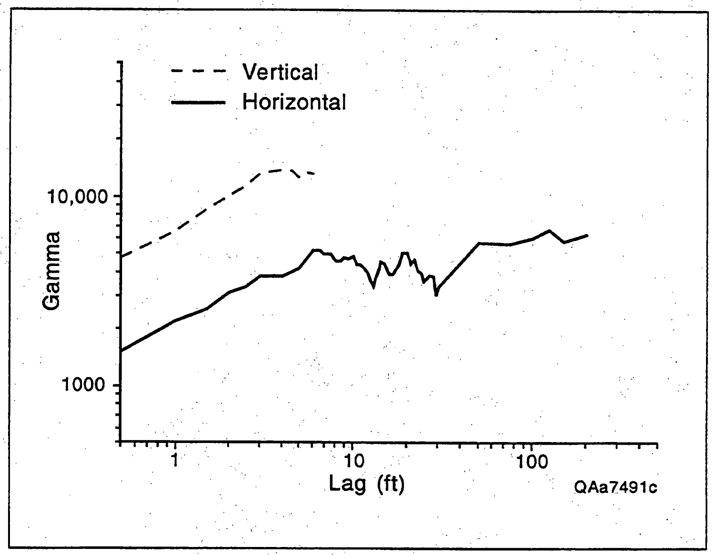


Figure 36. Semivariogram of permeability of upper delta front SC 5: Cedar Ridge.

MR 9, wave-dominated delta-front succession show an upward-increasing trend corresponding to vertical partitioning of lower, middle, and upper delta-front sandstone facies. These zones extend laterally for thousands to tens of thousands of feet. Landward of the shoreline, washover fan deposits consistently display an upward-decreasing trend that laterally pinches out into lagoonal mudstones and siltstones in a landward direction. By contrast, permeability profiles through the fluvial-dominated, delta-front sandstone successions in SC 2 are more erratic. Unlike the wave-dominated facies association in which high permeabilities were located in the most proximal upper portion of the sand body, highest permeabilities are located within the lower central portion of each distributary channel mouth-bar sandstone body.

Within the delta front of SC 5, the overall permeability patterns consist of a single upward-increasing permeability trend that is extremely persistent along depositional strike (10,000 ft) except where the succession has been replaced by distributary channel deposits (fig. 34). The overall upward-increasing trend reflects the basinward migration of lower to upper delta-front facies. However, close inspection reveals that the single upward-coarsening trend is an amalgamation of three minor upward-increasing trends. Each minor upward-increasing trend corresponds to a single upward-coarsening parasequence. In contrast to Dry Wash, parasequences in SC 5 are thin and have amalgamated into a single upward-shoaling trend displaying a high degree of lithologic homogeneity and extreme lateral continuity. The succession is truncated by a low relief surface and overlain by a set of beds that display an upward-deepening trend. The succession is interpreted to record reworking of the delta front by wave processes during delta lobe abandonment. Variations in a dip direction are associated with a systematic onshore to offshore facies transition.

The correlation of permeability can also be estimated by the semivariogram function. The increase in gamma with lag distance (variogram function) is used as a measure of spatial variability. A steeper slope indicates the greater spatial variability of the property measured. A comparison of vertical and horizontal semivariograms between different facies associations reveals a predictable relationship between the spatial distribution of permeability and facies characteristics. Wave-dominated upper delta-front (figs. 35 and 36) and washover deposits (fig. 37) are characterized by a high degree of variability vertically and an extremely low degree of variability laterally. The lack of any significant correlation range in the lateral direction reflects the fact that the most significant permeability variation occurs at a relatively small scale within the lithologically homogeneous, wave-dominated delta-

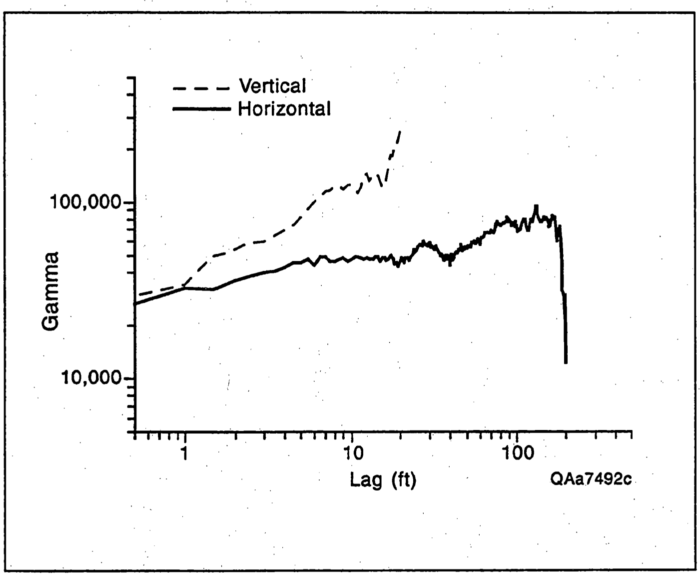


Figure 37. Semivariogram of permeability of washover deposits SC 2: Dry Wash.

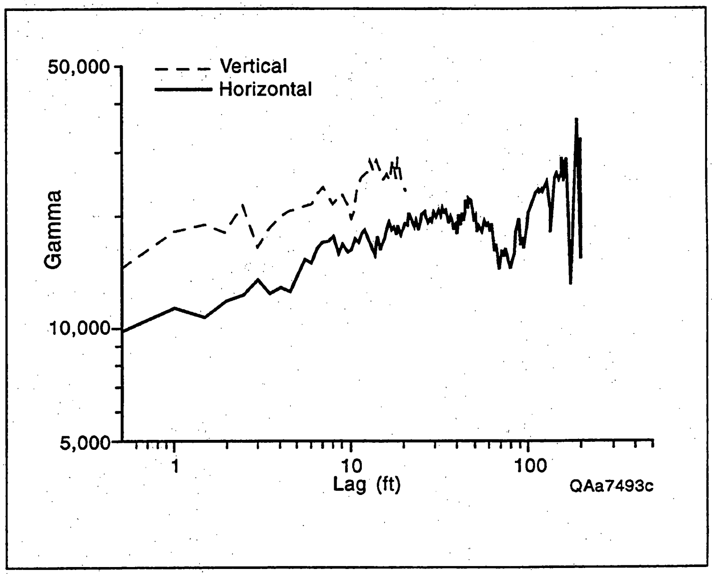


Figure 38. Semivariogram of permeability of distributary mouthbar facies of SC 2: Dry Wash.

front and washover sandstones. This pattern is typical of deposits that display a strong vertical partitioning of lithofacies, such as an upward-coarsening shoreface profile. Upper delta-front deposits of seaward- and landward-stepping stratigraphic cycles do not differ significantly. On the other hand, distributary mouth bar deposits (fig. 38) displayed correlation ranges that are similar to those observed within distributary channel belts, approximately 10 ft vertically and 150 ft laterally.

Distributary Channel

Distributary channel deposits of both landward- and seaward-stepping deltaic units displayed a number of similarities. In distributary channel belts coeval with seaward-stepping genetic sequences, considerable vertical variation in permeability exists, and profiles are composed of not one but several distinct trends. These trends are on the order of several to tens of feet vertically and tens to hundreds of feet laterally. At this scale, permeability patterns closely reflect the vertical stacking of individual macroforms within the multi-story channel belt. In a similar fashion, permeability patterns within distributary channel belts coeval to landward-stepping deltaic units reflect the multilateral arrangement of macroforms. The presence of thick, extensive lag deposits and fine-grained sediments along channel-base bounding surfaces tend to separate and compartmentalize individual macroforms.

Figure 39 relates facies architecture to permeability variation in the distributary channel belt within seaward-stepping SC 2. Only the uppermost, more fully preserved macroform capping the channel belt shows a classic upward-decreasing permeability trend. Instead, considerable permeability variation exists and profiles show several trends, with trends shown at several to tens of feet vertically, and tens to hundreds of feet laterally. Such permeability trends indicate that permeability distributions are not random but record multistory stacking of macroforms composing the channel belt.

Within landward-stepping distributary channel belts, permeability patterns largely follow the distribution of lithofacies (fig. 40). The upward-decreasing permeability trend reflects the strong vertical partitioning of lithofacies (308 md in trough cross-strata, 145 md in low-angle strata, and 88 md in contorted strata), which extend hundreds of feet laterally across the outcrop. This trend is disrupted by thick, mud-clast lag deposits (average of 44 md) that are coincident to inclined channel base bounding surfaces. Erosional discontinuities and bounding lithologies extend tens of feet to hundreds of feet laterally. Permeabilities are higher in central parts of channel belts than along the margins.

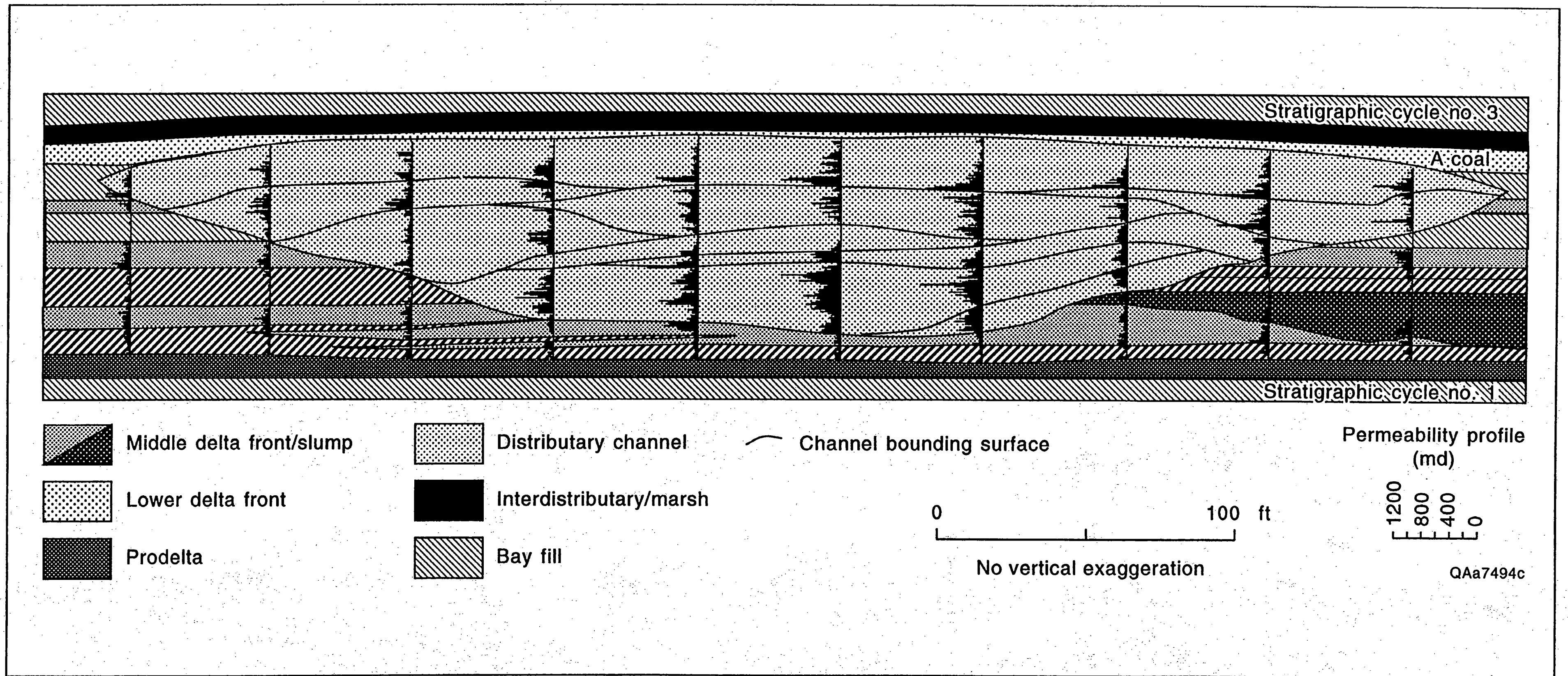


Figure 39. Permeability profiles and distributary channel architecture of Ferron SC 2: I-70.

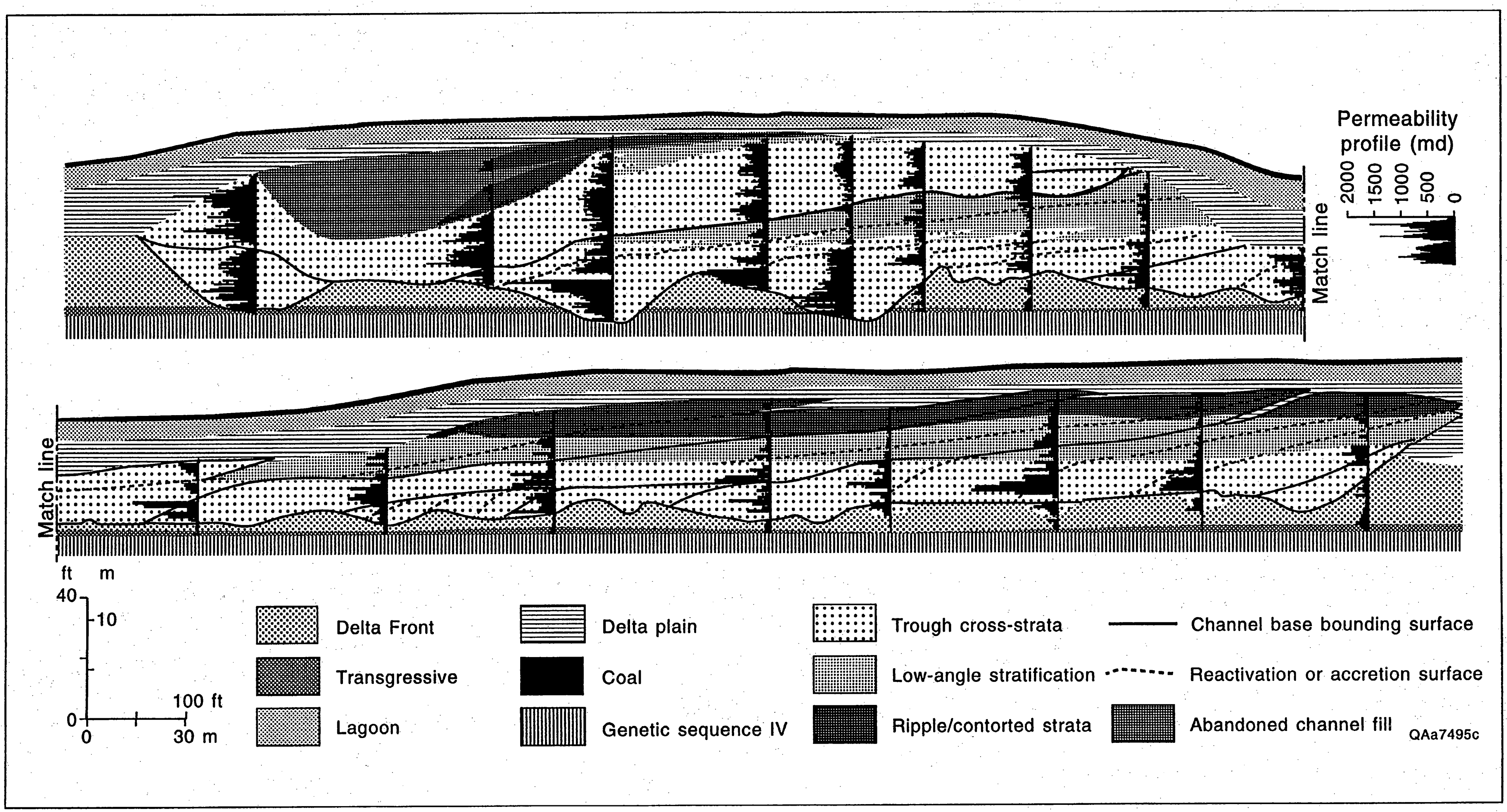


Figure 40. Permeability profiles and distributary channel architecture of Ferron SC 5: South Muddy Creek.

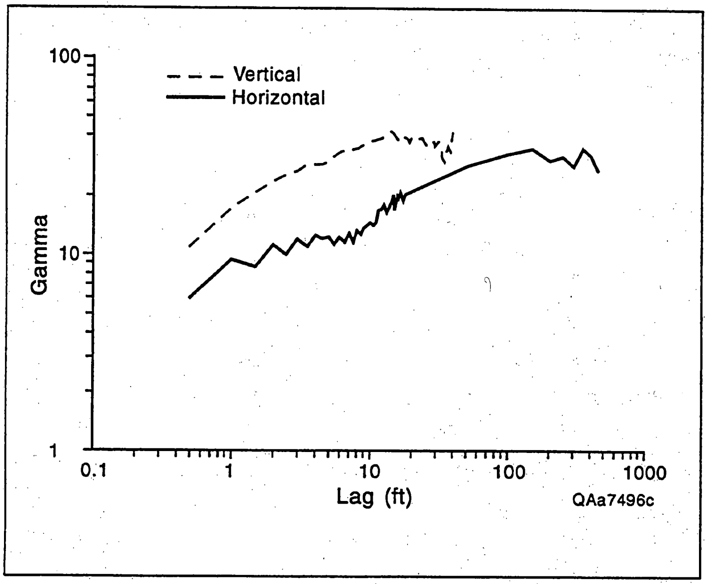


Figure 41. Semivariogram of permeability of seaward-stepping distributary channel facies of Ferron SC 2: I-70.

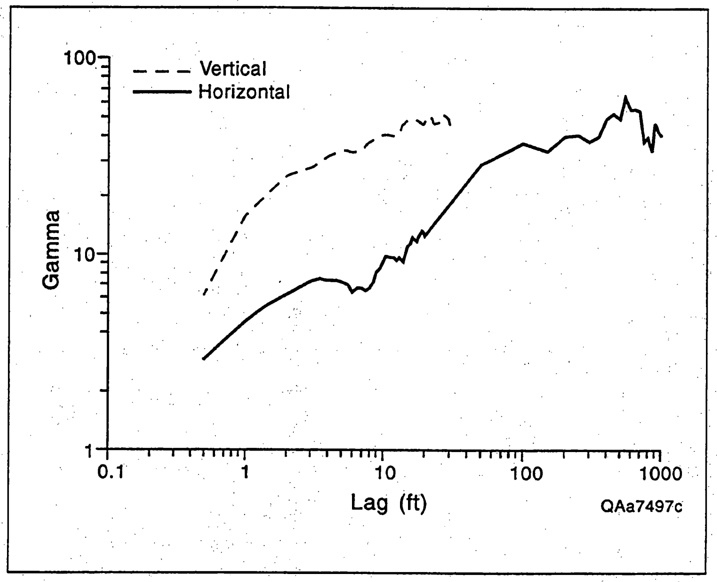


Figure 42. Semivariogram of permeability for distributary channel facies of Ferron SC 5: South Muddy Creek.

Vertical and horizontal semivariograms constructed for distributary channel sand bodies transverse to flow are shown in figures 41 and 42. Comparison of distributary channel sand bodies shows several similarities. Vertical and horizontal correlation ranges for all distributary channel belts studied are between 12 and 15 ft vertically and approximately 150 ft laterally. Although the horizontal correlation range is greater than the vertical, more than half the variation observed occurs at distances less than 25 ft. The correlation ranges are roughly equivalent to the average macroform dimensions and interpreted to reflect the distribution of low-permeability lithologies along channel base bounding surfaces. In the horizontal direction the correlation structure mimics the vertical correlation structure, differing primarily in scale.

The results suggest that the horizontal correlation structure may be predictable if based on a knowledge of the vertical correlation structure. The semivariogram structure does not differ significantly between landward- and seaward-stepping channel belts because the spatial variability is related to the average macroform dimensions, which do not differ significantly within the two channel belts.

Ferron Gas Field

Subsurface data from the Ferron gas field and outcrop information from nearby exposures of the Ferron Sandstone were integrated into an architectural model of reservoir heterogeneity within the Ferron gas field. Analysis of the field reveals that marine mudstones bounding stratigraphic cycles and parasequences or delta lobes compartmentalize the reservoir. Favorable sites for stratigraphic entrapment occur where proximal and distal portions of parasequences pinch out into lagoonal and marine shales, respectively.

The Ferron gas field lies 5 mi south and 3 mi east of the town of Ferron in east-central Utah. Gas has been produced from the Ferron field, which is located over the Ferron anticline, since 1957. Production is at a depth between 900 and 1,100 ft from the Cretaceous Ferron Sandstone (Tripp, 1989). As of 1990 there were 18 wells producing in the field, having a cumulative production of 10.2 Bcf of gas (Tripp, 1991). The Ferron anticline is approximately 6.5 mi in length and trends north-northeast. Two highs are present; the northern high has approximately 130 ft of structural closure, and the southern high has approximately 70 ft of closure. The southern high is located approximately 0.5 mi west and 3 mi south of the northern high. The southern high is located 2 mi west and 4 mi north of the Dry Wash study area. The relatively dense well control of 41 geophysical logs in a 20-mi^2 area, core from two stratigraphic test wells, and nearby outcrop exposures allowed study of the reservoir architecture of the Ferron gas field in detail.

In the Ferron gas field, the Ferron Sandstone is approximately 230 ft thick and bounded above by the marine Bluegate Shale and below by the marine Tununk Shale. Net sand values within the field range between 60 and 140 ft. Marine flooding surfaces divide the Ferron Sandstone into stratigraphic cycles and component parasequences. The Ferron Sandstone consists of three stratigraphic cycles designated from oldest to youngest as SC 2, SC 3, and SC 4 (fig. 43). In turn, each deltaic cycle is composed of a set of delta lobes or parasequences designated from oldest to youngest as SC 2a, SC 2b, and so forth. Facies characteristics of each unit can be resolved and vary systematically, depending on geographic position within the deltaic system. Facies successions within each interval consist of lower to upper delta-front strata in SC 2a; lagoonal, washover, foreshore, and upper delta-front strata in SC 2b; distal delta-front, prodelta, and marine-shelf strata in SC 3a; homogeneous, wave-dominated lower through upper delta-front strata in SC 3b; and distal delta-front, prodelta, and shelf strata in SC 4. On the basis of production information, mudstones associated with marine flooding surfaces divide the Ferron Sandstone into four productive intervals that correspond to SC 2a, SC 2b, SC 3a, and SC 3b.

Facies variations within separate delta lobes may act as stratigraphic traps as well as compartment boundaries. On the east side of the Ferron anticline, a stratigraphic trap occurs within SC 2c where washover, foreshore, and upper delta-front sandstones thin in a westerly direction and are replaced by fine-grained lagoonal deposits. A map view of sand thickness and productive wells within the SC 2b interval are shown in figure 44. The opposite trend occurs within overlying SC 3a. On the west side of the anticline, sand-rich distal delta-front deposits thin in a northeast direction and are replaced by fine-grained prodelta and marine-shelf deposits. A map view of productive wells and sand thickness in the SC 3a interval are shown in figure 45.

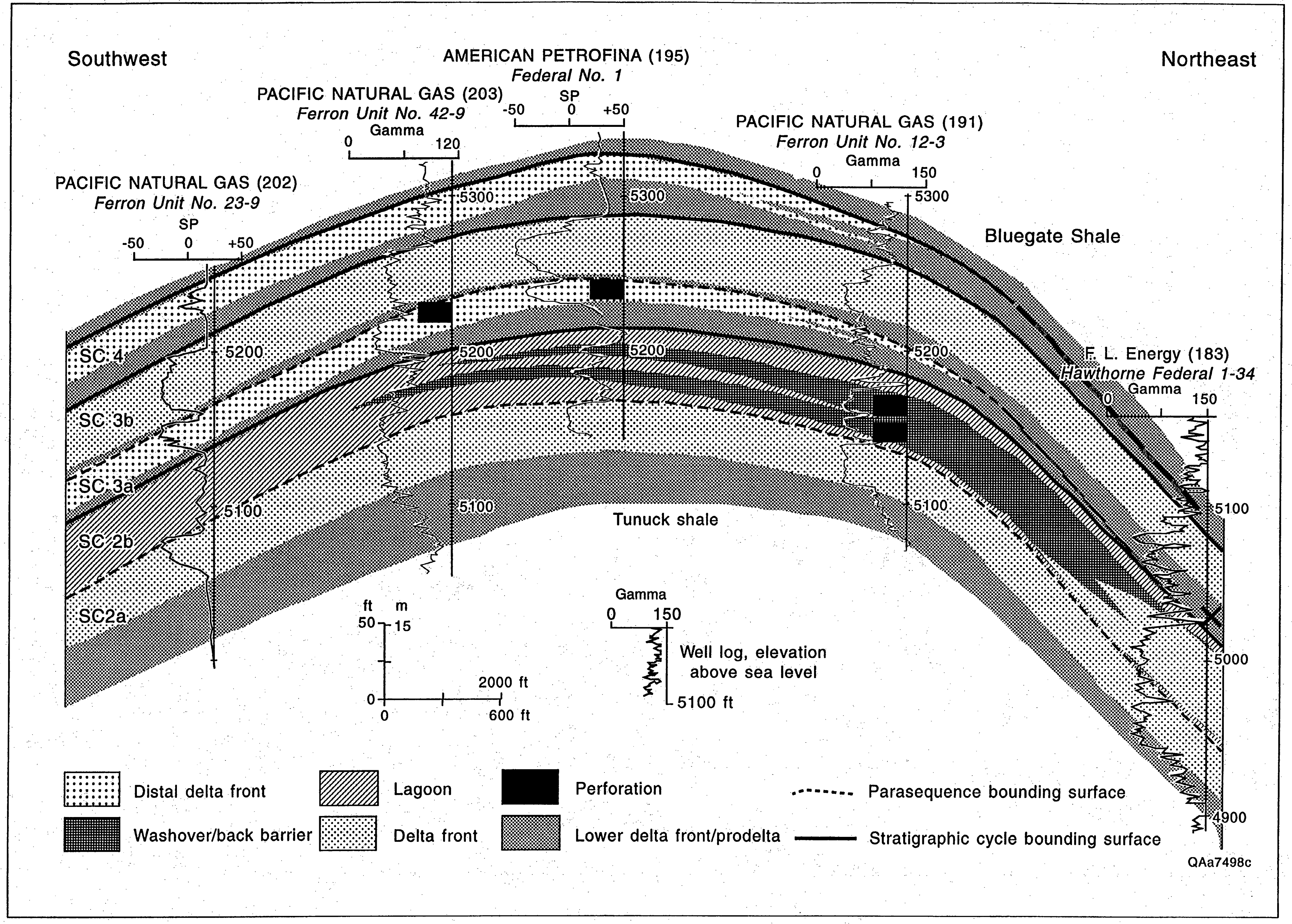


Figure 43. Cross section A–A′ (see fig. 6) through Ferron Sandstone at Ferron gas field.

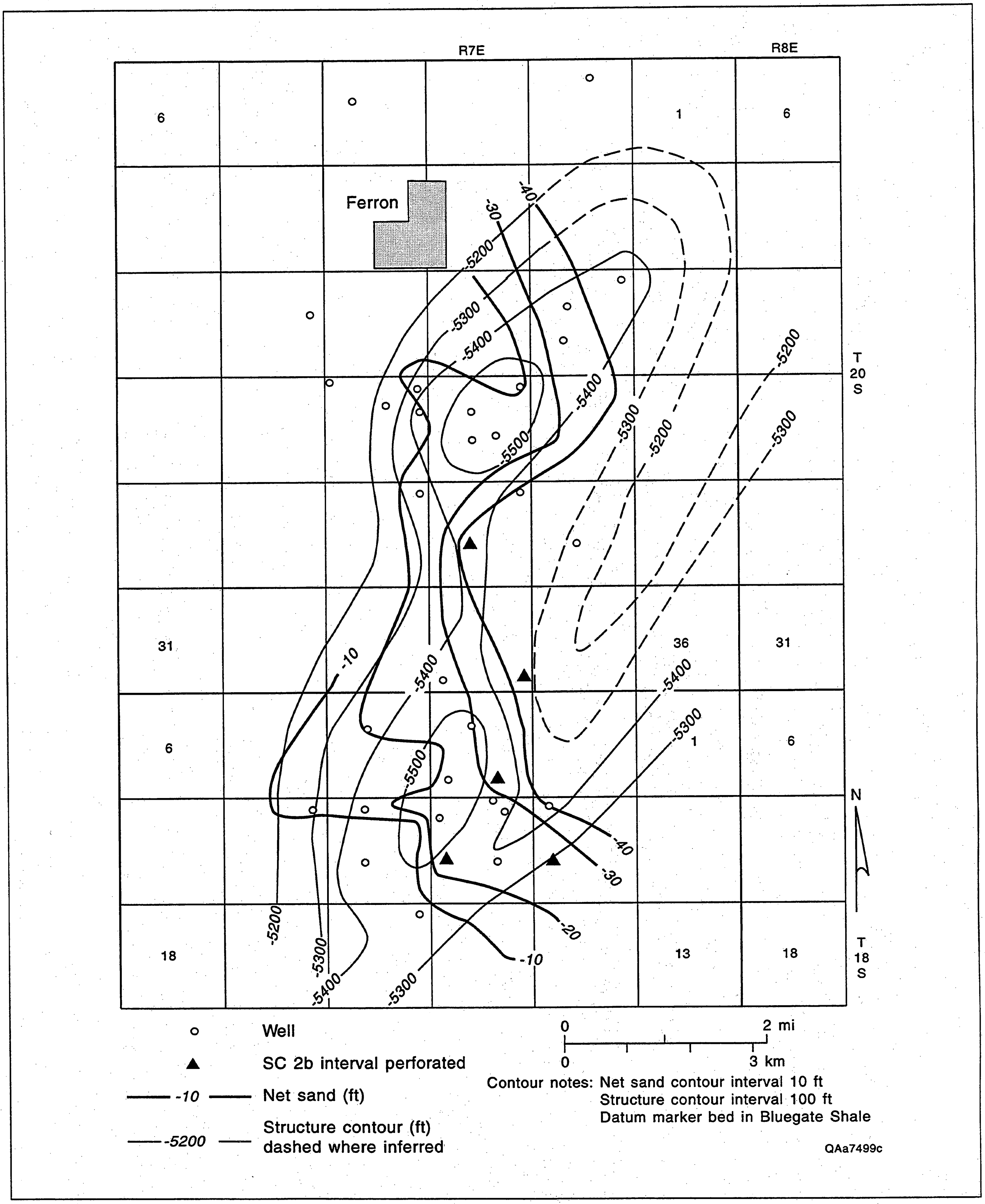


Figure 44. Sand thickness of SC 2b interval showing perforated wells. Interval interpretation as lagoonal, washover and back-barrier deposits adjacent to landward pinchout of delta lobe.

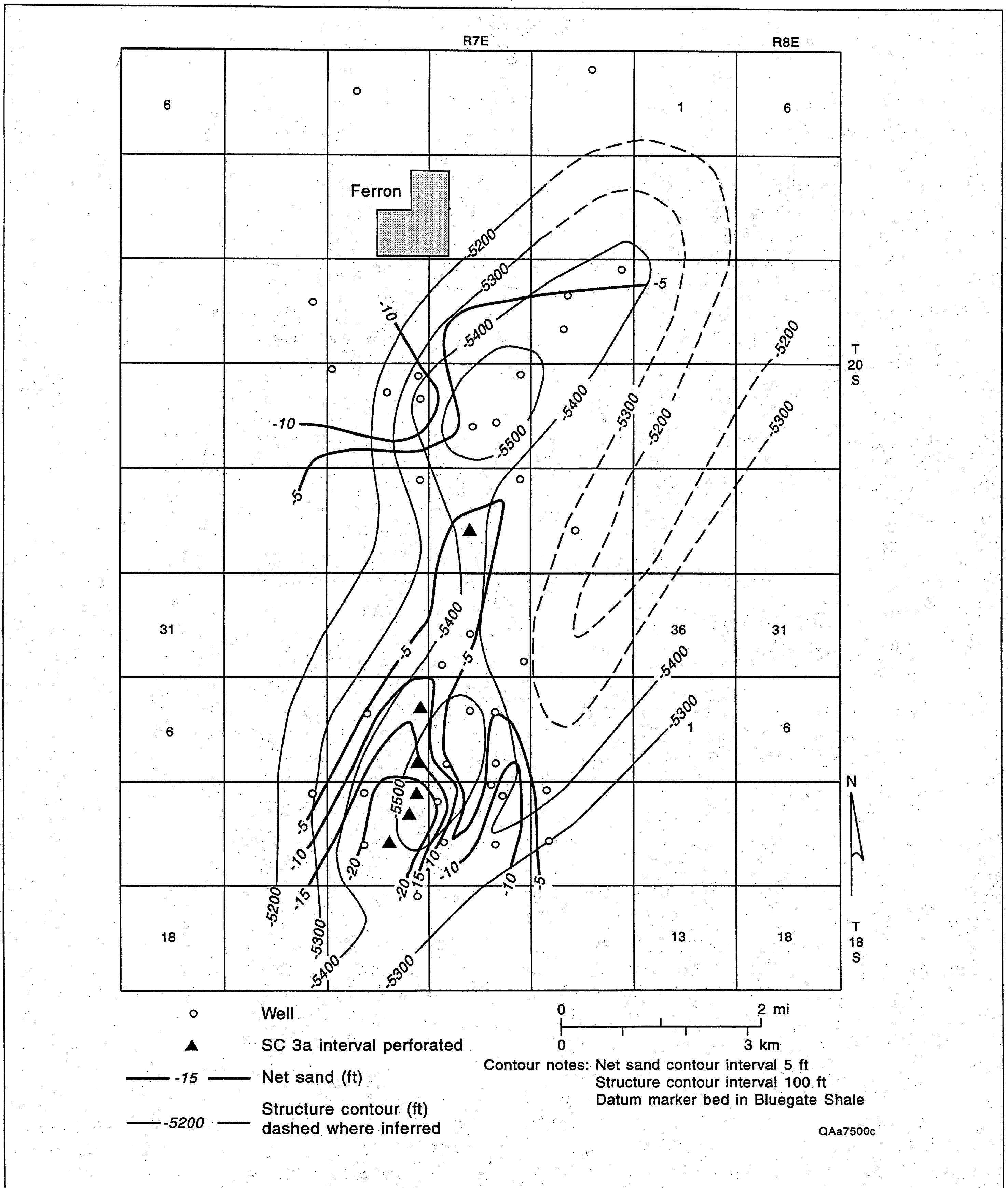


Figure 45. Sand thickness of SC 3a interval showing perforated wells. Interval interpreted as distal delta lobe.

Summary

Stratigraphic studies on the Upper Cretaceous Ferron Sandstone indicate a predictable pattern of sediment volume partitioning into coastal-plain and shoreface facies tracts according to the position of the progradational event within the overall hierarchy of seaward-stepping, aggradational, or landward-stepping events. Accompanying this differential partitioning of sediment volumes are changes in the geometry and internal complexity of shoreface and coastal-plain facies tracts. In general, the most heterogeneous facies tracts record the position of the greatest accommodation space and lowest sediment flux (landward-stepping distributary system and progradational delta front). By contrast, the most homogeneous facies tracts (seaward-stepping distributary system and landward-stepping delta front) record the position of the lowest accommodation space and highest sediment flux.

Recognition and Correlation Criteria

Well logs and cores provide sufficient information to distinguish landward- from seaward-stepping architectures. Within the coastal-plain strata, the vertically stacked to landward-stepping system tract displays increases in cycle thickness, facies diversity, and sand:shale content relative to seaward-stepping cycles. Within the delta-front strata, the seaward-stepping system tract displays increases in cycle thickness, facies diversity, and shale:sand content relative to landward-stepping cycles. Stratigraphic cycles, parasequences, delta-front clinoforms, and major facies associations are resolvable using conventional well log, core, and dipmeter data. Marine mudstones and coastal-plain carbonaceous shales coincident with stratigraphic cycle and parasequence bounding surfaces form correlatable horizons over the distance of several miles to tens of miles, respectively. However, parasequences and even stratigraphic cycles may be difficult to resolve within the vertically to landward-stepping systems tracts because of lack of facies offset and within the seaward-stepping system tract because of abrupt changes in depositional topography. Clinoform elements within the delta front are resolvable on the scale of hundreds to thousands of feet in core by documenting systematic changes in facies associations and degree of burrowing. Major facies associations are recognizable on the basis of lithologic diversity. Wave- and fluvial-dominated delta fronts are recognizable on the basis of sand:shale content, degree of burrowing, and overall facies diversity. Seaward- versus landward-stepping distributary channel belts are resolvable on the basis of sand:shale content, lithologic diversity, and nature of channel lags.

Bounding Element Architecture

Delta-front strata within seaward-stepping units are highly compartmentalized by marine and marginal marine shales coincident with stratigraphic cycle and parasequence bounding surfaces. Shales subdivide the delta front into numerous discrete offlapping to vertically stacked, upward-shoaling shoreline successions (parasequences or delta lobes) that form a divergent but generally dip-oriented sandy framework. Lithologic variation is high and varies between wave- and fluvial-dominated delta-front successions. Shales of lesser continuity include fine-grained bay-fill successions, which replace and separate delta lobes laterally. Bay fills are best developed within the seaward-stepping cycles at the position where the delta-front progrades basinward of the underlying stratigraphic cycle. Analysis of the Ferron gas field reveals that marine mudstones bounding parasequences or delta lobes within seaward-stepping cycles compartmentalize the field. Favorable sites for stratigraphic entrapment occur where proximal and distal portions of parasequences pinch out into lagoonal and marine shales, respectively.

Marine shales coincident to stratigraphic cycle boundaries vertically subdivide the landward-stepping system tract. Within landward-stepping stratigraphic cycles, parasequences and component mouth-bar deposits are amalgamated into a lithologically homogeneous, strike-elongate sand body. The absence or poor development of bay-fill successions and marine mudstones coincident to parasequence bounding surfaces reflects the dominance of wave and storm processes. Lithologic variation is minimal and limited to gradual upward shoaling and onshore to offshore facies transition.

Channel sand bodies associated with seaward-stepping units are preserved as ribbonlike sand bodies, encased in and widely separated from adjacent channel sand bodies by mud-rich delta-plain, bay-fill, and lower delta-front strata, providing excellent conditions for reservoir compartmentalization. Because of their distribution, the probability of contacting one of these sand-body types by conventional drilling strategies is relatively low. However, the crosscutting nature of distributary channel sand bodies with underlying delta-front deposits indicates that they are likely to have an important impact on fluid flow. Dip-aligned channel belts may act as conduits connecting delta-front strata of separate progradational events, providing no low-permeability flow boundaries are present along the facies contact. These relationships are almost reversed in landward-stepping deltaic successions. Within the delta plain, distributaries are preserved as a complex network of broad tabular sand bodies, elongate parallel to depositional dip, that encase adjacent fine, interdistributary deposits. Internal heterogeneities, related to abandoned channel fill, and mud-clast lags and mudstone drapes, formed principally along channel base bounding surfaces, severely disrupt lateral and vertical continuity.

Reservoir Quality and Quantity

Reservoir volumetrics reflect sediment partitioning trends. Volumetrically, distributary channel deposits make up the principal reservoir facies in landward-stepping stratigraphic cycles, whereas the reverse relationship is true of seaward-stepping stratigraphic cycles where delta-front strata compose the dominant reservoir facies. Reservoir quality and the spatial distribution of reservoir properties are largely determined by environment of deposition. Wave-dominated intervals are better sorted and more quartz-rich than are fluvial-dominated intervals; they predictably display higher porosity and permeability. The delta-front facies association consists of upward-coarsening successions with fine-grained pelagic sediments at their bases, grading upward into quartz-rich sandstones. Permeability increases from the base to the top of the cycle and displays minimal variation along strike, except where mud-rich abandoned channel fills have removed and replaced a portion of the otherwise homogeneous wave-dominated delta front. The best reservoir units occur at the top and near the landward pinchout of each upward-coarsening succession. In seaward-stepping units, the proximal and distal portions of the delta-front facies tract are where wave-dominated delta-front sand bodies are most likely to form, whereas in landward-stepping units the delta-front facies tract is mostly wave dominated.

Within distributary channel belts, permeability patterns reflect the geometric arrangement of channel forms. In distributary channel belts coeval with seaward-stepping cycles, permeability patterns are the composite of several trends that reflect the vertical stacking of channel forms within these multistory channel belts. Within landward-stepping cycles, permeability patterns display an upward-fining trend that reflects the strong vertical partitioning of stratal types. Laterally, this trend is disrupted by the presence of thick, mud-clast-rich lags deposited along channel base bounding surfaces within these multilateral channel belts.

Acknowledgments

This study was funded by the Gas Research Institute under contract number 5089-260-1902, with matching funds provided by the Delta Industrial Associates Project.

Former GRI project manager Anthony Gorody is thanked for his support and guidance throughout the project. Discussions with Tom Ryer, Mike Gardner, Edmund Gustason, Paul Anderson, and Rex Cole contributed significantly to our understanding of the Ferron Sandstone. We also thank Milagro Elneser, Craig Forester, and Larry Lake, who assisted us with geostatistics and petrophysics. Others contributing to the publication of this report were Joseph Yeh and Kirt Kempter, who assisted in various computer applications.

References

Barton, M.D., 1994, Outcrop characterization of architecture and permeability structure in fluvial-deltaic sandstones, Cretaceous Ferron Sandstone, Utah: The University of Texas at Austin, Ph.D. dissertation, 259 p.

Barton, M.D., and M.H. Gardner, 1992, Base-level controls on permeability variation in distributary-channel deposits, Cretaceous Ferron Sandstone, central Utah (abs.): SEPM, mid-year meeting, Fort Collins, Colorado, p. 12.

Campbell, C.V., 1967, Lamina, laminaset, bed and bedset: Sedimentology, v. 8, p. 7–26.

Cross, T.A., M.R. Baker, M.A. Chapin, M.S. Clark, M.H. Gardner, M.S. Hanson, M.A. Lessenger, L.D. Little, K-J McDonough, M.D. Sonnenfeld, D.W. Valasek, M.R. Williams, and D.N. Witter, 1993, Applications of high-resolution sequence stratigraphy to reservoir analysis, *in* R. Eschard and B. Doligez, eds., Reservoir characterization from outcrop observations: Editions Technip, p. 11–33.

Cross, T.A., 1988, Controls on coal distribution in transgressive-regressive cycles, Upper Cretaceous, western interior, U.S.A., *in* C.K. Wilgus, B.S. Hastings, C.G. St.C. Kendall, H.W. Posamentier, C.A. Ross, and J.C. van Wagoner, eds., Sea level changes: an integrated approach: SEPM, Special Publication No. 42, p. 371–380.

Davis, L.J., 1954, Stratigraphy of the Ferron Sandstone: IAPG, 5th Annual Field Guidebook, p. 55–58.

Fisher, R.S., M.D. Barton, and Noel Tyler, 1993a, Quantifying reservoir heterogeneity through outcrop characterization: 1. Architecture, lithology, and permeability distribution of a landward-stepping fluvial-deltaic sequence, Ferron Sandstone (Cretaceous), central Utah: The University of Texas at Austin, Bureau of Economic Geology, topical report prepared for the Gas Research Institute, GRI-93-0022, 132 p.

Fisher, R.S., M.D. Barton, and Noel Tyler, 1993b, Quantifying reservoir heterogeneity through outcrop characterization: 2. Architecture, lithology, and permeability distribution of a seaward-stepping fluvial-deltaic sequence, Ferron Sandstone (Cretaceous), central Utah: The University of Texas at Austin, Bureau of Economic Geology, topical report prepared for the Gas Research Institute, GRI-93-0023, 83 p.

Gardner, M.H., 1993, Sequence stratigraphy and facies architecture of the upper Cretaceous Ferron Sandstone member of the Mancos Shale, east-central Utah: Ph.D. dissertation, Colorado School of Mines, Golden Colorado, v. 1, 390 p.

__________ 1992, Sequence stratigrapy of the Ferron Sandstone, east-central Utah, *in* Noel Tyler, M.D. Barton, and R.S. Fisher, Architecture and permeability structure of fluvial-deltaic sandstones: a field guide to selected outcrops of the Ferron Sandstone, east-central Utah: The University of Texas at Austin, Bureau of Economic Geology, guidebook prepared for the May 20–22 field trip, p 1–4.

Gardner, M.H., and T.A. Cross, 1989, An Occam's razor approach toward separating eustatic, tectonic, and sediment supply controls of stratigraphic architecture: American Geophysical Union, Chapman Conference on Causes and Consequences of Long-Term Sea-Level Changes.

Garrison, J.R., Jr., and L.D. Smallwood, 1993, Preliminary analysis of the architecture, lithology, and permeability structure of a Ferron Sandstone sequence 2 distributary-channel belt, Willow Springs Wash, Emery County, Utah (abs.): 1993 AAPG-SEPM-EMD-DEG Rocky Mountain Section Meeting Guide, p. 41.

Gustason, E.R., 1993, Facies architectural analysis of progradational parasequence sets, upper coal-bearing Ferron Sandstone, central Utah: implications for reservoir description: 1993 AAPG-SEPM-EMD-DEG Rocky Mountain Section Meeting Guide, p. 44–45.

Gustason, E.R., T.A. Ryer, and P.B. Anderson, 1993, Integration of outcrop subsurface information for geological model building in fluvial-deltaic reservoirs, RMS/AAPG Core Workshop.

Hale, L.A., 1972, Depositional history of the Ferron Formation, central Utah, in plateau-basin and range transition zone: Utah Geological Association, p. 115–138.

Hale, L.A., and F.R. van de Graaf, 1964, Cretaceous stratigraphy and facies patterns—northwestern Utah and adjacent areas: IAPG, 13th Annual Field Guidebook, p. 115–138.

Jervey, M.T., 1988, Quantitative geological modeling of siliciclastic rock sequences and their seismic expression, *in* C.K. Wilgus, B.S. Hastings, C.G. St.C. Kendall, H.W. Posamentier, C.A. Ross, and J.C. van Wagoner, eds., Sea level changes: an integrated approach: SEPM, Special Publication No. 42, p. 47–69.

Katich, P.J., Jr., 1954, Cretaceous and early Tertiary stratigraphy of central and south-central Utah with emphasis on the Wasatch Plateau area: IAPG, 5th Annual Field Guidebook, p. 42–54.

Lowry, P., and T. Jacobsen, 1993, Sedimentological and reservoir characteristics of a fluvial-dominated delta-front sequence: Ferron Sandstone Member (Turonian), east-central Utah: *in* Ashton, M., ed., Advances in reservoir geology: Geological Society Special Publication No. 69, p. 81–103.

Lowry, P., and A. Raheim, 1991, Characterization of delta front sandstones from a fluvial-dominated delta system, *in* L.W. Lake, H.B. Carroll, and T.C. Wesson, eds., Reservoir characterization II: Academic Press, p. 665–676.

Lupton, C.T., 1916, Geology and coal resources of Castle valley in Carbon, Emery and Sevier counties, Utah: USGS Bulletin No. 628, 84 p.

Miller, M.A., J. Holder, H. Yang, Y. Jamal, K.E. Gray, R.S. Fisher, and Noel Tyler, 1993, Petrophysical and petrographic properties of the Ferron Sandstone: The University of Texas at Austin, Center for Petroleum and Geosystems Engineering, Topical Report GRI-93/0219, p. 1–95.

Ryer, T.A., 1981, Deltaic coals of the Ferron Sandstone Member of the Mancos Shale: predictive model for Cretaceous coal-bearing strata of the western interior: AAPG Bulletin, v. 65, no. 11, p. 2323–2340.

__________ 1977, Patterns of Cretaceous shallow-marine sedimentation, Coalville and Rockport areas, Utah: GSA Bulletin, v. 887, p. 177–188.

__________ 1982, Possible eustatic control on location of Utah Cretaceous coal fields: Utah Geological and Mineralogical Survey Bulletin 118, Proceedings, 5th ROMOCO Symposium, p. 89–93.

__________ 1983, Transgressive-regressive cycles and occurrence of coal in some upper Cretaceous strata of Utah: Geology, v. 11, p. 2007–210.

Ryer, T. A., and M. McPhillips, 1983, Early Late Cretaceous paleogeography of east-central Utah, *in* M.W. Reynolds and E.D. Dolly, eds., Mesozoic paleography of west-central United States: Rocky Mountain Section, SEPM, p. 253–272.

Ryer, T.A., E.R. Gustason, and P.B. Anderson, 1993, Stratigraphy and facies architecture of the Ferron Sandstone Member of Mancos Shale: UGA/RMS/AAPG field guide.

Ryer, T.A., and J.R. Lovekin, 1986, The upper Cretaceous Vernal delta of Utah-depositional or paleotectonic feature?, *in* J.A. Peterson, ed., Paleotectonics and sedimentation: AAPG Memoir 41, p. 497–509.

Stalkup, F.I., and W.J. Ebanks, 1986, Permeability variation in a sandstone barrier-tidal channel-tidal delta complex, Ferron Sandstone (Lower Cretaceous), central Utah: SPE Paper 15532, 13 p.

Thompson, S.L., 1985, Ferron Sandstone Member of the Mancos Shale: a Turonian mixed energy deltaic system: The University of Texas at Austin, Master's thesis, 165 p.

Tripp, C.N., 1991, Ferron oil and gas field, Utah, *in* T.C. Chidsey, Jr., ed., Geology of eastern Utah: Utah Geological Association Publication 19, p. 265–272.

Tripp, C.N., 1989, A hydrocarbon exploration model for the Cretaceous Ferron Sandstone Member of the Mancos, and the Dakota Group in the Wasatch Plateau and Castle Valley of east-central Utah, with emphasis on post-1980 subsurface data: Utah Department of Natural Resources Open-File Report 160, p. 1–81.

van Wagoner, J.C., R.M. Mitchum, K.M. Campion, and V.D. Rahmanian, 1990, Siliciclastic sequence stratigraphy: AAPG Methods in Exploration Series, No. 7, 55 p.