Geology and Stratigraphy of Fluvio-Deltaic Deposits in the Ivishak Formation: Applications for Development of Prudhoe Bay Field, Alaska[1]

Robert S. Tye,[2] Janok P. Bhattacharya,[2] James A. Lorsong,[3] Scott T. Sindelar,[4] Douglas G. Knock,[4] David D. Puls,[5] and Richard A. Levinson[4]

ABSTRACT

Significant remaining reserves in Prudhoe Bay field are confined within deltaic rocks at the base of the Triassic Ivishak sandstone. The initial stratigraphic characterization of the Prudhoe Bay reservoir was lithostratigraphically based, and it depicted this basal reservoir interval as tabular zones between marine shale and overlying coarse-grained, fluvial sandstones. A reassessment of this interval based on cores and genetic-stratigraphic correlations depicts en echelon, offlapping, fluvially dominated deltaic wedges.

Reservoir-quality rocks occur in distributary mouth bar, distributary channel, and fluvial facies associations. A paleogeographic reconstruction of one delta lobe includes an alluvial plain crossed by channels of possibly braided or low-sinuosity rivers. This alluvial plain graded into a delta plain cut by distributary channels that fed distributary mouth bars on a broad delta front. River dominance is inferred from the abundance of unidirectional current structures, normally graded beds, soft-sediment deformation, and general absence of wave-formed, tidal, and biogenic structures. Slumping and growth faulting locally replaced coarsening-upward deltaic successions with sharp-based, overthickened mouth bar and distributary channel deposits.

Mudstones deposited following delta-lobe abandonment form laterally extensive flow barriers between lobes. Compartmentalization is most pronounced distally, where deltaic sandstones are overlain by and pass laterally into marine shale. Proximally, fluvial and deltaic sandstones are juxtaposed across erosional contacts, improving reservoir continuity.

This stratigraphic interpretation is corroborated by production and surveillance data plus an interference test. Locally, stratigraphy and poor waterflood performance reflect completions in diachronous sandstones that originated in separate deltaic lobes. Previously, poor well performances were attributed to sandstone pinch-outs. In some cases, production can be enhanced with recompletions rather than infill drilling. Nonconventional wells planned and completed with the benefit of detailed facies-association correlations currently are recovering millions of barrels of previously bypassed oil.

INTRODUCTION

As with all oil fields, development practices at Prudhoe Bay field on Alaska's North Slope (Figure 1) have evolved as the field has matured. As a consequence, descriptions of the reservoir made during early field production, when the most permeable zones were perforated, became unsatisfactory for matching well performance as lower permeability rocks were perforated (Szabo and Meyers, 1993). With the onset of declining production in the 1980s, it was determined that a significant portion of Prudhoe's remaining reserves reside within fluvio-deltaic sandstones at the base of the reservoir. These rocks are operationally referred to as the Romeo interval (Figure 2). Romeo oil had been notoriously more difficult to produce than oil in the overlying nonmarine strata possessing higher

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[2]ARCO 2300 West Plano Parkway, Plano, Texas 75075-8499; e-mail: rtye@is.arco.com

[3]ARCO El-Djazair, 2300 West Plano Parkway, Plano, Texas 75075-8499.

[4]ARCO Alaska, Inc. 700 G Street, Anchorage, Alaska 99510-0360.

[5]Exxon Azerbaijan Operating Company, Landmark, Suite 300, 96 Nizami Street, Baku, 370000, Azerbaijan Republic.

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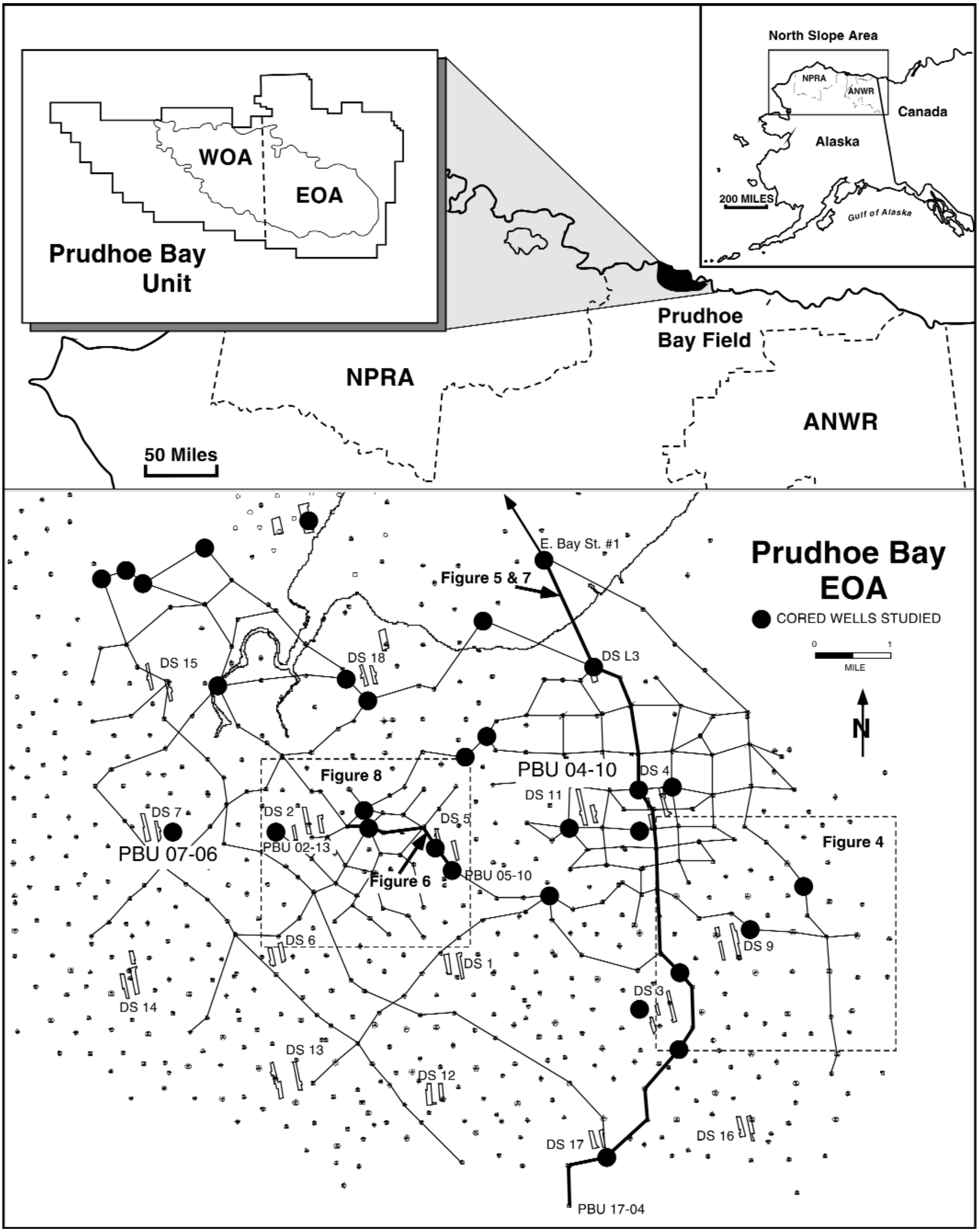


Figure 1—The Alaskan North Slope and location of Prudhoe Bay field between the National Petroleum Reserve (NPRA) and the Arctic National Wildlife Refuge (ANWR). ARCO operates the eastern operating area (EOA). Locations of cross sections (Figures 5–7) and cored wells are shown. Boxes highlight locations of Figures 4 and 8, respectively. PBU = Prudhoe Bay unit.

porosities and permeabilities; moreover, limited geologic information (core descriptions), erratic production histories, and poor producibility exacerbated the Romeo's reputation as comprising lithologically heterogeneous and discontinuous strata.

In light of declining production, the present reservoir engineering focus at Prudhoe Bay is on evaluating reservoir sweep efficiency and the impact and economics of various recovery mechanisms (e.g., gravity drainage, waterflood, estimated oil recovery). It has been proposed that immediate production increases can be attained and maintained through the selective drilling of Romeo infill wells on 80 or 40 ac (32 or 16 ha) spacings; however, reservoir sweep efficiency in the Romeo at present well spacings (160 and 80 ac; 64 and 32 ha) is equivocal. Additionally, controversy has arisen concerning the most efficient recovery methods to be used.

Following equity agreements, previously unavailable cores were released for geologic analyses. These additional data helped revise existing reservoir descriptions; therefore, ARCO, BP, and Exxon established teams of geologists, geophysicists, and reservoir engineers to describe the Romeo interval and to conduct flow simulations for various development scenarios. This interdisciplinary group provided a full-field geologic, geophysical, and petrophysical characterization of the Romeo interval (Bellamy, 1993; Richards et al., 1994). Additionally, both prior to, and simultaneously with, the multicompany program, ARCO geoscientists and engineers initiated smaller scale, two- and three-dimensional reservoir description projects to address specific development issues within the eastern operating area (EOA) (Figure 1) (Lorsong et al., 1994; Tye et al., 1994).

Prudhoe Bay Field

Prudhoe Bay field lies on the Alaska coastal plain 264 mi (425 km) north of the Arctic Circle between Naval Petroleum Reserve (NPRA) No. 4 and the Arctic National Wildlife Refuge (ANWR) (Figure 1). Production from Permian–Triassic sandstones and conglomerates of the Sadlerochit Group (Figure 2) was 1.5 MMSTB/day (million stock tank bbl/day) at field start-up in 1977 (Szabo and Meyers, 1993). The Sadlerochit Group unconformably overlies the Lisburne Group and comprises the Echooka Formation, the Kavik shale, and the Ivishak Formation, the main reservoir interval at Prudhoe Bay field. Where it crops out in ANWR, the Ivishak is divided into the Kavik, Ledge Sandstone, and Fire Creek members (Crowder, 1990); however, these stratigraphic divisions are not carried into the subsurface.

Gentle southerly structural dip combined with a north-bounding fault, an unconformity truncation to the east (LCU, Figure 2), and overlying shales create the trap and seal. In-place reserve estimates have risen as development has progressed. Morgridge and Smith (1972) reported reserves of 9.6 billion bbl of oil and 26 tcf (trillion cubic feet) of gas. By 1990, in-place reserve estimates were updated to 22 billion bbl of oil and 47 tcf of gas (Atkinson et al., 1990). Szabo and Meyers (1993) argued that diligent reservoir management practices implemented since field start-up account for a 25% increase in recoverable reserves.

Previous Ivishak Interpretations

A deltaic origin has been embraced for basal Ivishak (Romeo) strata since field discovery (Detterman, 1970; Morgridge and Smith, 1972; Eckelmann et al., 1975; Jones and Spears, 1976; Wadman et al., 1979; Jamison et al., 1980; Melvin and Knight, 1984; Lawton et al., 1987; McMillen and Colvin, 1987; Atkinson et al., 1988, 1990; Begg et al., 1992). This interpretation is founded primarily on the Ivishak's apparent conformable stratigraphy in which basal marine shales grade upward through shallow-marine and finally into fluvial strata. Fluvial strata have been described as braided-river deposits on a coastal plain (Eckelmann et al., 1975; Jones and Spears, 1976; Wadman et al., 1979; Melvin and Knight, 1984; Lawton et al., 1987; Atkinson et al., 1990) or on a large alluvial fan (McGowen and Bloch, 1985; McGowen et al., 1987). More specifically, Romeo deltaic deposits have been interpreted as those of fan deltas or multiple coastal deltas fed by several coeval fluvial systems. Lawton et al. (1987) interpreted the preponderance of distributary channel and mouth bar deposits as indicative of river-dominated delta deposition; Begg et al. (1992) reached a similar conclusion.

Initially, the Ivishak Formation in Prudhoe Bay field was subdivided into four equity zones characterized by differing log responses (Figure 2) (Eckelmann et al., 1975; Jones and Spears, 1976; Atkinson et al., 1988, 1990). Log response is strongly tied to lithology (Atkinson et al., 1988, 1990; Melvin and Knight, 1984); thus, well-to-well correlation of the four zones imposes a lithostratigraphic framework on the Ivishak Formation. These zones constituted operational subdivisions for reservoir engineering and geologic analyses (Wadman et al., 1979; Melvin and Knight, 1984).

Atkinson et al. (1988, 1990) recognized that reservoir performance was strongly influenced by shales. These workers separated the Ivishak into three sandstone to conglomerate units (Romeo,

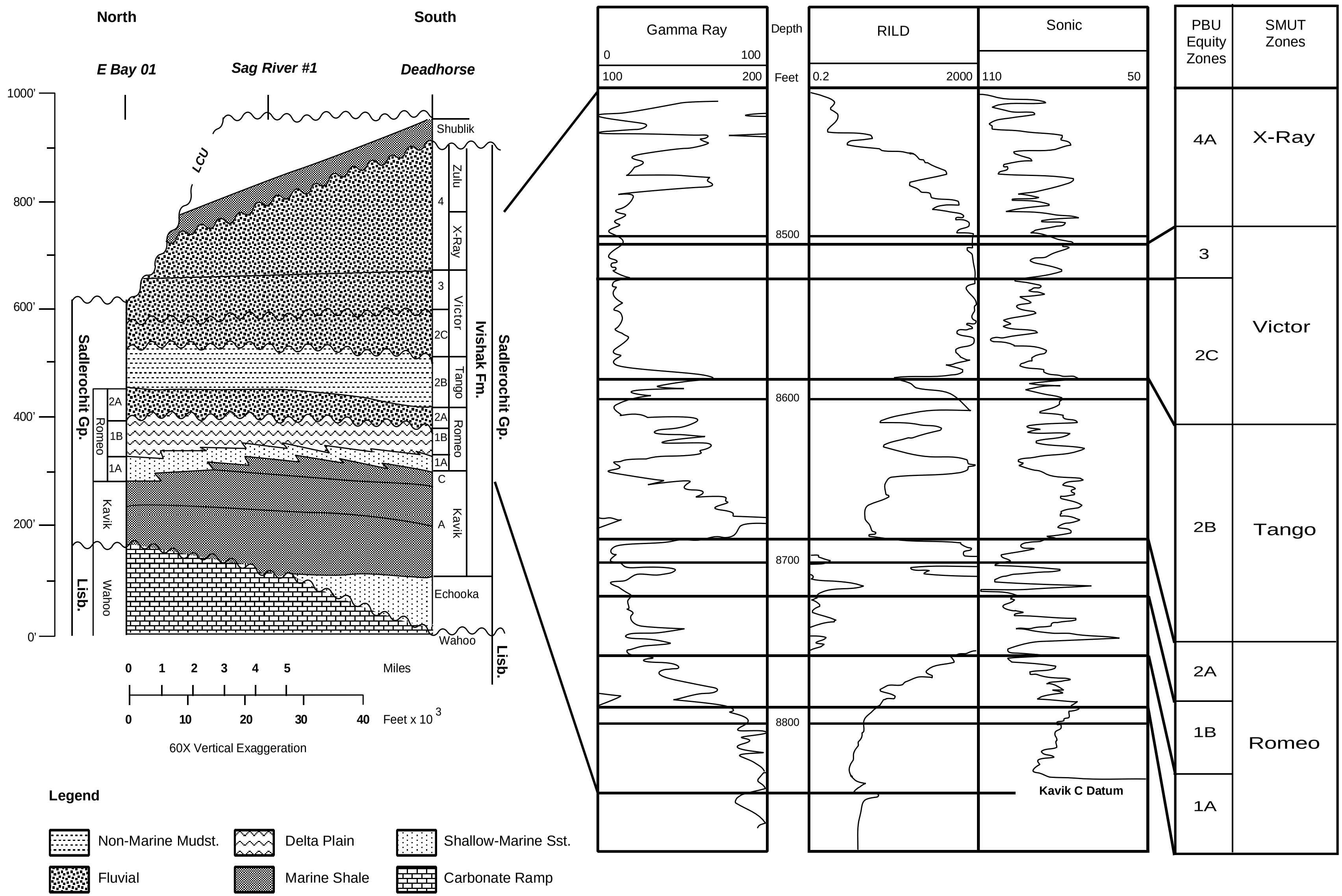


Figure 2—Generalized stratigraphic section with gamma-ray, deep induction, and sonic logs from well 04-10 illustrating log character of the Ivishak Formation. Note the Kavik C marker at the base that is the datum in all cross sections. Two Sadlerochit stratigraphic layering schemes (zones 1A–4A and Romeo through X-Ray) established during field development are depicted. The Romeo interval ([PBu] Prudhoe Bay unit equity zones 1A–2A) is the focus of this paper. LCU = Lower Cretaceous unconformity.

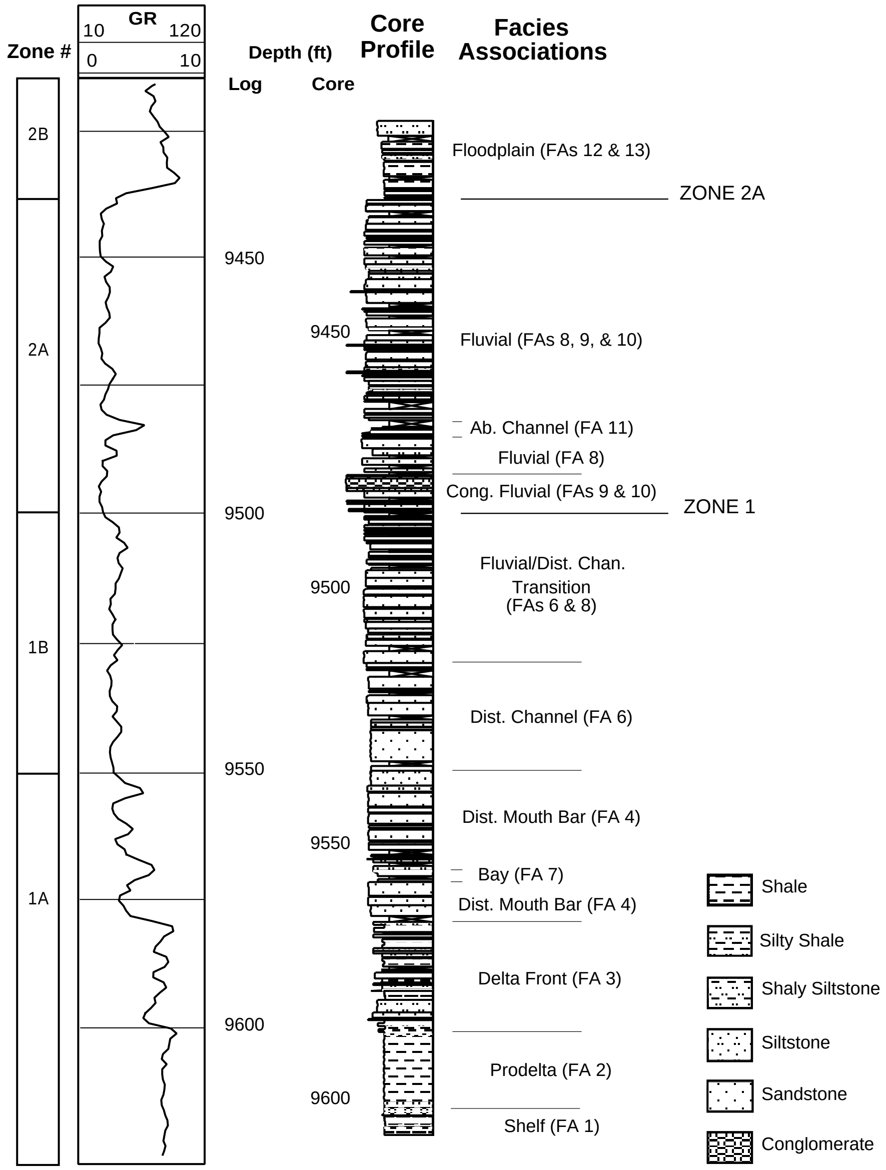


Figure 3—Typical stacking pattern and gamma-ray response of Romeo lithofacies and facies associations (well 07-06) (see Figure 1 for well location).

Victor, and Zulu, Figure 2). These stratigraphic divisions were termed "flow units," emphasizing their significance as hydraulic layers. Atkinson et al. (1988) divided the Romeo flow unit into two subunits on the basis of better reservoir-quality rock at the top and lesser quality rock below. These subunits correspond to different depositional facies. The lowermost unit (1A) consists primarily of prodelta and distal-delta front, whereas the upper unit (1B) contains distributary mouth bar and distributary channel deposits. Cross sections implied lateral persistence of subunits, prompting their treatment as tabular layers of relatively uniform thickness (Melvin and Knight, 1984; Atkinson et al., 1990).

Difficulties in field development, possibly attributable to reservoir stratigraphy, became apparent as basal Ivishak sandstones were targeted, thus spurring additional geological studies (Begg et al., 1992; Bellamy, 1993; Bhattacharya et al., 1994; Lorsong et al., 1994; Richards et al., 1994; Tye et al., 1994; Puls et al., 1995). These studies benefited from access to a large number of previously unavailable (preserved) cores. Newly acquired sedimentologic insights and genetic stratigraphic concepts warrant new interpretations of Romeo stratal geometries, specifically the relationship of lower Romeo clinoform strata with Kavik shales. This interpretation contrasts with the layer-cake stratigraphy previously depicted and requires a more complex interpretation of flow units. The focus of this paper is how this interpretation influences the density, placement, and type of wells drilled, as well as completion practices in the Romeo. Accompanying work (Lorsong et al., 1994) focused on methods to quantify this geologic description for reservoir simulation.

Objectives and Methods

The main objective of this study was to use core descriptions, facies interpretations, and stratigraphic correlations to geologically characterize productive and nonproductive intervals of the Romeo within selected regions of the EOA. Approximately 5000 ft (1525 m) of core were described from 27 wells (Figure 1). Descriptions focused on recognizing sedimentary facies and emphasized interpreting sedimentary processes. Through core analyses, regularly occurring facies associations (see the Appendix) and vertical relationships were recognized (Figure 3). Facies associations were used as the basic correlation units of the Romeo interval, they were mapped within specific stratigraphic intervals, and they constitute the building blocks for reservoir simulation models.

Seventeen cross sections incorporating approximately 250 wells (Figure 1) were constructed across the EOA. Sections were datumed within the underlying Kavik shale. Well data (log and core) were correlated following the concepts outlined in Fisher et al. (1969), Brown (1969), Frazier (1974), Galloway (1989), and van Wagoner et al. (1990). Following the examples of these workers, our study emphasizes identifying and correlating time-equivalent, genetically linked sedimentary facies in interpreting resultant depositional systems and systems tracts. Well performance, limited pressure data, and facies relationships (Reading, 1986; Bhattacharya and Walker, 1992; Posamentier et al., 1993) guided geologic correlation.

Choosing a Datum

Recognizing a stratigraphic datum is perhaps the most important decision made in the early stages of a subsurface appraisal project. Previous work at Prudhoe Bay suggested that FA 1 (facies association 1) sandstones could be calibrated to easily identifiable and areally extensive wireline log markers. Thus, with corroborating core data, a Kavik (FA 1) marine-flooding surface, assumed to have been flat during Ivishak deposition, was picked as the datum (Figure 2). A condensed section above the flooding surface (Loutit et al., 1988; Bhattacharya and Posamentier, 1994) is manifested as a highly radioactive gamma-ray response. Where this marker was not penetrated, stratigraphically higher picks corresponding to shaly facies associations were used to approximate a well's stratigraphic position.

FACIES ASSOCIATIONS AND DEPOSITIONAL INTERPRETATIONS

Core data provide the foundation on which our geologic observations, interpretations, and conclusions are based. Distinguishing sedimentologic and stratigraphic characteristics of each sedimentary facies and facies association, as well as the contacts separating them, are described and interpreted in the Appendix and summarized in Table 1.

Our study follows previously presented facies schemes for basal Ivishak strata (Melvin and Knight, 1984; Lawton et al., 1987; Atkinson et al., 1988; Begg et al., 1992); however, newly available core data enabled us to add sedimentologic and stratigraphic detail. With refined geologic insights gained from the core descriptions, we interpreted 13 facies associations representing 11 depositional settings (shelf, prodelta, delta front, distributary mouth bar, distributary channel, shoreface, bay, fluvial channel, abandoned channel, crevasse splay, and flood plain) (Table 1, Appendix). These depositional facies associations were correlated and mapped within time-stratigraphic boundaries.

NATURE OF THE ROMEO DELTAS

Although most previous workers agree about a deltaic origin for Romeo sandstones (Morgridge and Smith 1972; Eckelmann et al., 1975; Wadman et al., 1979; Lawton et al., 1987; Atkinson et al., 1990), our interpretation of basal Ivishak deposits differs somewhat from an alluvial fan-delta system (Melvin and Knight, 1984) or the braided-river/delta-front setting of Atkinson et al. (1990). Interpretational differences focus primarily on the size of the fluvial feeder system, slope and scale of the deltaic plain, and dominant river-mouth processes controlling sediment distribution. Instead of interpreting the Ivishak as a conformable delta front to braided-stream sequence (Atkinson et al., 1988, 1990), we envision it as a marine to deltaic and fluvial succession punctuated by numerous tectonically induced unconformities. Episodic uplift of the source area, not interfingering lithofacies, is deemed responsible for the grain size variability and changes in fluvial style noted in the nonmarine strata overlying the Romeo.

Our reconstruction of the Romeo interval depicts southeastward-oriented low-gradient and fine-grained fluvial systems that extended 100 km (62 mi) or more from the source area (Figure 4).

Table 1. Summary of Sedimentary Characteristics*

Facies Assoc.	Lithology	Texture	Physical Structure	Biogenic Structure
FA 1	Mudstone and sandstone	Claystone to very fine grained	Symmetrical ripple lamination; hummocky cross-stratification	Numerous burrow traces including *Teichichnus*, *Rosselia*, *Planolites*, and *Zoophycos*
FA 2	Heterolithic mudstone, siltstone (30%), and sandstone (5%)	Claystone to very fine grained	Load casts, microfaults, and fluid-escape pipes; normal grading; symmetric and asymmetric ripple cross-lamination	Rare burrows including *Teichichnus*, *Planolites*, *Thalassinoides*, pectin casts; macerated organic debris
FA 3	Heterolithic claystone and siltstone (60%), and very fine grained sandstone (40%); trace of fine- to medium-grained sandstone	Claystone to very fine grained	Normal grading, symmetric and asymmetric ripple cross-lamination; rare hummocky cross-stratification; ball-and-pillow, convoluted, and overturned bedding, faulting, and dewatering features	Macerated organic debris; rare burrow traces
FA 4	Sandstone (90%) with minor siltstone and mudstone (10%)	Very fine (50%), fine grained (30%), and medium grained (10%)	Flat lamination; low-angle cross-beds; truncation surfaces; symmetric, combined-flow, and asymmetric-current ripple lamination; fluid-escape features and synsedimentary faults	Sparsely burrowed; macerated organic debris
FA 5	Sandstone	Very fine to fine grained	Normal grading; flat to low-angle laminae; symmetric and combined-flow ripple laminae; rare asymmetric-ripple laminae; reactivation and scour surfaces; hummocky cross-stratification	Moderate burrow traces including *Macaronichus*, *Palaeophycus*, *Teichichnus*, and *Skolithos*; macerated organic debris
FA 6	Sandstone (95%); minor chert pebbles, siltstone and mudstone (5%)	Medium (50%), fine (30%) to very fine grained (15%)	Sharp based; trough and planar tabular cross-bedding, parallel lamination and asymmetric-ripple lamination	Macerated organic debris
FA 7	Heterolithic mudstone, siltstone (80%), and minor sandstone (20%)	Claystone to very fine grained	Symmetric- and asymmetric-ripple lamination; lenticular beds; loading and mud cracks	Sparse burrows including *Arenicolites*
FA 8	Sandstone (97%); chert granules and pebbles (2%); minor mudstone (1%)	Medium (60%), fine (30%) to very fine grained (7%)	Parallel lamination; planar cross-bedding; asymmetric-ripple lamination	Not observed
FA 9	Conglomerate, pebbly sandstone, sandstone (99%); minor mudstone (1%)	Coarse to fine grained	Poorly stratified to cross-bedded; normally graded; asymmetric-ripple lamination	Not observed
FA 10	Conglomerate, sandy conglomerate	Coarse grained	Poorly stratified	
FA 11	Heterolithic mudstone (55%) and sandstone (45%)	Claystone (55%), very fine grained (40%) and medium to fine grained (5%)	Asymmetric-ripple lamination; soft-sediment deformation	Not observed
FA 12	Heterolithic mudstone (20%) and sandstone (80%)	Mudstone (20%), very fine grained (50%), fine grained (20%), and coarse to medium grained (10%)	Asymmetric- and symmetric-ripple lamination; soft-sediment deformation	Rare *Scoyenia*
FA 13	Mudstone, siltstone, rare sandstone	Claystone to very fine grained	Irregular lamination; mud cracks, slickensides	Rare *Scoyenia*; pedogenic features; root traces; mottling

*Porosity and permeability values were provided by F. Paskvan (1993, personal communication) and represent mean values calculated from log and core data.

Table 1. Continued.

Macroscopic Diagenetic Features	Gamma-Ray Log Character	Interpreted Depositional Environment, Permeability, and Porosity	Comparison to Previous Depositional Interpretations
Framboidal and nodular pyrite	Upward coarsening; sharp-based sandstones	Marine shelf	Not recognized
Nodular and bedded siderite	Overall upward-coarsening sharp-based sandstones	Prodelta; mean permeability = 3.4 md; mean porosity = 6.6%	Prodelta (Lawton et al., 1987); prodelta and distal delta front (Atkinson et al., 1988)
Nodular and bedded siderite	Coarsening upward to serrated	Distal delta front; mean permeability= 5.0 md; mean porosity = 10.4%	Distal delta front (Atkinson et al., 1988); distal bar (Lawton et al., 1987)
Siderite	Overall upward coarsening; rarely blocky or serrated	Proximal delta front; distributary mouth bar; mean permeability= 151.5 md; mean porosity = 20.3%	Distributary mouth bar (Atkinson et al., 1988); proximal bar (Lawton et al., 1987)
Not observed	Upward coarsening	Shoreface; wave-influenced distributary mouth bar; mean permeability= 91.0 md; mean porosity = 19.9%	Not recognized
Not observed	Stacked, fining-upward units	Distributary channel; mean permeability= 315.4 md; mean porosity = 22.9%	Distributary channel complex (Lawton et al., 1987)
Siderite/limonite cementation	Shaly to serrated	Interdistributary bay, swamp, marsh; mean permeability= 15.4 md; mean porosity = 15.1%	Bay/marsh (Lawton et al., 1987)
Siderite	Sharp based, fining upward to blocky; clay-clast conglomerates produce high gamma-ray response	Fluvial channel; mean permeability= 910 md; mean porosity = 26%	Sandy meandering to braided fluvial (Lawton et al., 1987)
Siderite	Sharp to irregularly based, fining upward to blocky; clay-clast conglomerates produce high gamma-ray response	Fluvial channel; mean permeability= 477.9 md; mean porosity = 24%	Fluvial channel (Atkinson et al., 1988); braided fluvial complex (Lawton et al., 1987)
Not observed	Sharp based, blocky; clay-clast conglomerates produce high gamma-ray response	Fluvial channel; mean permeability= 1333.5 md; mean porosity = 27%	Fluvial channel (Atkinson et al., 1988); braided fluvial complex (Lawton et al., 1987)
Pyrite and siderite	Gradationally based; serrated to upward fining	Abandoned channel (distributary and fluvial); mean permeability= 198.9 md; mean porosity = 17.6%	Abandoned channel (Lawton et al., 1987; Atkinson et al., 1988)
Not observed	Sharp or gradationally based; upward coarsening or fining; serrated	Crevasse splay, lacustrine delta, natural levee, bayhead delta; mean permeability= 215.4 md; mean porosity = 21.7%	Flood plain/pond (Atkinson et al., 1988; Lawton et al., 1987)
Pyrite and siderite; rare iron oxides	Serrated to shaly	Alluvial flood plain; mean permeability= 30.1 md; mean porosity = 15.1%	Paleosols (Atkinson et al., 1988)

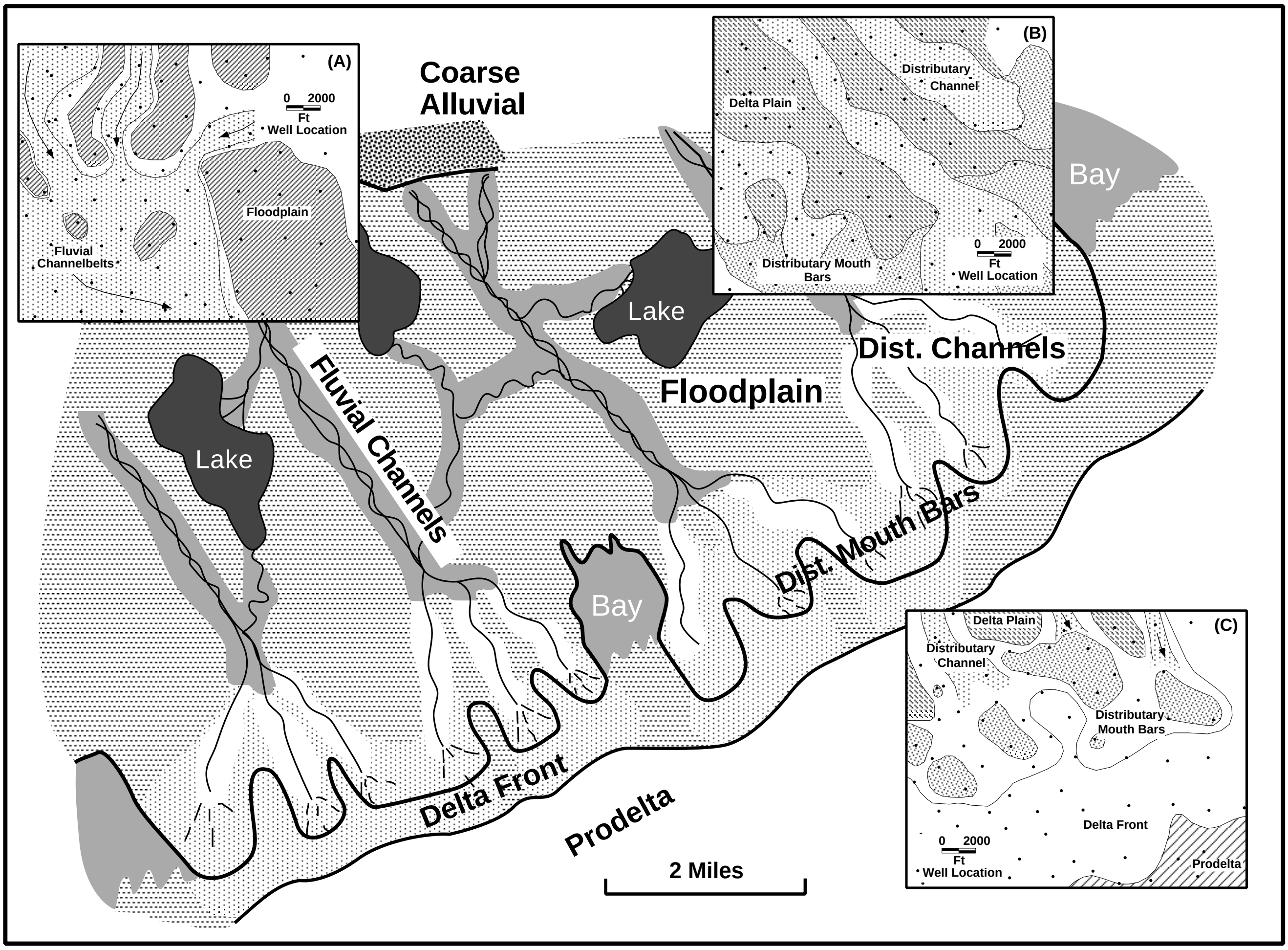


Figure 4—Schematic paleogeographic representation of Romeo facies associations as they existed during deposition. Insets (see location box on Figure 1) are facies association maps based on wireline-log and core interpretations for three Romeo stratigraphic layers. Facies association maps are placed in their interpreted proximal (A) to distal (C) paleogeographic positions. North is to the top.

Shallow lakes or muddy flood plains intermittently filled by crevasse splays and lacustrine deltas may have laterally separated these major fluvial systems. Approaching the basin, fluvial channels bifurcated forming a delta plain. Distributary mouth bar, delta front, and prodelta facies associations were deposited seaward of the distributary channels. Delta lobes were dominated by fluvial influence and frictional river-mouth processes (Wright, 1977; Coleman and Prior, 1982). Areas between distributary channels and laterally adjacent to delta lobes constituted low-energy interdistributary bays where mud deposition dominated. Some of these mud-prone areas may have become completely enclosed to form lagoons and marsh environments, whereas other areas graded laterally into prodelta and shelfal settings. The low amount of burrowing, abundant soft-sediment deformation (loading and growth faulting), and the limited preservation of wave-formed sedimentary structures in the deltaic facies associations suggest that riverine processes were dominant in constructing Romeo deltas. River-dominance resulted in rapid lateral facies changes and, consequently, a high degree of lateral and vertical heterogeneity. Deltas terminated downdip by pinching out into Kavik shale.

Shoal-water lobate deltas, such as the LaFourche or Atchafalaya deltas of the Mississippi system (Fisher et al., 1969; van Heerden and Roberts, 1988), the Po delta of eastern Italy (Ori, 1993), the Rhone delta of southern France (Russell, 1942), the Danube of eastern Romania, or deltas on the Alaskan Beaufort Sea coast (Naidu and Mowatt, 1975; Walker, 1975), may be analogous to the Romeo deltas in terms of their general morphology and the nature of fluvial feeder systems. Beaufort Sea deltas are most similar in grain size.

STRATIGRAPHY

A variety of facies association contacts identifiable from logs and cores are interpretable as key Kavik and Romeo stratigraphic markers. These markers were correlated using a genetic approach in which time-equivalent rock units bounded by surfaces of erosion and nondeposition are correlated, rather than simply linking lithologically similar rock units. The strength of identifying depositional facies and correlating coeval stratigraphic units is that this method results in an accurate depiction of the reservoir stratigraphy. This approach allows better understanding and prediction of facies associations between wells and their connectivity, and improves methods for distributing rock properties in reservoir models.

Stratigraphic Surfaces and Reservoir Compartmentalization

Transgressive Surfaces

Sandstone-mudstone contacts capping coarsening- and thickening-upward bed sets are interpreted and correlated as transgressive surfaces of erosion or marine-flooding surfaces (Weimer and Sonnenberg, 1989; van Wagoner et al., 1990; Weimer, 1992; Bhattacharya, 1993). A few cores exhibit evidence of marine erosion and reworking at these contacts; however, delta-lobe subsidence or transgression was sufficiently rapid to preserve most of the shoreline facies associations (FA 3–FA 5).

Identifying and correlating surfaces created during delta abandonment are important because these surfaces are overlain by mudstone lithofacies (FA 2 and FA 7) within the reservoir interval. The arrangement of mudstones is the most important factor controlling flow in the reservoir. Thus, an accurate depiction of the size, distribution, and orientation of mudstones is critical. Of particular concern to reservoir compartmentalization is their regional extent and integrity. In developing our model, common questions focused on the mudstones and whether they represent autocyclic delta-lobe switching and transgression or whether they are related to regional allocyclic transgressions, and how the mudstones were altered during subsequent delta progradation.

Within nonmarine strata, mottled mudstones represent alternately flooded and exposed alluvial soils. Abrupt upward transitions from mottled mudstones into laminated silty mudstones (FA 13) are interpreted as representing flood plain submergence and lake formation (Coleman, 1966; Tye and Coleman, 1989a, b). This transition can be considered a nonmarine flooding surface (Shanley and McCabe, 1994). Nonmarine flooding surfaces also cap lacustrine deltas and crevasse-splay sandstones (FA 12).

Sequence Boundaries vs. Channel Diastems

In several wells, (17-01, 17-04, 5-10, 3-06; Figures 5–7) distributary mouth bar or distributary channel sandstones sharply overlie prodelta mudstones. These abrupt contacts and missing facies are interpreted to represent basinward shoreline shifts that formed regressive surfaces of erosion or sequence boundaries by relative sea level falls (Plint, 1988; van Wagoner et al., 1990; Hunt and Tucker, 1992; Bhattacharya, 1993; Posamentier et al., 1993; Nummedal and Molenaar, 1995). Although these surfaces cannot be correlated regionally, a basinward-stepping stratigraphic succession formed (Figure 5). Theoretically, one could define each of these offlapping units as individual sequences; however, we believe that this violates the essence of sequence stratigraphy, that is, to define regionally extensive stratigraphic units bounded by sequence boundaries and correlative conformities.

Channelized facies associations are assumed to have erosional bases. Unfortunately, in a field-scale evaluation of fluvio-deltaic strata, it is difficult to distinguish sequence boundaries from localized channel diastems; nevertheless, evaluating these erosional surfaces was critical because they dissect previously deposited prodelta (FA 2) or bay (FA 7) shales. Localized channel incision decreases shale effectiveness as a flow barrier. In many cases, channel bases are mantled by mud chips, indicating breakup of a previously existing shale. Some apparently thick shales indicated by wireline logs were observed in core to be mud-chip layers overlying partially preserved bay shale.

Cross Sections

Numerous shingled, offlapping units are evident within basal Romeo strata in the EOA (Figure 5). These shingled units represent individual delta lobes bounded by flooding surfaces and overlain by prodelta shales. Delta-lobe profiles are manifested as gently dipping (approximately 0.3°) clinoforms. Clinoforms dip to the southeast, extend basinward into shale, and merge or downlap onto the Kavik datum.

Along depositional strike (Figure 6), the most obvious feature is the lateral interfingering or juxtaposition of sandstone facies (distributary mouth

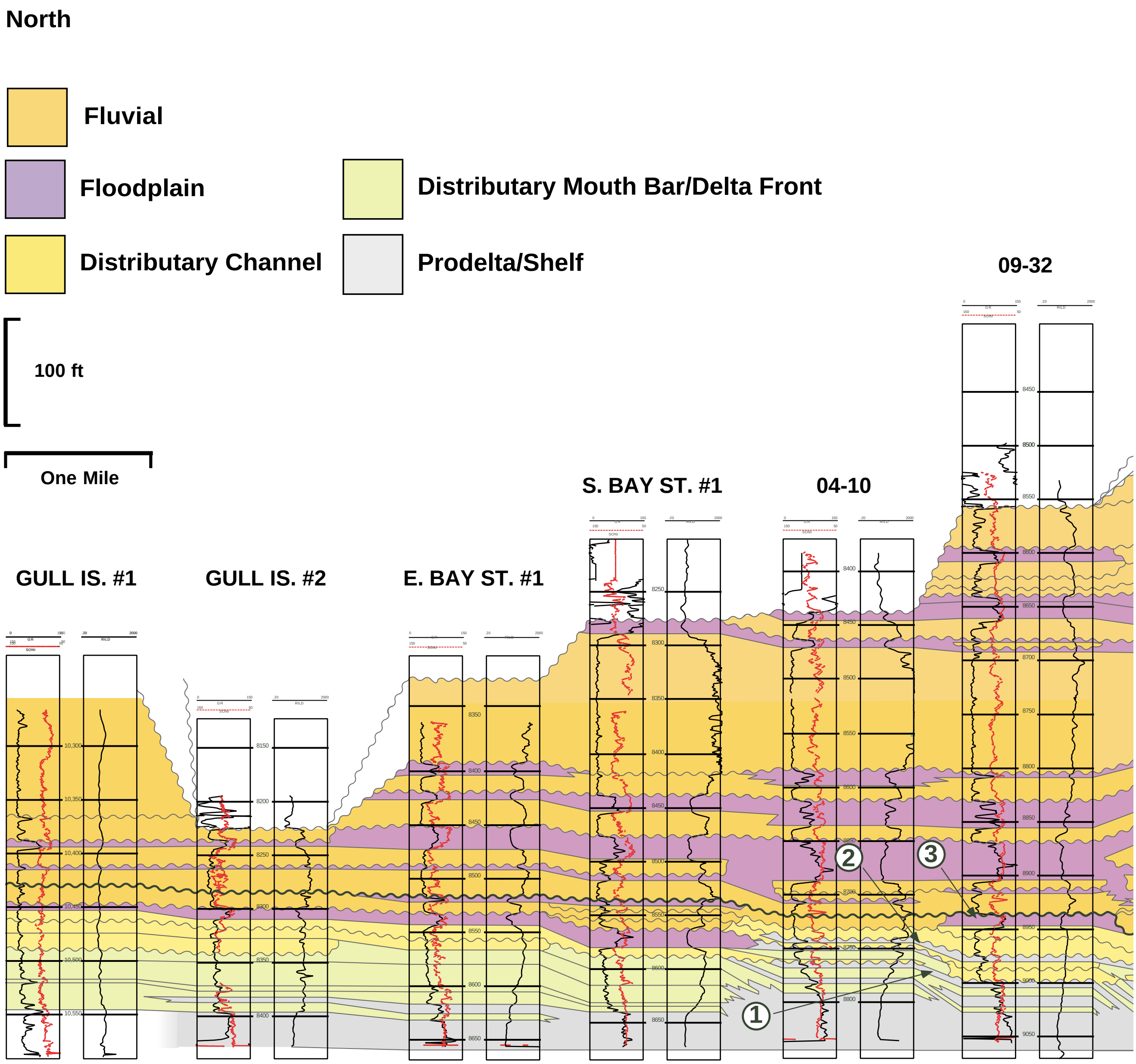


Figure 5—North-south wireline log correlations across Prudhoe Bay field (see Figure 1 for cross section location). Multiple, stacked, coarsening-upward depositional packages representing successive delta-lobe progradations underlie nonmarine strata. Surfaces capping coarsening-upward successions and overlain by mudstone are interpreted as transgressive surfaces of erosion that dip gently (0.3°) to the southeast. Lithofacies constituting these coarsening-upward packages become shalier toward the southeast. Note the progradational and downstepping geometry of the deltaic and fluvial strata.

bar and distributary channel deposits) with muddier facies (delta-front and bay/prodelta deposits). Stratification is fairly consistent, but facies association correlations are complex (Figures 5–7) (see also Lawton et al., 1987). Delta-front deposits (FA 3) pinch out into prodelta shales at delta-lobe margins. Flooding surfaces separate delta-front strata from overlying distributary mouth bar and distributary channel sandstones (wells 5-04, 5-10, Figure 6). Four to five bay shales are correlated within the lower half of the Romeo, but only two bay shales extend across the section. No upper Romeo shales correlate across the 6.5-km- (4-mi-) long cross section; moreover, this section displays both gradational prodelta to delta-front transitions (wells 2-13 to 5-25, Figure 6), as well as abrupt, sharp-based transitions (wells 5-4

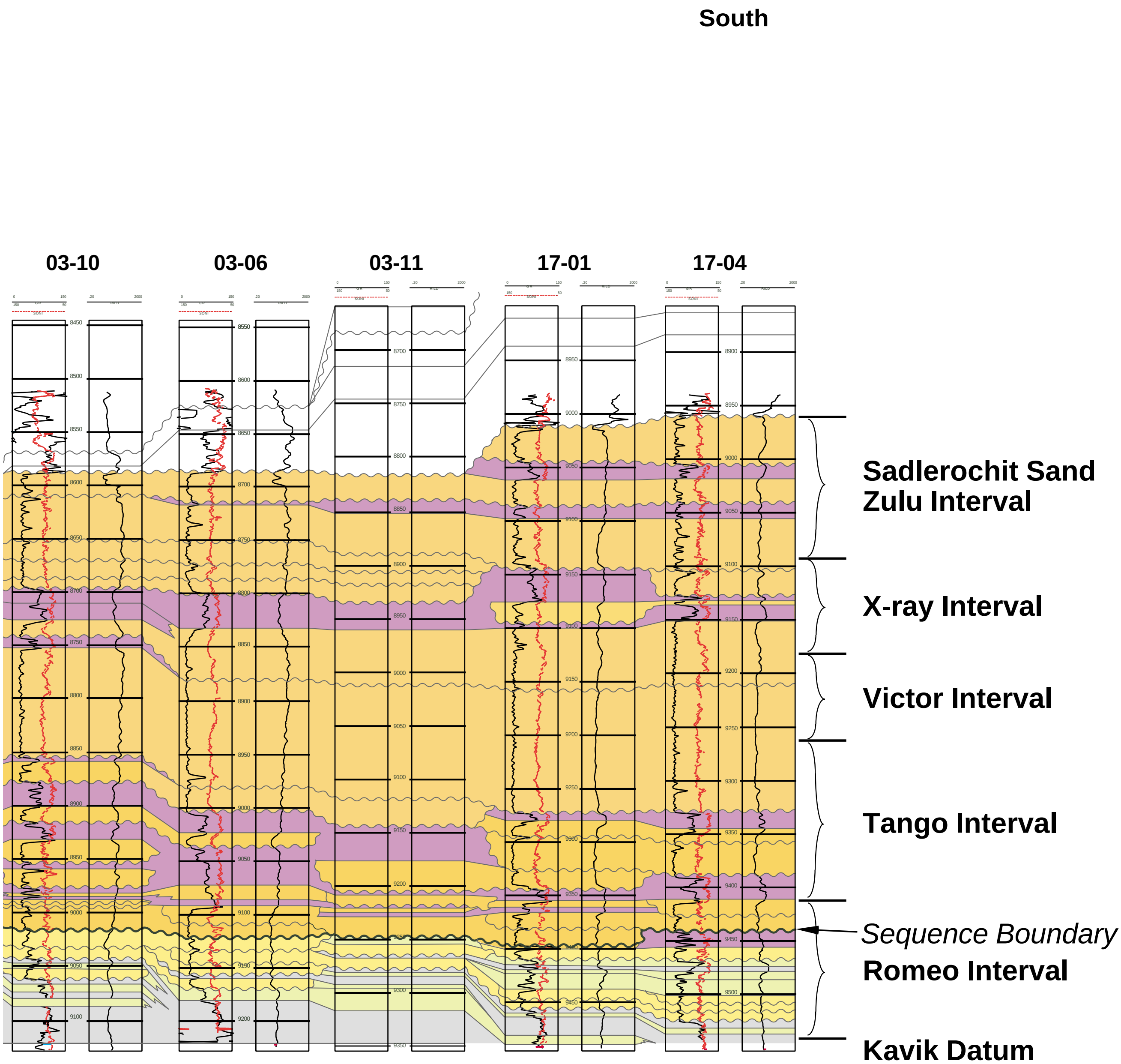


Figure 5—Continued.

and 5-10, Figure 6). Clinoforms corresponding with prodelta or bay facies that dip gently basinward are essentially flat when viewed along depositional strike.

Herein lies the critical difference that stratigraphic interpretations can have on reservoir description because recognizing the gently dipping nature of the basal reservoir sandstones results in a very different stratigraphic picture of the reservoir than that previously held (compare Figure 7A and B). Across the field, the stratigraphy is not tabular. The interpretation (Figure 7B) demonstrates how sandstone-prone Ivishak deltaic wedges interfinger downdip with bay and prodelta/shelf shales. As a result, shales within the Romeo do not correlate fieldwide; most Romeo shales can be correlated over distances of a few kilometers or less. Shales terminate updip where they pass into sandier facies (FA 3, FA 4) or are eroded by overlying channelized facies associations (FA 6).

Wireline log correlations (Figure 2) display a geometry in which regionally, the Kavik shale thickens seaward (to the south). In Figure 5, note the variable shale thickness separating the lowermost Romeo sandstone from the Kavik datum and, more

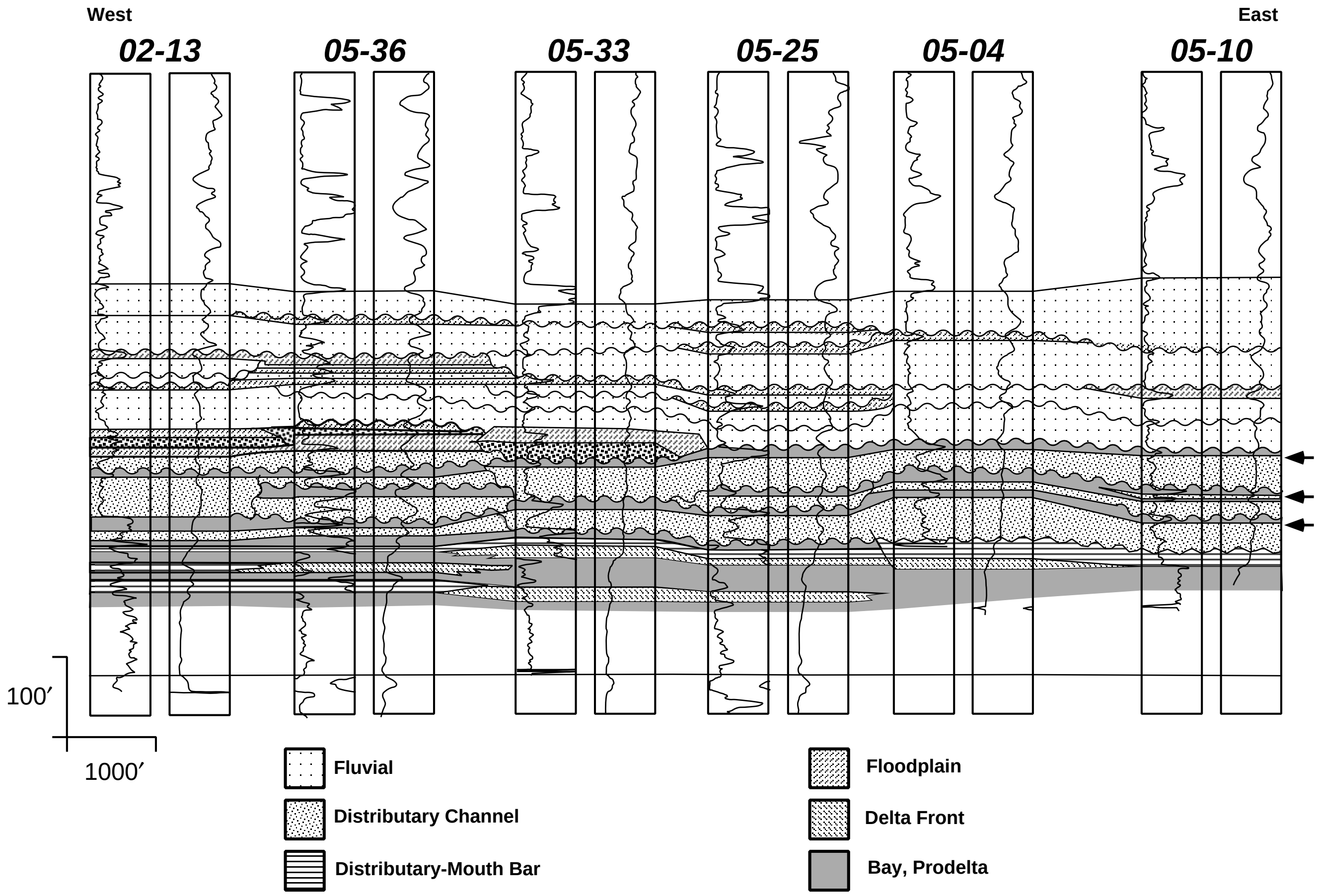


Figure 6—West-east cross section depicts the stratigraphy of the Romeo interval in the drill site (DS) 5 area. The continuity of fluvial and deltaic sandstones is shown, as are mudstones that may form fluid-flow barriers. See Figure 1 for cross section location. Arrows highlight surfaces across which deltaic sandstones are overlain by bay/prodelta shale. These surfaces are subhorizontal in strike view and form clinoforms along depositional dip (see Figure 5).

important, observe that within the field limits this thickness does not increase basinward. Subtle facies changes coincide with these changes in stratal geometry. To the north (well S. Bay St. 01, Figure 5), aggradational wave-influenced shoreline facies (FA 5) characterize lower Romeo sandstones. In central wells (4-10 and 9-05, Figures 5, 7), delta-front and distributary mouth bar facies associations (FA 3 and FA 4) that gradationally overlie 15 m (49 ft) of shale comprise Romeo sandstones. Farther basinward (wells 17-01 and 17-04, Figure 5), but at the southern limit of the field, distributary channel sandstones (FA 6) erosionally overlie prodelta shales (FA 2) approximately 8 m (26 ft) above the Kavik marker.

Amalgamated wave-influenced shoreline facies to the north of well 4-10 (Figure 5) imply that these lower Romeo strata are highstand deltaic deposits formed during a stillstand or gradual sea level rise. Thick downstepping successions of proximal facies associations in a basinward position (FA 4, FA 6, and FA 8; wells 17-01 and 17-04, Figure 5) suggest deposition during relative sea level falls or forced regressions, such as those described by Plint (1988), Posamentier et al. (1993), Tesson et al. (1990), Bhattacharya (1993), and Nummedal and Molenaar (1995).

Once delta deposition filled available space, fluvial systems overran the delta platform and built a delta farther seaward. Correlations and truncated markers indicate an abrupt change from deltaic to fluvial deposition (Figure 5), implying sequence boundary formation as a result of rapid fluvial progradation. Alternatively, this surface could be an amalgamation of channel bases (i.e., diastems); however, above the stratigraphic horizon marking a change from deltaic to fluvial facies associations, deltaic strata are not observed fieldwide. Additionally, granular to pebble-size grains are not observed in the deltaic or shoreface facies associations, implying that the coarser grained fluvial facies associations (FA 9 and FA 10) are not genetically linked to the deltaic depositional system.

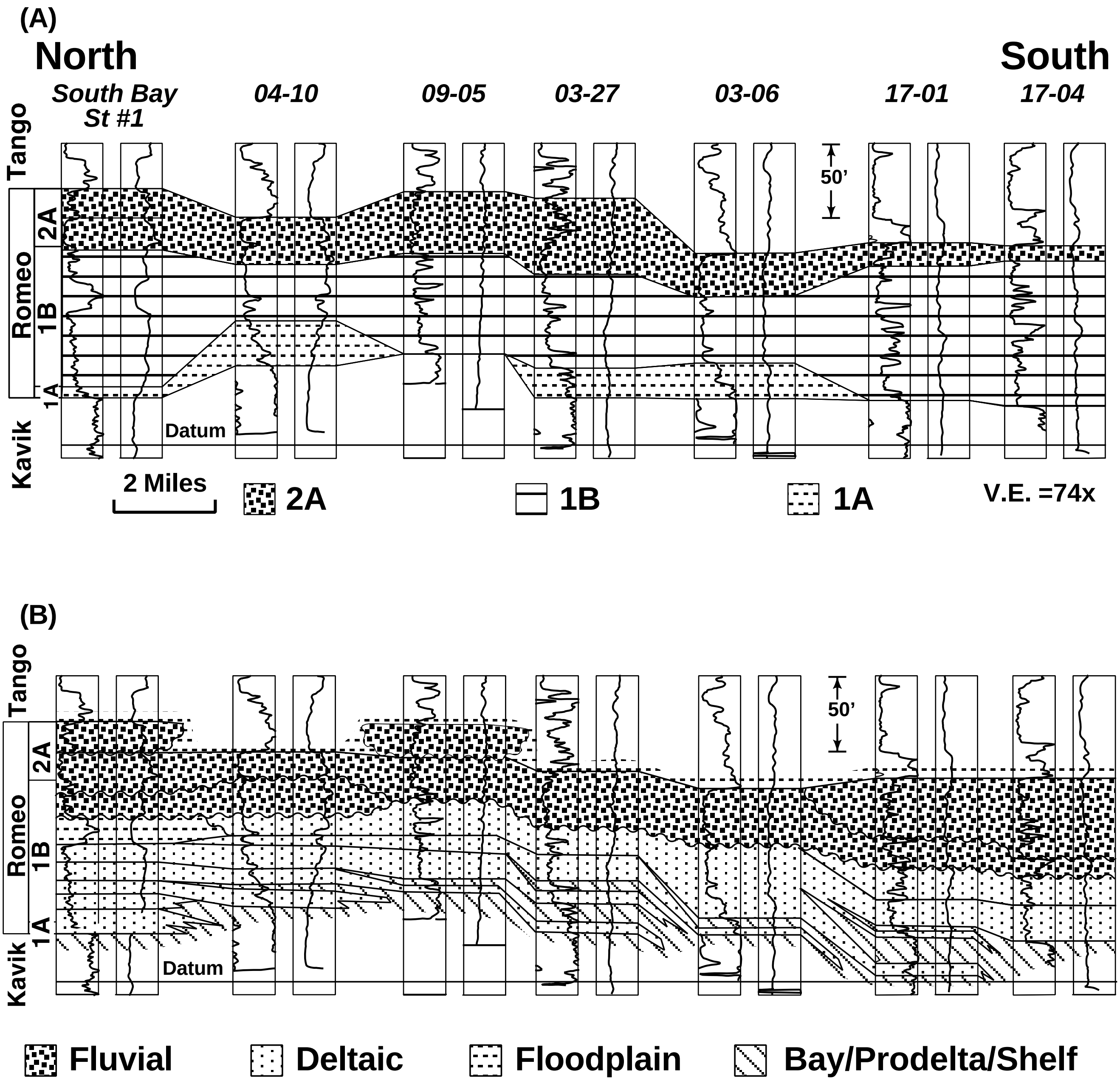


Figure 7—Comparison of (A) prestudy and (B) poststudy stratigraphic interpretations of the Romeo interval. (A) Cross section depicting Prudhoe Bay unit equity zone stratigraphy, which essentially is a lithostratigraphic correlation of equity zones 2A, 1B, and 1A. Note the uniform tabular arrangement of these units. Only zone 1A shows stratigraphic discontinuity. In early reservoir simulations, these units were treated as reservoir layers. (B) Same cross section as in (A), but illustrating an alternative interpretation. Implications on reservoir characterization discussed in text. Simplified from Figure 5.

Facies Association Maps

Well data have shown that distributary mouth bar, distributary channel, and sandy fluvial facies associations constitute the most productive Romeo strata. Identifying and mapping coeval sandstone facies associations within Romeo wedges and maps of the intercalated shale facies (Figure 8) are used to quantify the spatial distribution of rock types and to build reservoir layers for flow-simulation models (Lorsong et al., 1994). Numerous between-well facies terminations occur through gradational facies changes and channel terminations. Facies association continuity and, therefore, permeability

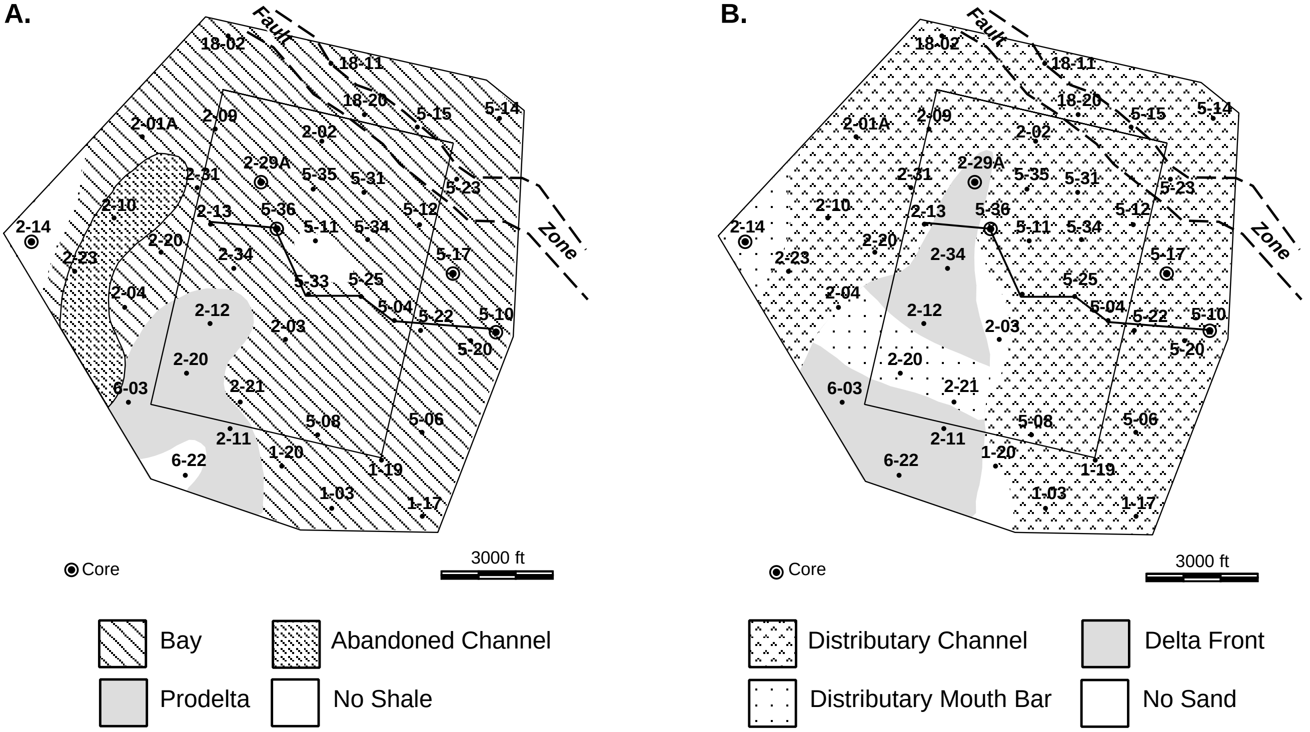


Figure 8—Maps showing the distribution and types of (A) shale and (B) sandstone facies associations present within a single reservoir layer. Facies associations were used to distribute permeability values and transmissibility modifiers for simulation purposes. See Lorsong et al. (1994).

trends are largely dependent on the degree of channelization in the deltaic and nonmarine sections.

Shales

Maps delineate shale continuity and the lateral variability in shale facies associations including clay-clast conglomerates. Figures 5 and 8A show that shale types within a single reservoir layer (Lorsong et al., 1994) are areally variable. In places, shales cover areas greater than the well spacing; however, locally, shales are absent owing to erosion by an overlying channel, or their previous presence is suggested by clay-clast conglomerates. Shale map overlays suggest vertical communication among sandstone layers is possible, albeit tortuous (Figure 9). Additionally, the degree and magnitude of faulting can decrease the effectiveness of these shales to retard flow.

Shale stratigraphy is critical to both the waterflood and gravity-drainage recovery processes and, as with most fields, gas and water handling costs at Prudhoe Bay are economically critical. Where oil targets occur near the base of the reservoir, overlying shales shield sandstones from gas encroachment or slumped injected water; moreover, shales act as barriers between injector-producer well pairs as demonstrated by one interference test in DS 4 (drill site 4) (Figure 1) designed to determine (1) sandstone producibility/injectivity, (2) sandstone continuity, and (3) the effectiveness of shales as flow barriers (D. Freyder, 1994, personal communication). The effectiveness of shales as flow barriers was confirmed when receivers in the producing well (04-40) did not sense the signal from the injection well (04-42, Figure 10). The pretest stratigraphic interpretation predicted a continuous shale separating perforations between the two wells. Well-test data could be matched without altering this shale stratigraphy; therefore, problems indicating reservoir heterogeneity (poor history matches) often can be solved by stratigraphically aligning perforations (reperforating wells).

Sandstones

Because Ivishak porosity and permeability populations closely correspond to lithofacies (Begg et al., 1992; F. Paskvan, 1992, personal communication), we mapped facies associations to predict interwell permeability trends; therefore, facies association maps of time-equivalent stratigraphic intervals served as permeability patterns for reservoir layers. Figure 8B illustrates the geometries of distributary channel and distributary mouth bar facies associations from one reservoir layer

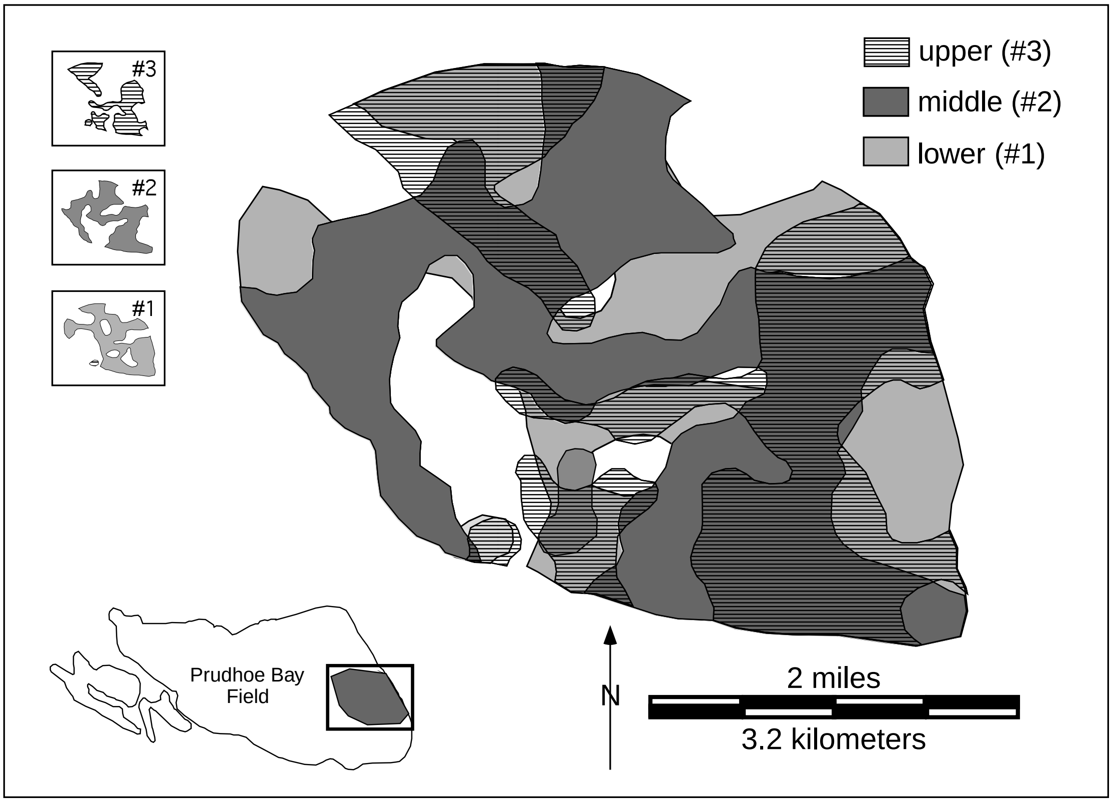


Figure 9—Generalized distribution of three stratigraphically distinct shales in an eastern part of Prudhoe Bay field. Average well spacing is 1500 ft (457 m). Note that in places, all three shales are absent due to nondeposition or erosion, whereas in other locations all three shales separate adjacent reservoir layers. Only with this level of detailed stratigraphic interpretation can gravity drainage, waterflood, and enhanced oil recovery depletion mechanisms be effectively managed. Insets show the complete coverage for each shale. See Figure 5 for a cross-sectional view of shales 1, 2, and 3.

(Lorsong et al., 1994). Note the north-to-south trend of the distributary channel sandstone and its bifurcation where it incised into distributary mouth bar and delta-front deposits. This facies association map suggests sufficient sandstone continuity to recover reserves with existing wells; however, caution is warranted because this picture does not show reservoir segmentation due to faulting, nor does it depict the fluid distribution in the layer. In specific areas, production can be accelerated with infill wells whose locations are optimized using facies association maps of the target interval.

STRATIGRAPHIC AND ENGINEERING IMPLICATIONS ON FIELD DEVELOPMENT

A perusal of geologic literature will net numerous examples of how an understanding of stratigraphy, structure, depositional systems (facies analyses), and petrography can affect exploration and development projects (e.g., Ranganathan and Tye, 1986; Tye et al., 1986; Tillman and Jordan, 1987; Flint et al., 1989; Putnam, 1989; Wood and Hopkins, 1989, 1992; Hopkins et al., 1991; Gibbons et al., 1993; Harker et al., 1993; Posamentier and Chamberlain, 1993; Pattison and Walker, 1994; Schafer and Posamentier, 1994; Wilson and Posamentier, 1994; Bryant et al., 1995); moreover, Ebanks (1987) and Johnson and Stewart (1985) succinctly summarized and clearly demonstrated how linking geologic and engineering data throughout all phases of field development is important. Ebanks went a step further by stating that because of unanticipated geologic problems most tertiary recovery projects attempted have failed to achieve expected goals.

At Prudhoe Bay field, a holistic approach to field development has evolved as operators gained experience. The following three examples illustrate how a combination of reservoir description, engineering analyses, and advances in drilling technology have directly affected field operations in the eastern operating area (Figure 1). Reservoir management strategies combining stratigraphy and well

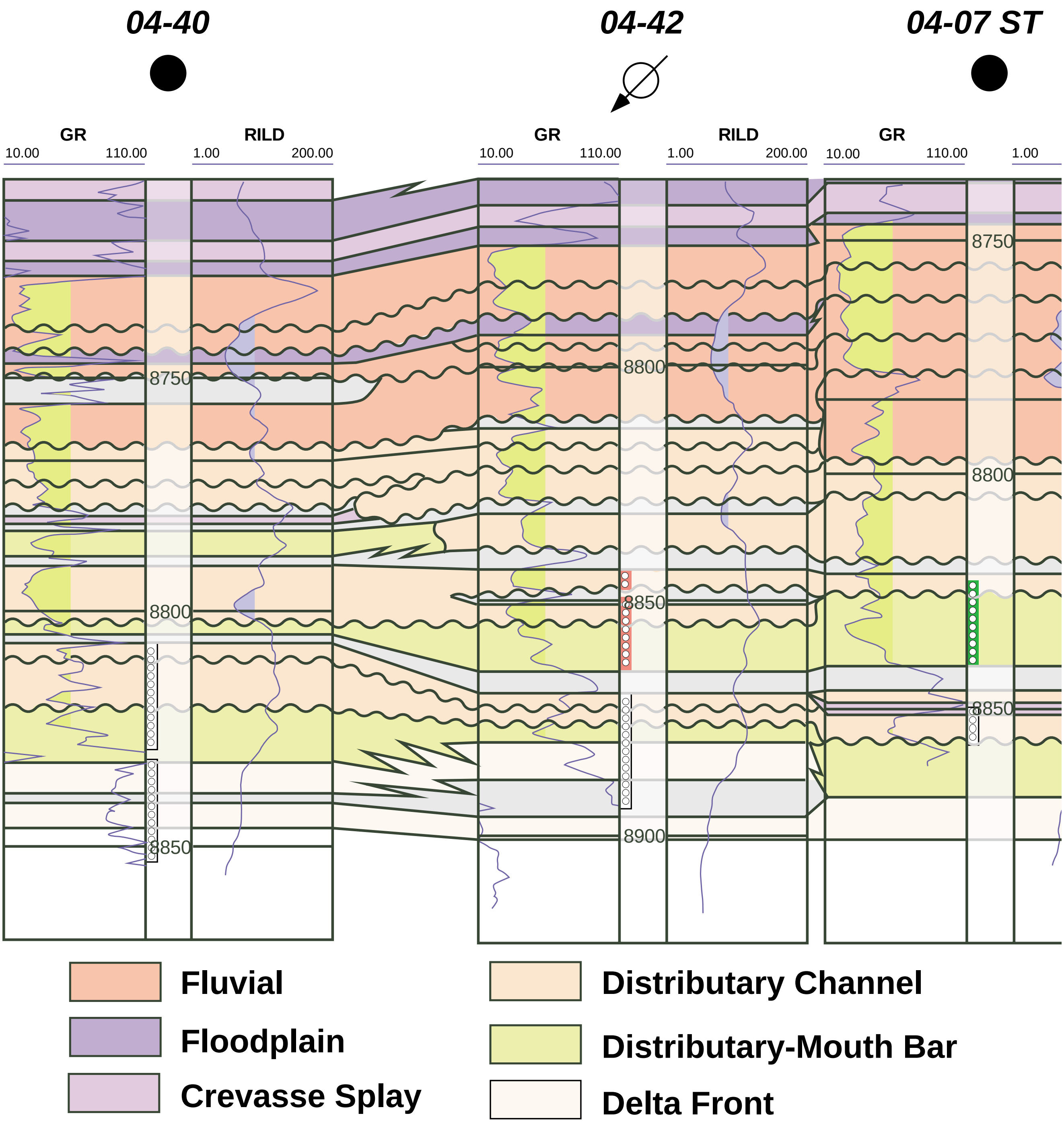
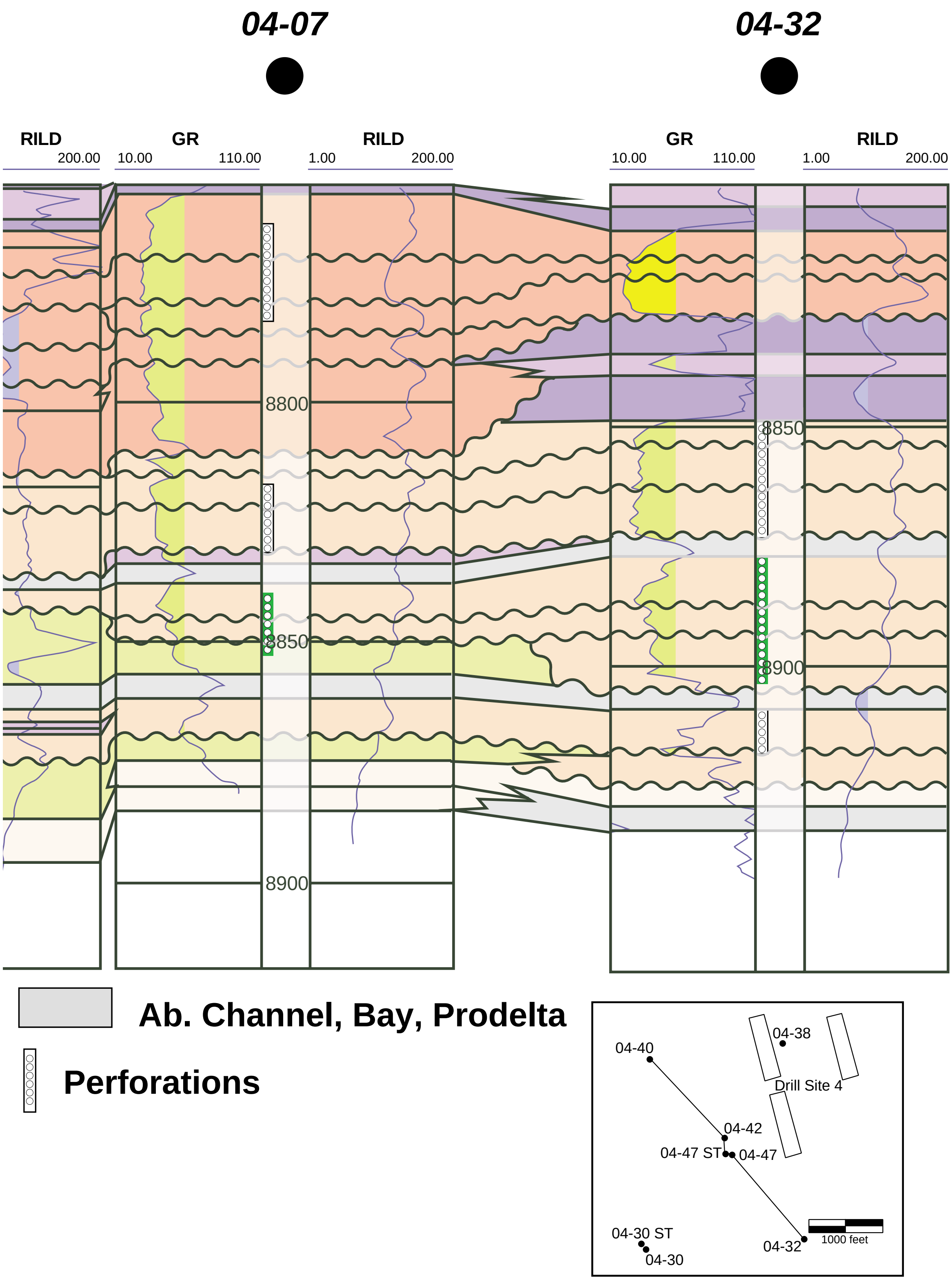


Figure 10—Northwest-southeast–oriented cross section through five wells in drill site (DS) 4 (see inset). Stratigraphic interpretation shown was made prior to a pulse test conducted to determine interwell sandstone continuity. Perforations stimulated in well 04-42 are shown in red; those in which the pulse was received are shown in green. Note the intervening shale between sandstones perforated in well 04-42 and those perforated in 04-40. The pulse signal from 04-42 was never received in well 04-40.



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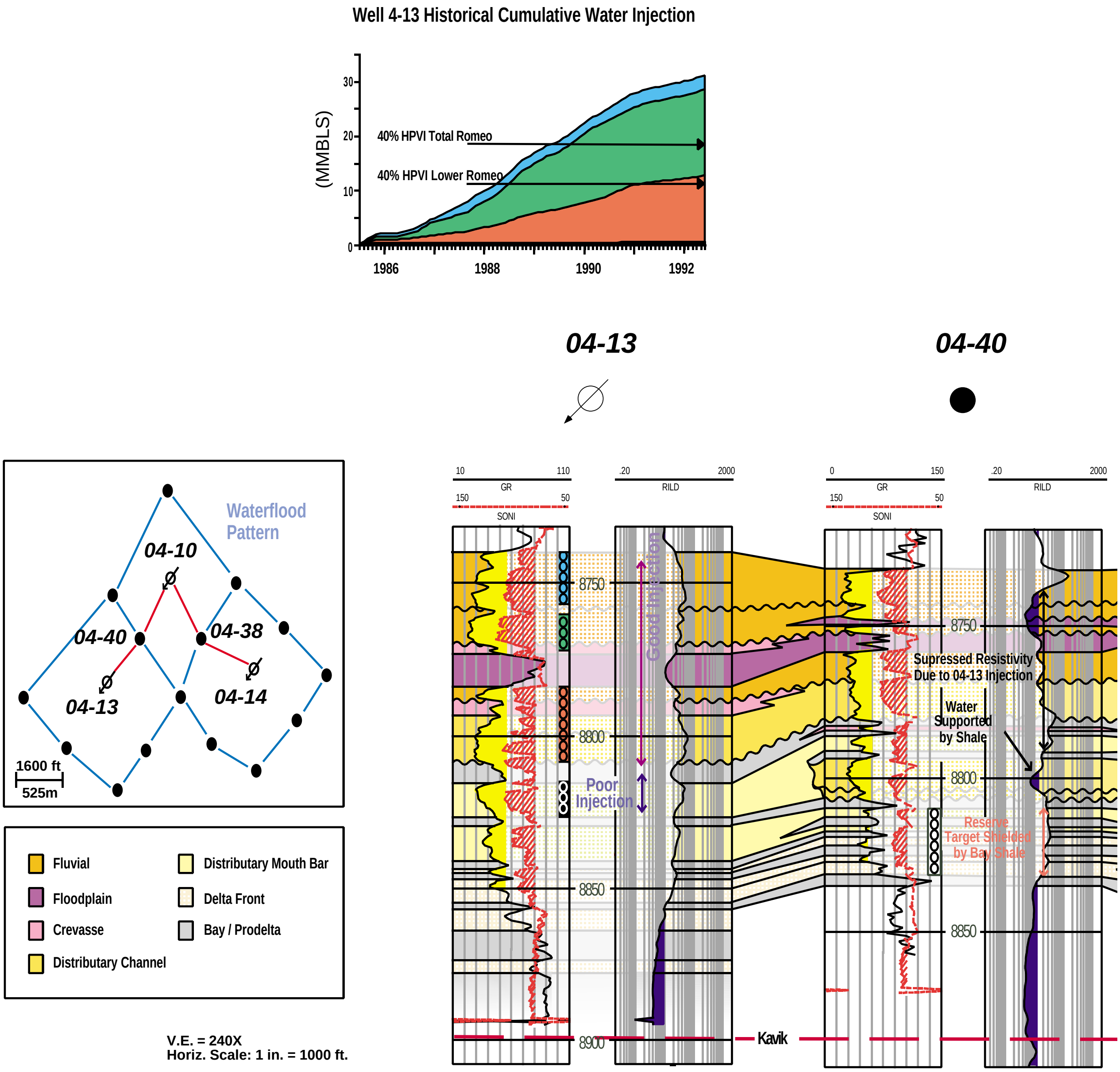


Figure 11—Cross section showing alternating injection (circle with arrow) and production (solid circle) wells over a small part of the waterflood area in Prudhoe Bay field. Porous fluvio-deltaic sandstones are highlighted yellow (gamma-ray logs) with a red slash (sonic logs). Watered-out sandstones are indicated by blue shading on the resistivity logs. Cumulative water injection profiles are shown for wells 04-13, 04-10, and 04-14. Note that water volumes on the injection profiles are color coded with the perforations. Basal sandstones (black perforations) have been poorly swept by the waterflood.

histories focused on the following goals: (1) designing producer/injector patterns for maximum efficiency, (2) establishing stratigraphic alignment of perforations in waterflood injector/producer well pairs, (3) identifying remaining reserve targets from well injection/production histories, and (4) using nonconventional wells to optimize rates and recoveries.

Reserve Target Identification and Optimization: Drill Site-04 Waterflood Performance

The cross section in Figure 11 illustrates alternating injection and production wells covering a small part of the waterflood area in Prudhoe Bay field.

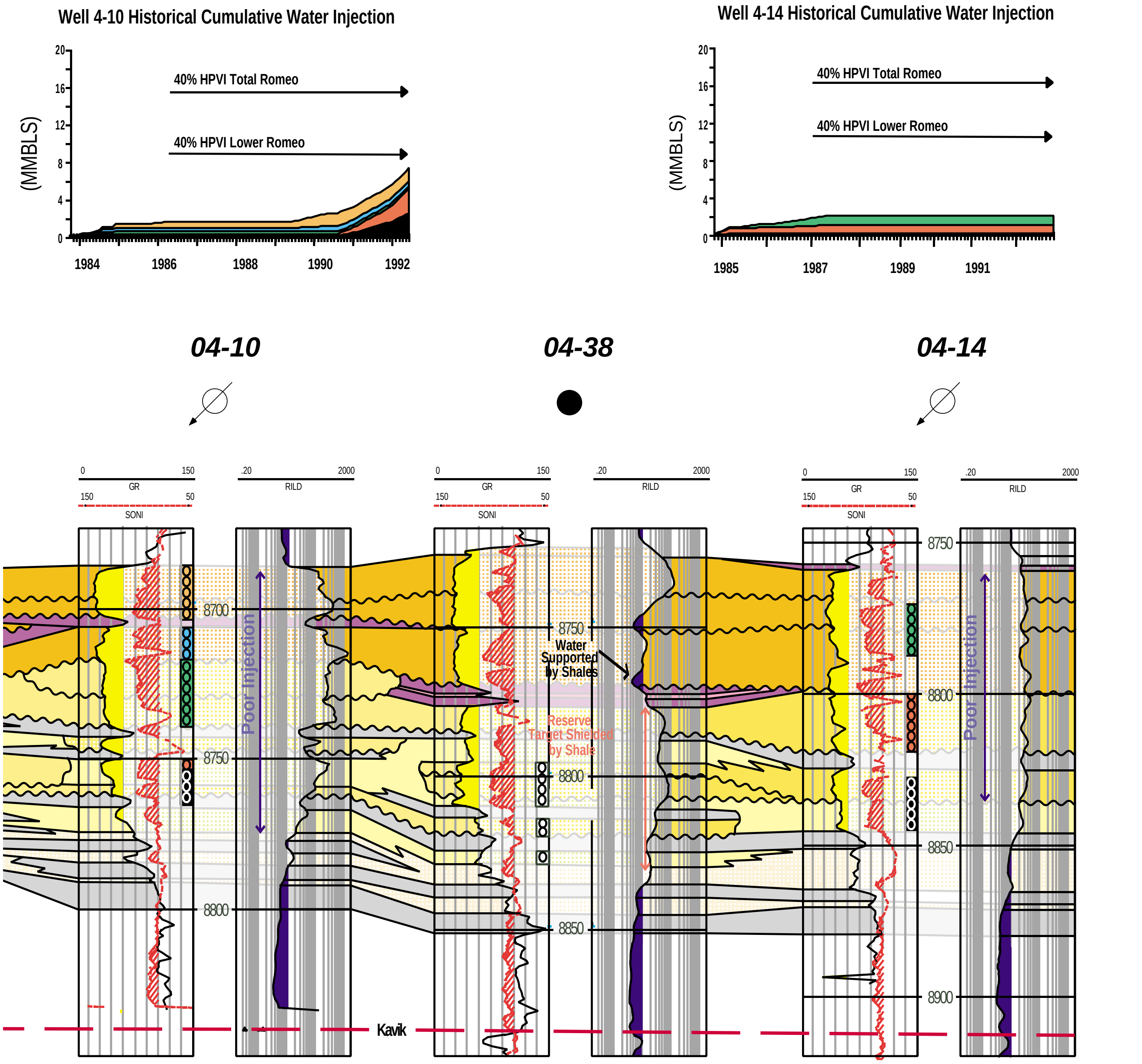


Figure 11—Continued.

Analyses of injector/producer pairs identified inadequate waterflood support (zones of low injection in wells 04-13, 04-10, and 04-14) and remaining reserve targets (bypassed oil in basal sandstones in wells 04-40 and 04-38). Interwell continuity of fluvio-deltaic sandstones and shales is shown by the correlations and is supported by the pressure-transient analysis discussed previously. Thin, extensive shales create vertical flow barriers, but also aid in waterflood containment. Model runs indicate that 40% hydrocarbon pore volume injection (HPVI) would adequately sweep infill locations at 04-40 and 04-38; however, cumulative water-injection profiles reveal overall poor water emplacement in the Romeo, except for the upper three perforated intervals in well 04-13.

A consequence of reservoir simulations of DS-04 (Lorsong et al., 1994) has been the drilling of infill wells into the Romeo interval on 40 ac (16 ha) spacing. These wells were completed only in deltaic sandstones (FA 4, distributary mouth bar and FA 6, distributary channel; Table 1). The intention was to dedicate water injection and pressure support to virgin reservoir zones and to produce from horizontal wells perforated only in the Romeo. Restricting perforations to deltaic Romeo sandstones obviates competition between low-permeability fine-grained

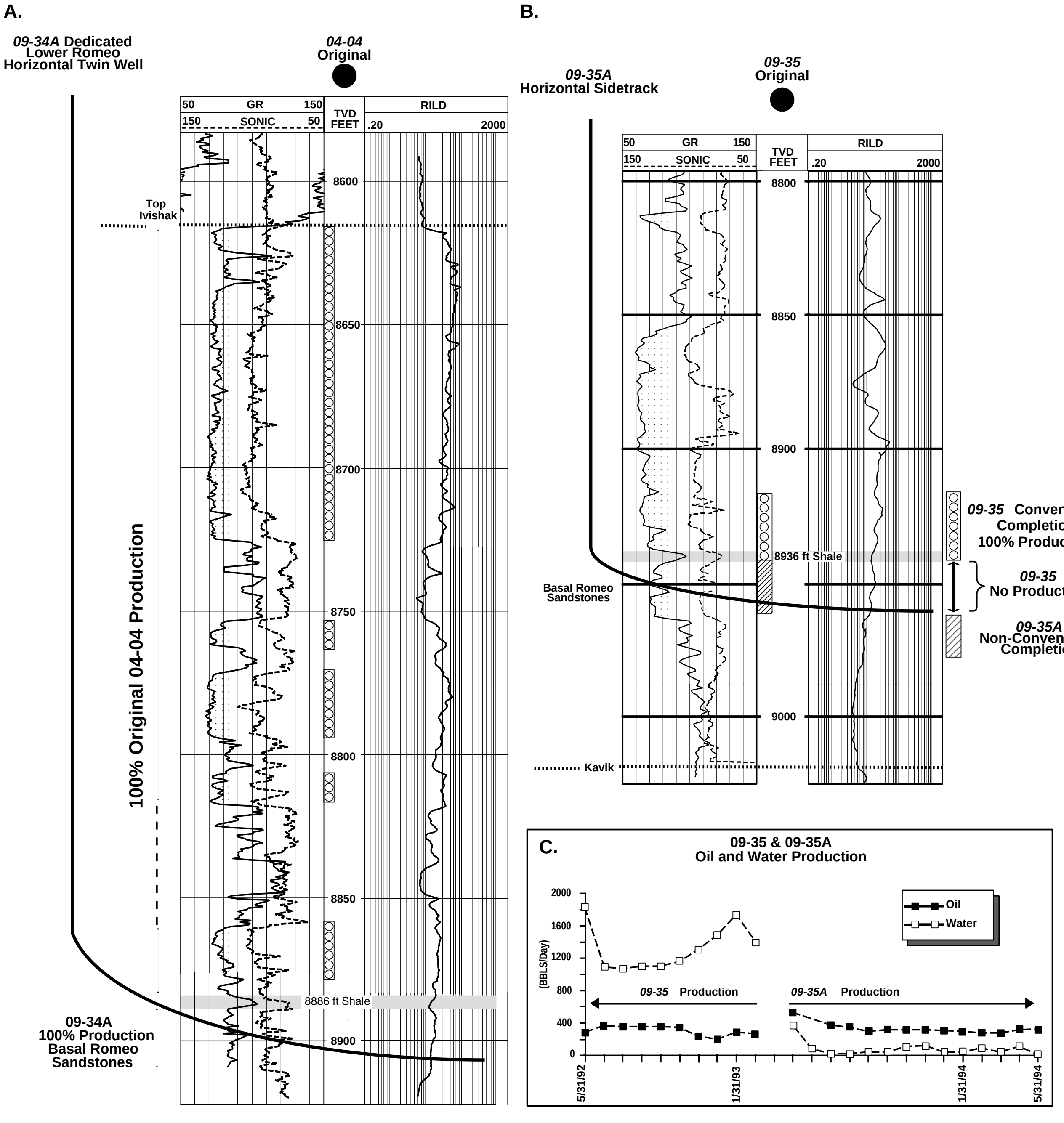


Figure 12—Wireline logs for wells 04-04 and 09-35. (A) Horizontal well 09-34A was drilled as a sidetrack to well 04-04, targeting basal sandstones and using the 8986 ft (2740 m) shale as a shield against water influx. (B) Well 09-35A is a horizontal sidetrack drilled to well 09-35. Well 09-35A was designed to produce from the basal Romeo sandstones [725 ft (221 m) slotted liner] without competition from stratigraphically higher perforations, and to use the 8936 ft (2725 m) shale as a shield from slumping water. Stippled pattern on gamma-ray logs denotes productive sandstones. (C) Comparison of oil and water production data for wells 09-35 and 09-35A. Note the slight increase in oil rate and dramatic decrease in water production from well 09-35A.

sandstones (FA 4) and overlying high-permeability sandstones and conglomerates (FA 6, FA 8, FA 9, and FA 10; Table 1). Additionally, recompletions comprising squeeze jobs and reperforations were performed to ensure stratigraphic and structural agreement between perforated zones in injection and production wells, thus increasing producible Romeo reserves.

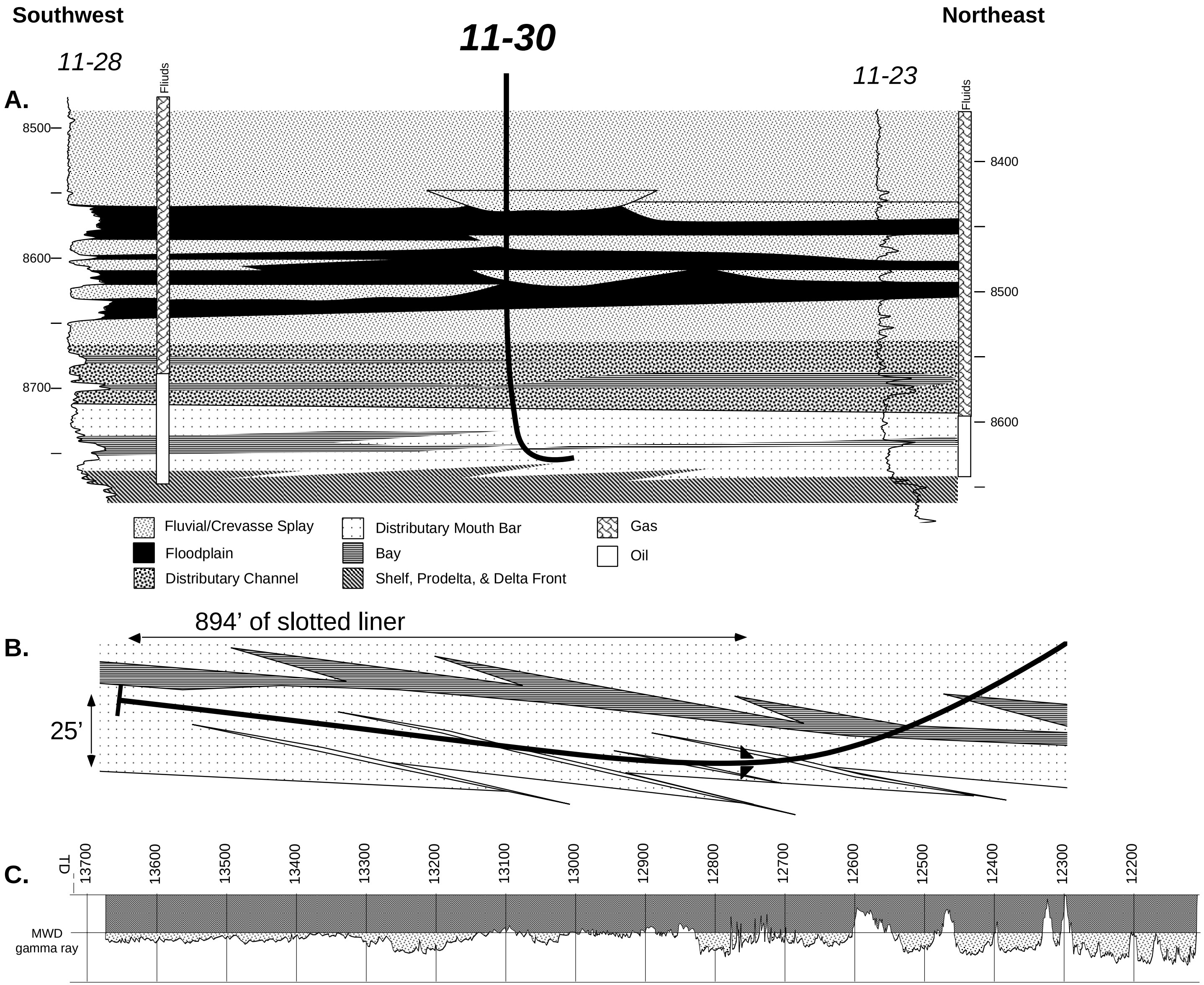


Figure 13—(A) Cross section illustrating facies association interpretations between wells 11-28 and 11-23 and the predrill strategy for placing well 11-30. The horizontal trajectory of 11-30 is perpendicular to the cross section. (B) Schematic representation of the well-bore path through distributary mouth bar sandstones beneath a bay shale. (C) MWD (measured while drilling) gamma-ray log through distributary mouth bar sandstones. Gray vs. light stippling denotes a 50 API cutoff.

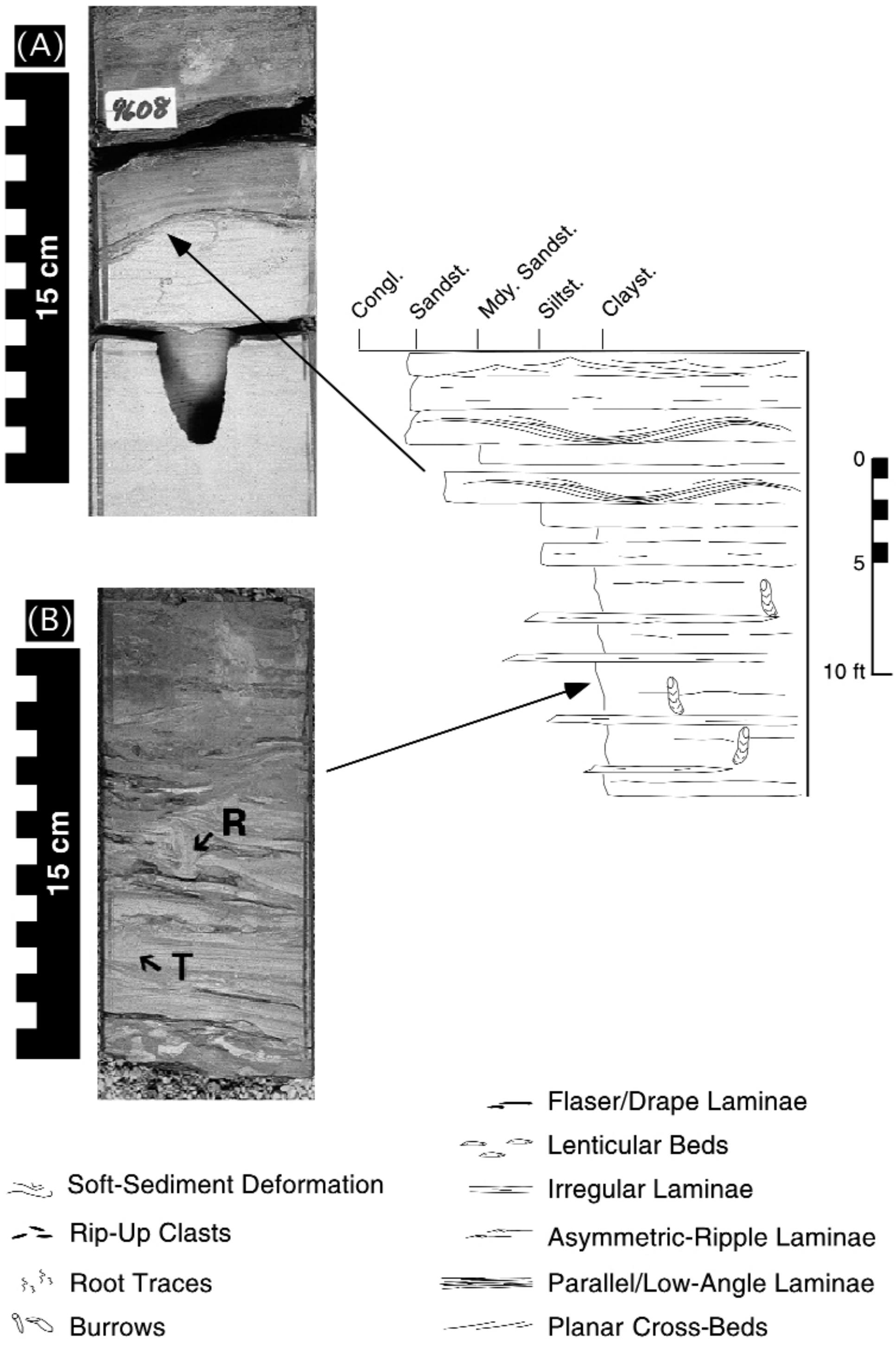


Figure 14—Representative photographs and core sketch of facies association (FA) 1. (A) Sharp lithologic contact in FA 1 (arrow) at a possible marine-flooding surface. Depth is 9608 ft (2930 m). (B) Burrowed and symmetric-ripple laminated muddy sandstone containing *Rosselia* (R) and *Thalassinoides* (T) burrows. Samples from well 09-06. Depth is 9647.5 ft (2942 m).

Nonconventional Well Completions

Horizontal Sidetracks

Maximum reserve recovery commonly is unattainable in conventionally completed wells because of hydraulic competition between multiple perforated intervals. For example, spinner logs in wells 04-04 and 09-35 indicated all production (100% flow) came from perforations in sandstones above shales at 8886 and 8936 ft (2710 and 2725 m), respectively, (Figure 12). Oil rates from these high-quality fluvial sandstones in well 04-04 (Figure 12A) approximated 2100 BOPD (bbl of oil per day) with a gas-to-oil ratio (GOR) of 14,000, whereas oil rates from 09-35 were

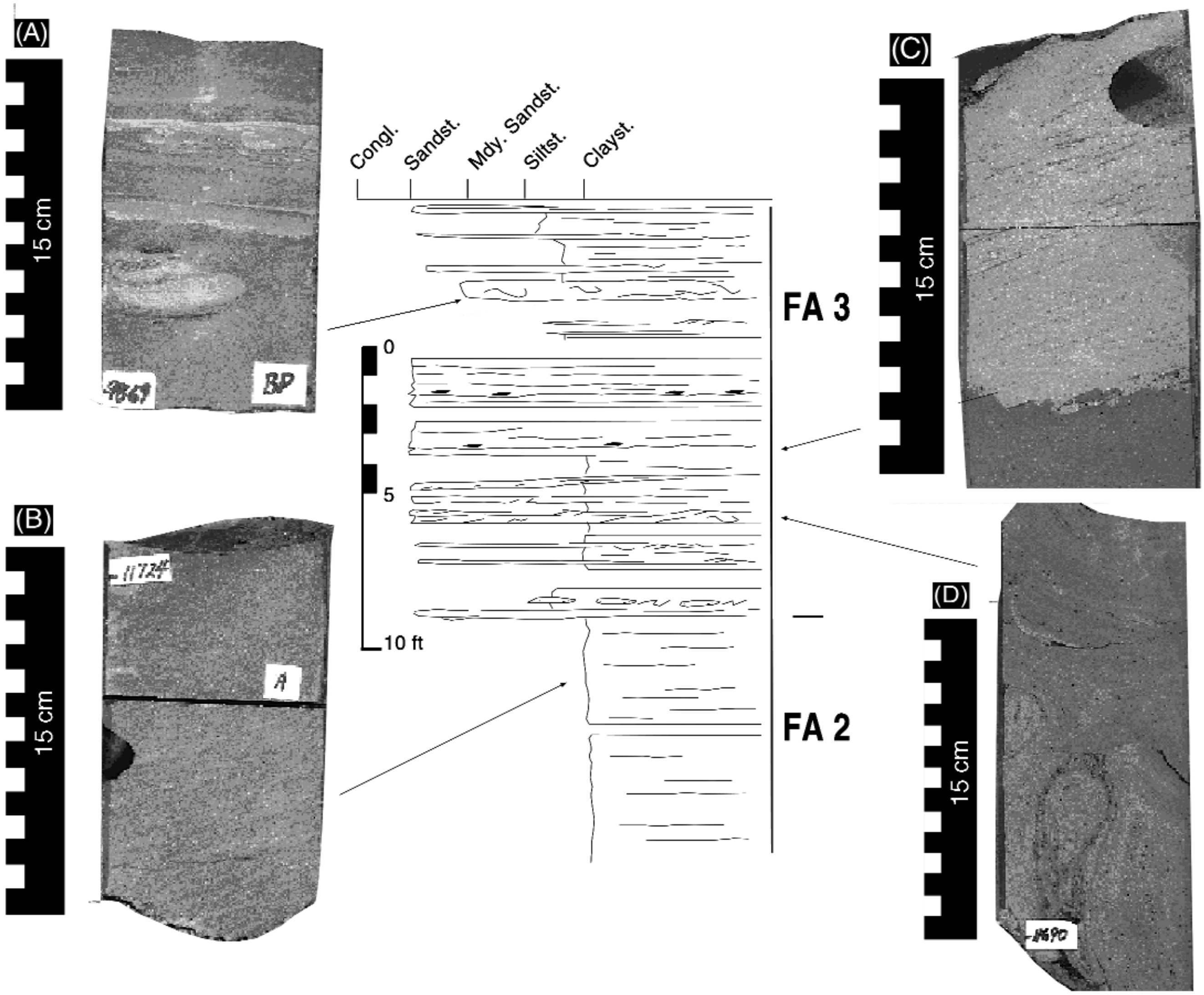


Figure 15—Representative photographs and core sketch of facies association (FA) 2 and FA 3. (A) Load casts in FA 2 mudstone (well 15-10, 9869 ft; 3010 m). (B) Deformed muddy FA 2 siltstone (well 15-21, 11,724 ft; 3575 m). (C) Flat-laminated to current-ripple laminated FA 3 sandstone. Note sharp sandstone base and mudstone chips (well 15-21, 11,717.5 ft; 3573 m). (D) Soft-sediment deformed (dewatering and slump?) FA 3 silty sandstone with abundant carbonaceous debris (well 15-21, 11,690 ft; 3565 m).

300 BOPD (Figure 12B, C). Both wells experienced high (up to 85%) and increasing water cuts. Nonrecovery of oil from underlying, low-permeability sandstones (approximately 80–200 md) constituted bypassed reserves.

To recover bypassed reserves from basal deltaic sandstones, horizontal sidetrack wells, 09-34A and 09-35A, were drilled as dedicated lower Romeo twins to wells 04-04 and 09-35 (Figure 12A, B). Distributary mouth bar sandstones were targeted and the well plans were designed to use the 8886 ft (2710 m) shale in well 04-04 and the 8936 ft (2725 m) shale in well 09-35 as shields against water influx. The placement of the 09-34A horizontal well bore within deltaic sandstones resulted in new production from this interval at an oil rate of 700–800 BOPD and a significant decrease in water and gas production (water cut 2% and GOR 800). Increased oil rates and a decreased water fraction were also realized in well 09-35 (Figure 12C). Although spinner logs were not run across the lower Romeo, these wells confirmed the producibility of basal low-permeability deltaic sandstones with a low water cut. Established productivity from this stratigraphic interval was the catalyst for a successful series of dedicated lower

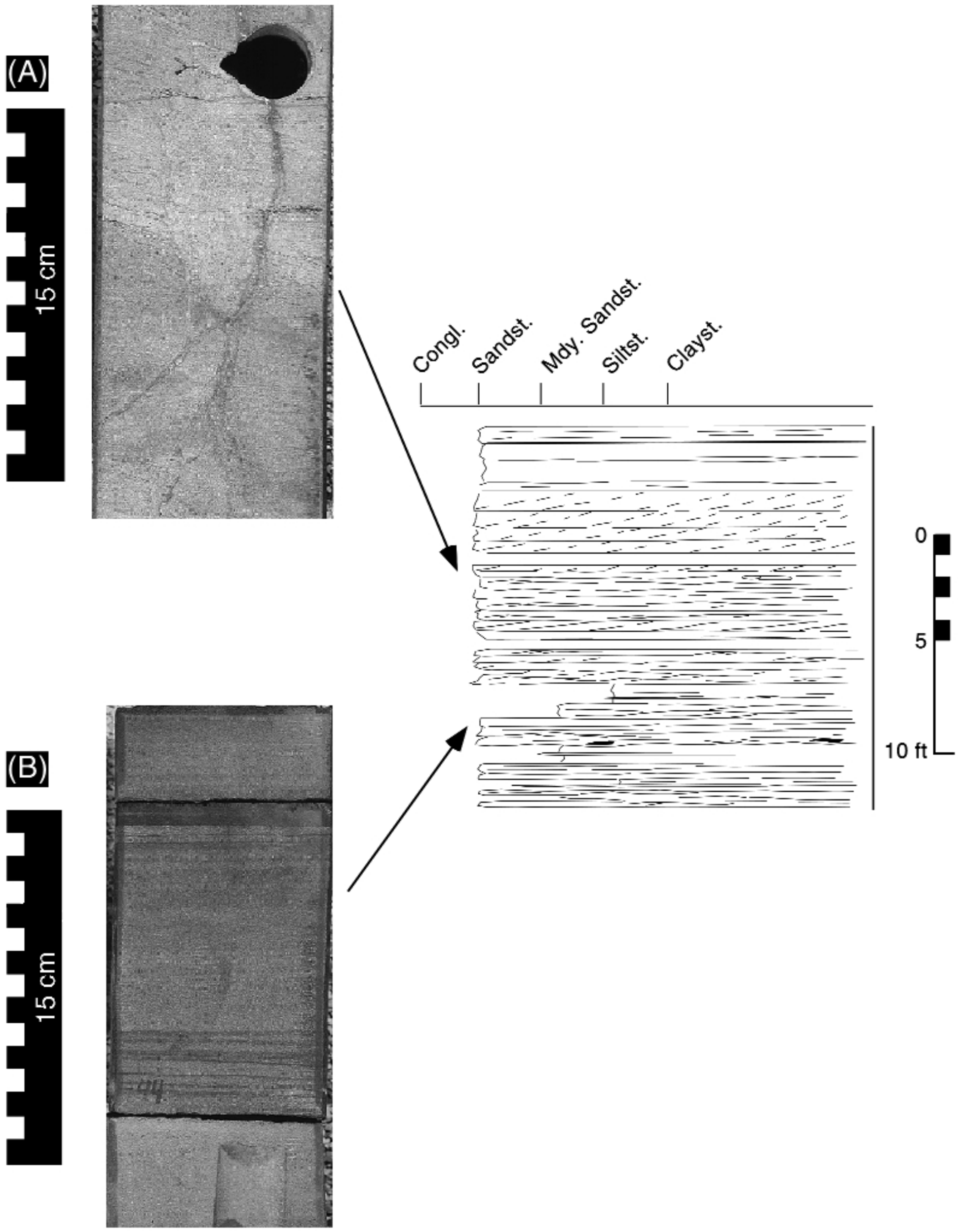


Figure 16—Representative photographs and core sketch of facies association (FA) 4. (A) Water-escape pipes and synsedimentary faults in FA 4 sandstone (well 09-44, 11,122 ft; 3392 m). (B) Flat-laminated FA 4 sandstone with laminae accentuated by macerated organic material (well 15-10, 9844 ft; 3002 m).

Romeo production and water-injection wells in areas where production from lower quality deltaic reservoirs and higher quality fluvial reservoirs overlap.

Upstructure 80 ac (32 ha) Infill

Field pressure support is maintained via gas-cap expansion, thus ongoing oil production has reduced the total oil column available for development. Upstructure along the northern field boundary, oil columns less than 52 ft (16 m) thick, contained within lower Romeo deltaic sandstones, commonly are the only remaining target. Additionally, reserves cannot drain downdip because of the basinward decrease in permeability that occurs as distributary channel and distributary mouth bar deposits grade into low-permeability delta-front and prodelta deposits. Where completed in these remaining oil wedges, conventional wells tend to be low-rate producers and experience early gas breakthrough. By increasing reservoir exposure and stand-off to gas, horizontal wells produced with low drawdown pressures target the lowest producible sandstones of the Romeo and offer a viable alternative to vertical wells for recovering the remaining oil.

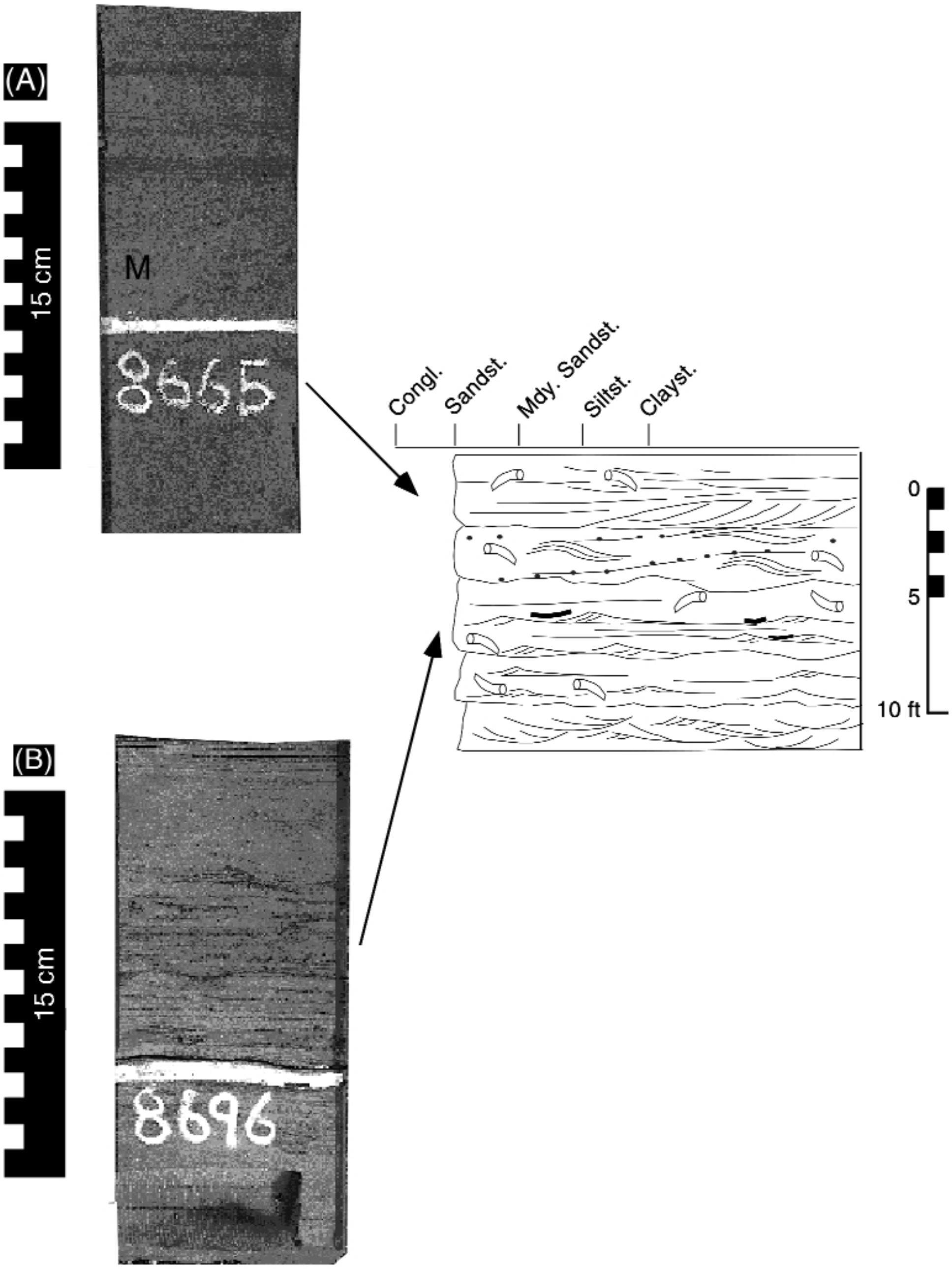


Figure 17—Representative photographs and core sketch of facies association (FA) 5. (A) *Macaronichnus simplicatus* (M) burrows in FA 5. (B) Symmetric-ripple laminated and burrowed FA 5 sandstone.

The 11-30 horizontal well (Figure 13) was drilled at one of the few remaining 80 ac (32 ha) locations downdip of the gas cap limit. This well illustrates how a linkage of reservoir description and drilling technology can culminate in a successful Romeo development. Prognoses predicted a 19-ft- (6-m-) thick distributary mouth bar sandstone (FA 4) at the base of the Romeo [8800 ft (2684 m) total vertical depth, Figure 13A] and an overlying extensive interdistributary bay shale (FA 7) that could act as a shield from the gas cap. Reservoir-target choices were optimized using both net sandstone and facies association maps, as well as geostatistical realizations of coeval facies associations. Potentially gas-conductive faults were avoided through detailed mapping using three-dimensional seismic data.

The well was designed to achieve a 90° hole angle at casing point in the targeted sandstone, drill out a horizontal section, and complete with a slotted liner. After setting casing, an 894-ft- (272-m-) long horizontal section was drilled entirely within the targeted sandstone (Figure 13B). Of this, 475 ft (144 m) was

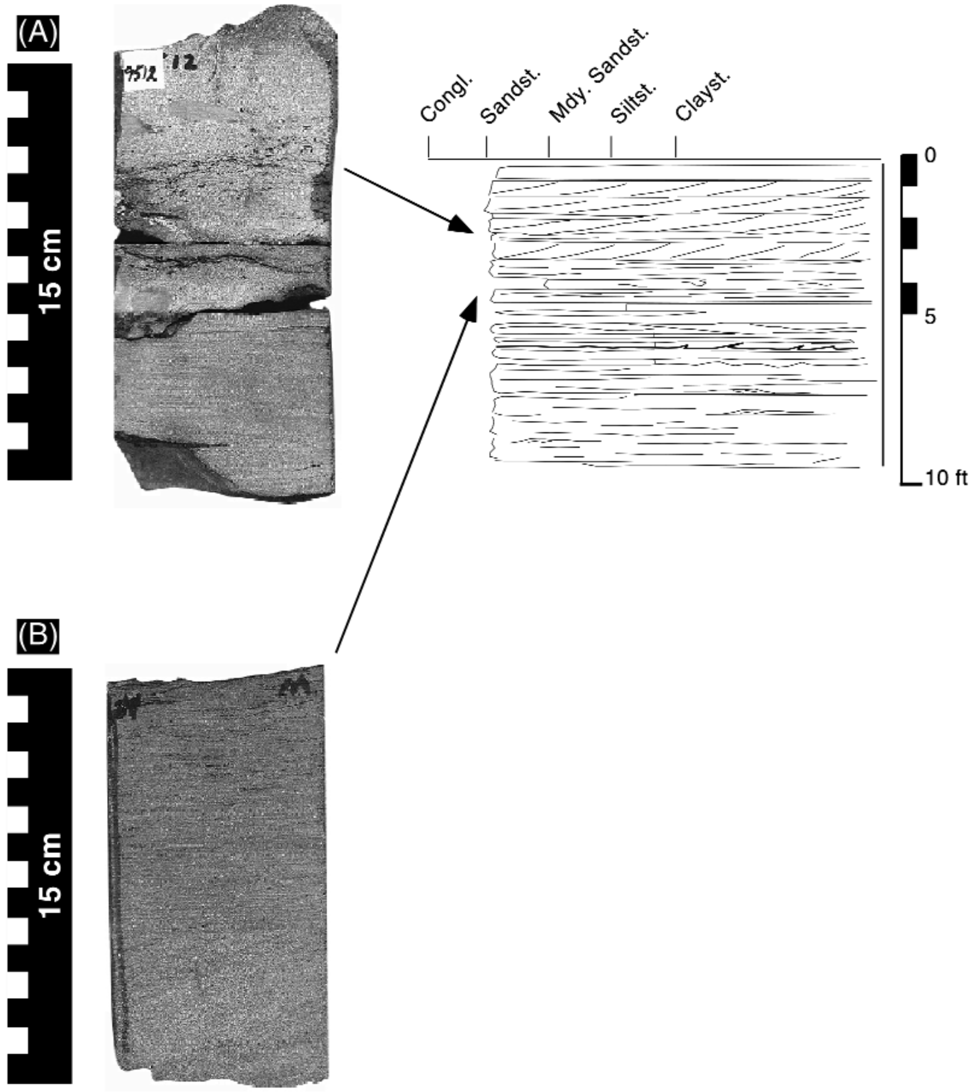


Figure 18—Representative photographs and core sketch of facies association (FA) 6. (A) Basal FA 6 sandstone containing organic debris and clay clasts (well 09-06, 9512 ft; 2901 m). (B) Cross-bedded and asymmetric-ripple laminated FA 6 sandstone (well 09-06, 9499.3 ft; 2897 m).

determined to be net pay (based on gamma-ray cutoff and well cuttings) (Figure 13C). Current production has stabilized at 1600 BOPD with a low gas-to-oil ratio. This well was largely successful due to an improved understanding of sand-body geometry and the use of shale as a shield from the gas cap.

CONCLUSIONS

Stratigraphic analyses of basal Ivishak sandstone deposits in Prudhoe Bay field, Alaska, using depositional interpretations based on core data and concepts of genetic stratigraphy and incorporating well history data have demonstrated that the basal section of the reservoir comprises coarsening-upward sandstone sequences interbedded with shales. Strata were deposited in river-dominated deltas. Mudstones deposited following delta-lobe abandonment separate the delta lobes. In the eastern portion of the field, fluvio-deltaic deposits are overlain by extensive flood plain deposits.

Genetic-stratigraphic correlations revised traditional lithostratigraphic depictions of tabular reservoir zones between a basal marine shale and overlying nonmarine strata. This stratigraphic reassessment depicts en echelon, offlapping fluvially dominated deltaic wedges. Within a discrete deltaic complex, productive intervals include, in order of increasing relative quality, (1) distributary mouth bar and (2) distributary channel facies associations. Marine and bay shales separating delta lobes form locally extensive, but not field-wide, flow barriers. Reservoir compartmentalization is most pronounced distally, where deltaic

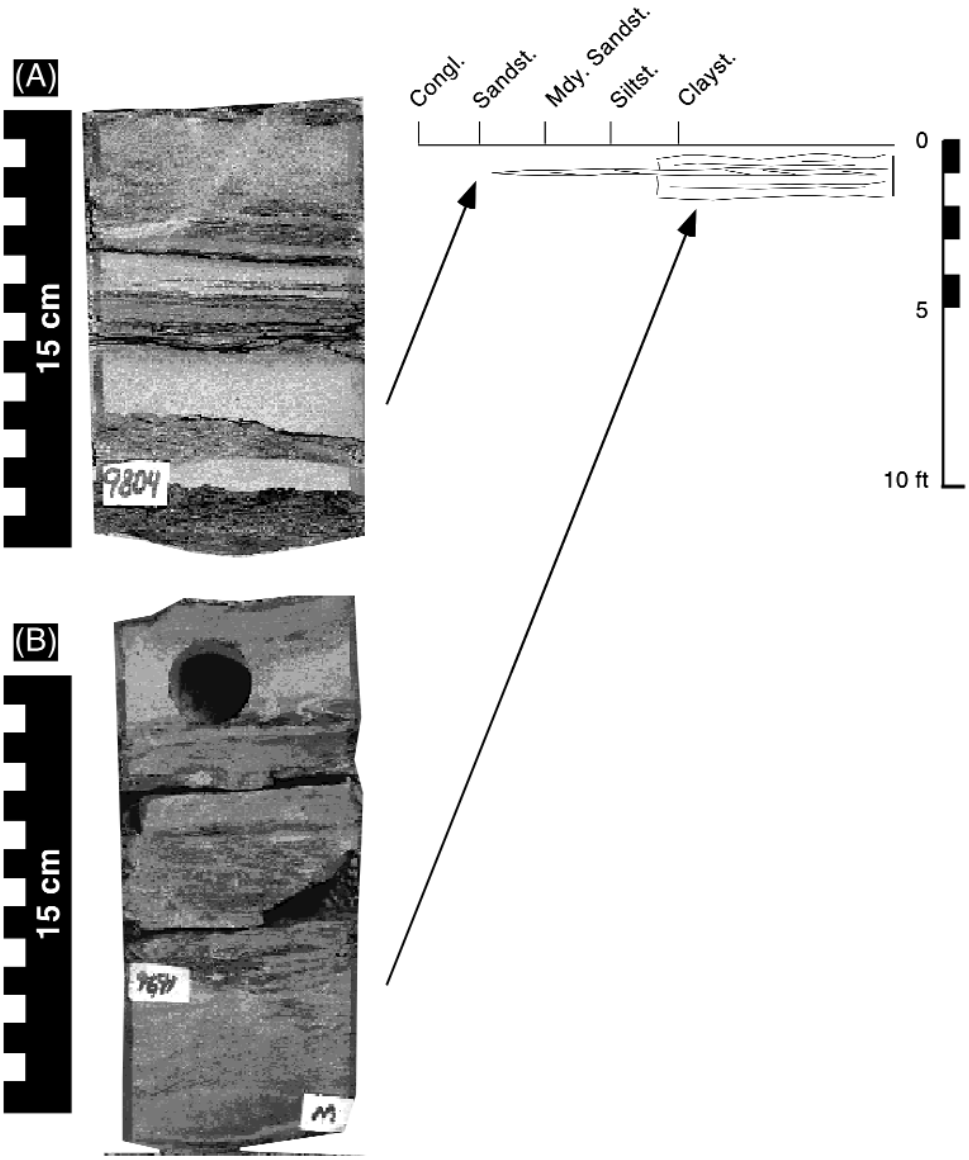


Figure 19—Representative photographs and core sketch of facies association (FA) 7. (A) Heterolithic FA 7 siltstone and mudstone (well 15-10, 9804 ft; 2990 m). (B) Sandy burrowed FA 7 mudstone with (syneresis?) cracks; note sharp (erosional?) upper and lower surfaces of sandstones (well 02-14, 9691 ft; 2955 m).

sandstones are overlain by and pinch out into marine shale. Proximally, fluvial and deltaic sandstones are juxtaposed across erosional contacts, improving reservoir continuity.

Economic oil rates can best be attained and maintained from horizontal wells targeted at specific reservoir intervals and using laterally extensive shales to provide vertical shields from gas and water. Thin, continuous shales strongly control vertical fluid movements within the reservoir. Detailed modeling of shale continuity, connectivity, and placement is vital in accurately assessing remaining reserves' potential and location. These results could not have been achieved with reservoir models that did not integrate detailed geology and well history data.

APPENDIX

Detailed Sedimentary Descriptions of Facies Associations and Their Depositional Interpretations

Facies Association 1 (Marine Shelf)

Dark gray, massive to laminated mudstone interbedded with very fine grained sandstones comprise this facies association, which is restricted to the Kavik Member of the Ivishak Formation (Figures 2 and 14). Sandstones exhibit symmetric-ripple and low-angle intersecting laminae. Burrow abundance is high to moderate and decreases upward in the sandier facies. Trace fauna include examples of dwarf *Teichichnus, Rosselia, Planolites,* and *Zoophycos*. Pyrite blebs and nodules, up to a few centimeters across, are ubiquitous.

FA (facies association) 1 characterizes the lower Kavik Member of the Ivishak Formation, and is organized into coarsening- and thickening-upward units ranging from 6 to 100 ft (2 to 30 m) thick. Tops of coarsening-upward subunits are expressed as sharp

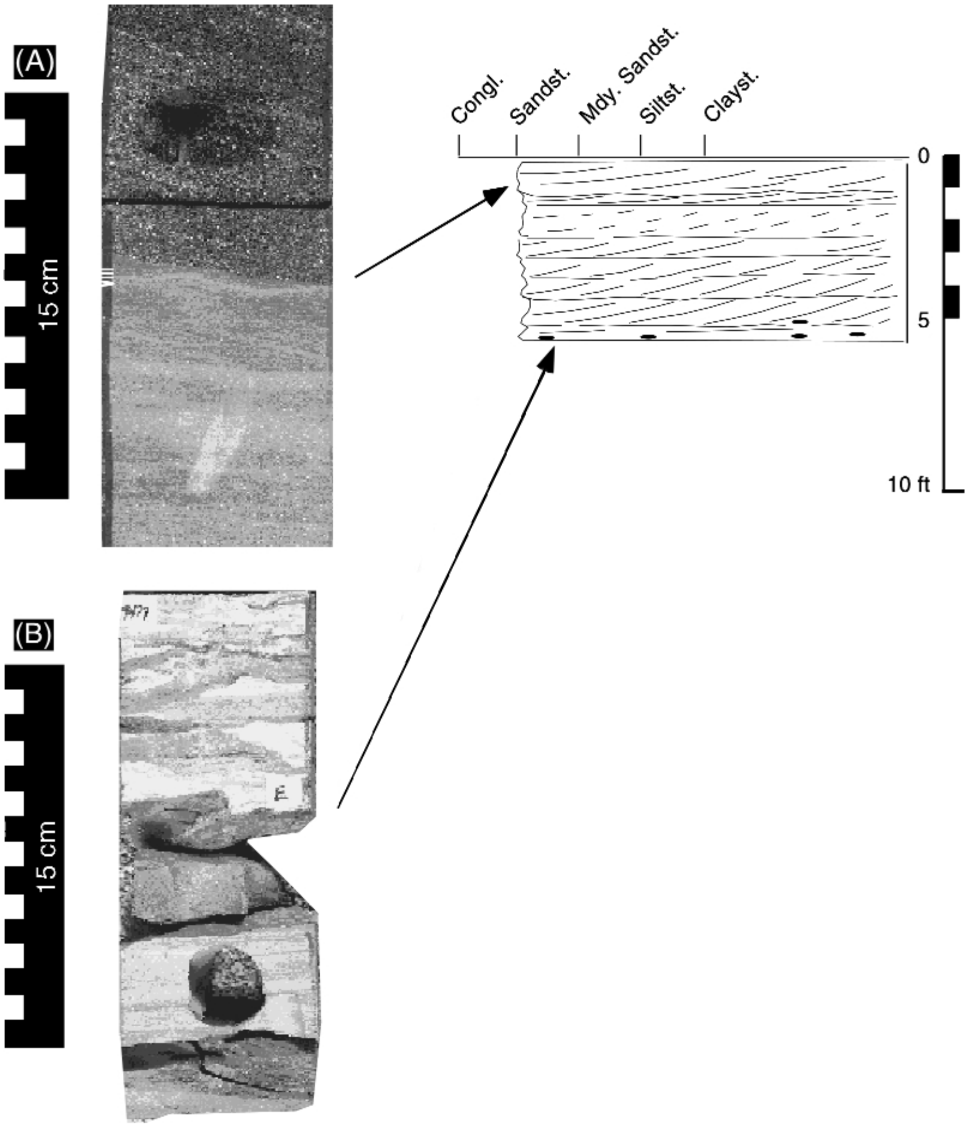


Figure 20—Representative photographs and core sketch of facies association (FA) 8. (A) Sharp-based, cross-bedded FA 8 sandstone (well 03-10, 9588.5 ft; 2924 m). (B) Clay-clast conglomerate in basal FA 8 sandstone (well 09-06, 9477 ft; 2890 m) overlying interbedded bay fill (FA 7).

transitions from sandstone into mudstone. Three such units can be correlated and mapped with some confidence across the study area, although the upper unit is more difficult to recognize in updip wells.

Sedimentary structures and trace fossils (*Cruziana* ichnofacies) (Pemberton et al., 1992) indicate marine deposition in shallow-shelfal depths. Stunted burrows may indicate temperature or turbidity stresses (G. W. Pemberton, 1993, personal communication). Interbedded lithologies, in addition to bioturbation and symmetric-ripple laminae, suggest variable depositional energies. Low-angle intersecting laminae (possible hummocky cross-stratification) imply storm-wave processes and are thought to be characteristic of deposition below fair-weather wave base. Shelfal depths are estimated to have been 250 ft (76 m) based on the maximum thickness of coarsening-upward cycles ≤108 ft (≤33 m) plus the assumption that the shallowest facies were deposited below fair-weather wave base. Sharp upper contacts between sandstones and mudstones represent deepening or abandonment across flooding surfaces (van Wagoner et al., 1990; Bhattacharya, 1993).

Facies Association 2 (Prodelta)

FA 2 is similar to FA 1; both coarsen upward and are composed dominantly of dark gray mudstone (Figure 15); however, FA 2 is easily distinguished from FA 1 by its pervasive physical sedimentary structures indicating rapid sediment deposition and instability and by significantly decreased biogenic traces. FA 2 mudstones are interbedded with siltstone and very fine grained sandstone beds. FA 2 always overlies FA 1. Lithofacies are organized into coarsening- and thickening-upward bed sets ranging from 6 to 60 ft (2 to 18 m). Upper contacts with the sandier facies of the Ivishak sandstone are gradational to sharp.

Abundant normally graded laminae, soft-sediment deformation, and the scarcity of wave-formed features suggest rapid rates of sediment accumulation in the prodelta region of a river-dominated delta (Scruton, 1960; Coleman and Gagliano, 1965; Coleman and Prior, 1982). Magnesium-rich siderite nodules (Mozely, 1989), as well as body fossils and trace fauna, indicate a marine setting, although burrow scarcity implies conditions were not conducive for prolific faunal activity. Suppressed biogenic activity reflects fluctuating salinities or temperatures

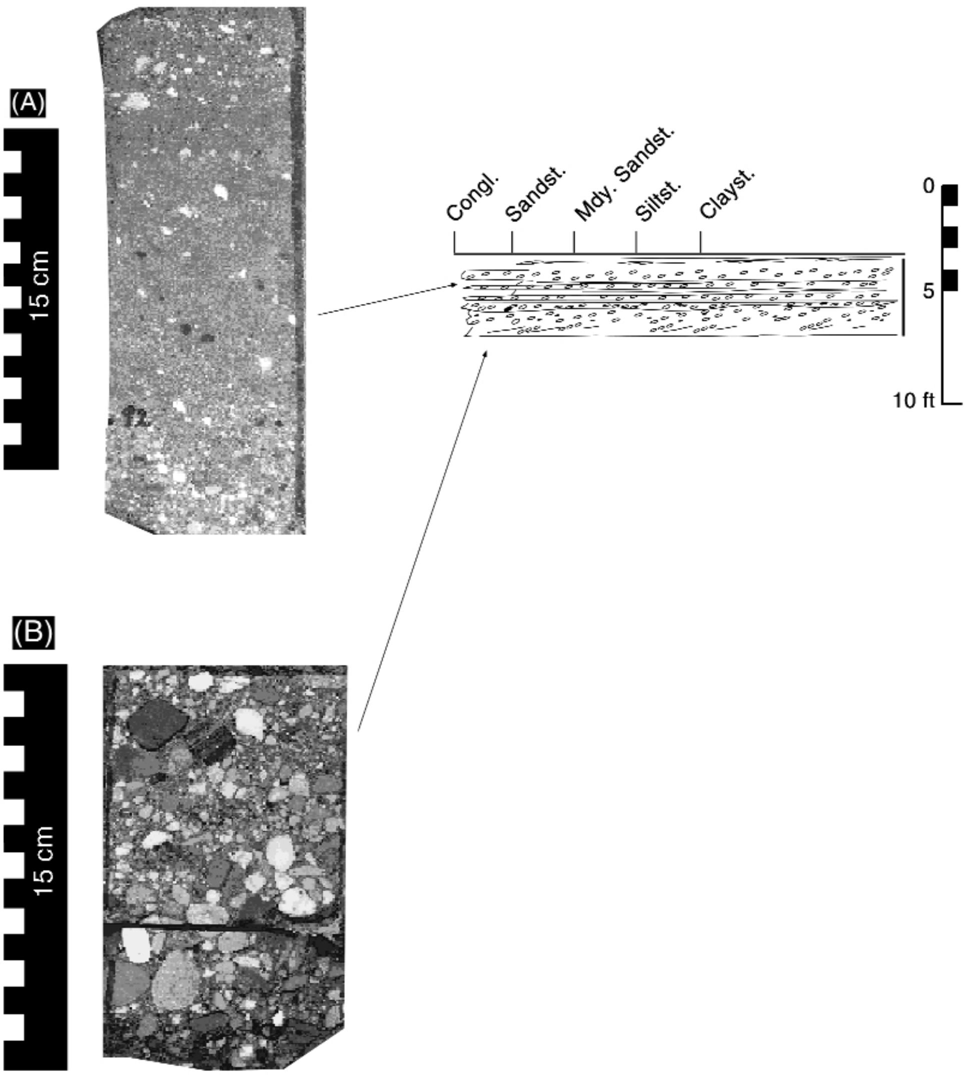


Figure 21—Representative photographs and core sketch of facies association (FA) 9 and FA 10. (A) Cross-bedded FA 9 sandstone (well 03-06, 9782 ft; 2983 m). (B) Variably rounded black, gray, and white chert pebbles in FA 10 (well 03-10, 9475 ft; 2889 m).

combined with a large suspended-sediment load and rapid deposition. Much of the sediment probably was deposited through gravitational settling from suspended-sediment plumes. Symmetric-ripple laminations suggest minor reworking by storm waves and deposition below fair-weather wave base. Dewatering and loading features resulted from sediment instabilities and density contrasts between rapidly deposited clay, silt, and sand. Maximum water depths approached 213 ft (65 m).

Facies Association 3 (Delta Front)

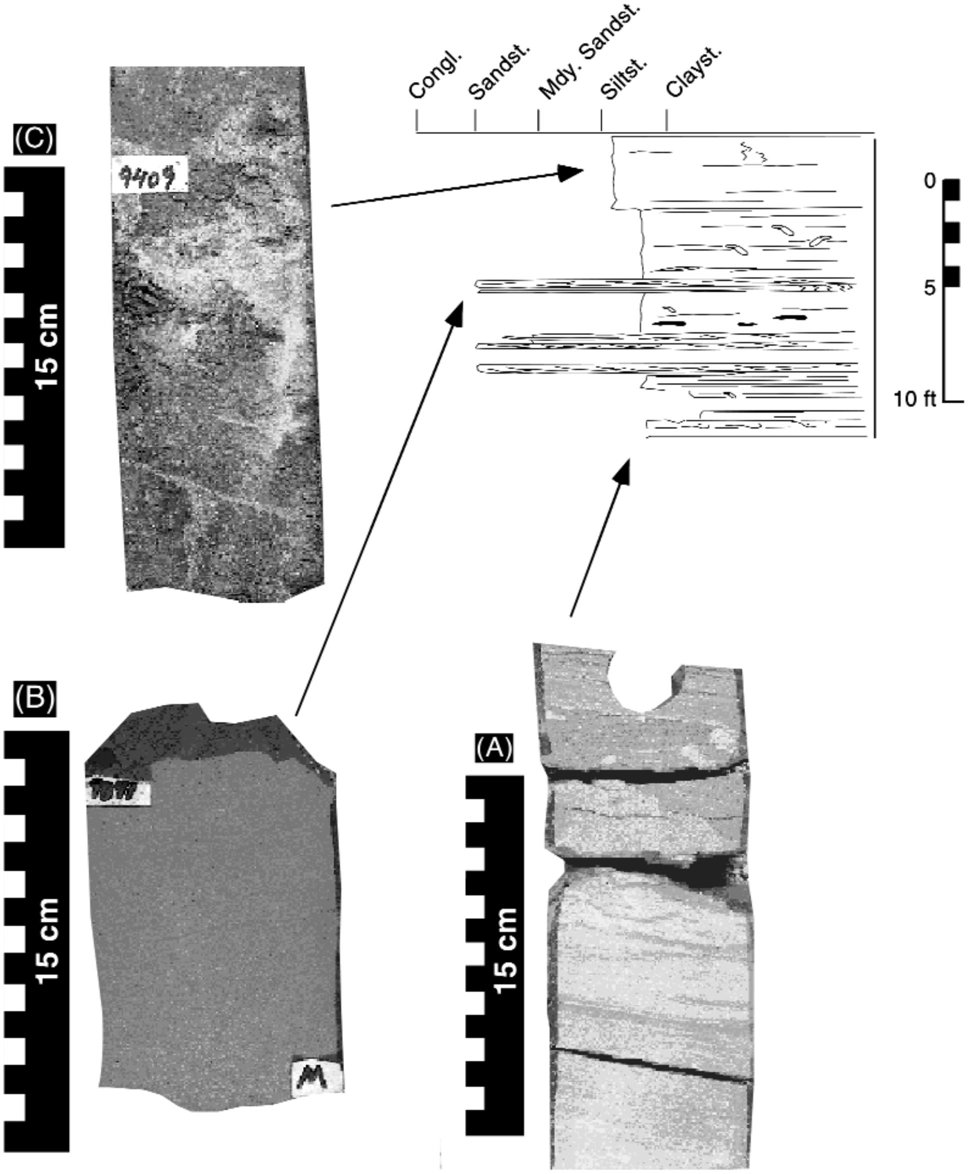
FA 3 comprises dominantly dark gray mudstone and very fine grained sandstone (Figure 15). These lithologies form coarsening-upward or irregularly bedded packages up to 37 ft (12 m) thick. Sandstone beds may reach 3 ft (1 m) thick, are commonly sharp based with a mud chip lag and are normally graded. FA 3 gradationally overlies FA 2 and the contact is placed where sandstone exceeds siltstone abundance; however, in places, FA 3 is missing. At these locations, FA 2 mudstone is abruptly overlain by FA 4 sandstone. In a few cores, FA 3 is sharply overlain by FA 2.

A delta-front depositional setting is suggested for FA 3. Lithologies and sedimentary structures indicate deposition in water depths shallower than those inferred for FA 2 and FA 1 (<100 ft; 30 m). Asymmetric-ripple laminations associated with normally graded laminae imply alternating traction-current and suspension deposition. Periodic rapid sediment accumulation is indicated by climbing current-ripple laminae. Rare wave-ripple lamination and hummocky cross-stratification indicate the minor influence of periodic storms. Soft-sediment deformation features are ubiquitous, and a nearly complete lack of trace fauna indicate inhospitable conditions caused by substrate instability, turbidity, salinity, or energy stresses.

Facies Association 4 (Distributary Mouth Bar)

FA 4 is dominantly sandstone and ranges from 3 to 43 ft (1 to 13 m) in thickness. FA 4 generally exhibits an upward increase in grain size from very fine to fine-grained sandstone. Sandstones are massive to parallel laminated. Disseminated carbonaceous debris ("coffee grounds") drape and accentuate laminae and thin beds. Cross lamination is rare (Figure 16). Soft-sediment deformation

Figure 22—Representative photographs and core sketch of facies association (FA) 11, FA 12, and FA 13. (A) Heterolithic FA 11 sandstone, siltstone, and mudstone (well 02-29A, 9627.5 ft; 2936 m). (B) Asymmetric-ripple laminated, very fine grained FA 12 sandstone (well 03-06, 9841 ft; 3001 m). (C) Pedogenically altered and mottled FA 13 mudstone (well 09-06, 9409 ft; 2869 m).



features are common. Biogenic structures are sparse to absent (Table 1). FA 4 exhibits gradational to sharp contacts with underlying facies associations (FA 3 and FA 2). FA 2 or FA 7 mudstones or FA 6 sandstones commonly overlie FA 4.

FA 4 is interpreted as distributary mouth bar deposits within a fluvially dominated delta. Water depths in which distributary mouth bars accumulated probably did not exceed 30 ft (9 m). The predominance of flat-laminated sandstones and organic laminae suggests suspension fallout and sediment deposition from hypopycnal plumes as flow expansion at distributary mouths caused current deceleration. Nested fining-upward units may represent waning-flood flows. Asymmetric current-ripple lamination and scours indicate deposition and erosion by traction currents emanating from distributary channels. Localized low-angle stratification and symmetric- and combined-flow ripple lamination suggest wave and storm influence. Siltstone and mudstone layers represent low-energy periods during which mouth bars were temporarily abandoned and draped with mud.

Facies Association 5 (Shoreface)

FA 5 (Figure 17) is rare. It is similar to FA 4 in that it coarsens upward and is dominantly sandstone. FA 5 comprises very fine to fine-grained sandstone with numerous siltstone and mudstone drapes and may reach 60 ft (18 m) in thickness. Symmetric- and combined-flow ripple laminae imply a dominance of wave processes. Unlike other sandy facies associations, FA 5 is moderately burrowed. Trace fauna include *Macaronichnus simplicatus*, *Paleophycus*, *Teichichnus*, and *Skolithos*. Burrows commonly are confined to the siltier tops of normally graded sandstone beds.

This facies association is interpreted as representing deposition in a wave- and storm-dominated shoreface. Its paleogeomorphic setting is similar to that of FA 4, except that FA 5 was deposited away from the influence of distributary channels. Parallel and symmetric-ripple lamination, hummocky cross-stratification, and burrowing indicate dominance of marine processes. The low trace faunal diversity implies that this setting may have been stressful to organisms, possibly reflecting a deltaic influence (G. W. Pemberton, 1993, personal communication).

Facies Association 6 (Distributary Channel)

FA 6 is common in the lower and middle portions of the Romeo interval in all wells and commonly erosionally overlies FA 4 or FA 3 (rarely, FA 2). FA 6 is dominantly a fine-grained sandstone with minor siltstone and claystone (Figure 18). FA 6 may reach 60 ft (18 m) in thickness and can be subdivided into a series of stacked fining-upward subunits of roughly 10 ft (3 m) thick. Scoured bases marked by mud-chip lags up to 0.3 ft (0.1 m) thick are common. Fining-upward units show an upward transition from cross-bedding to parallel stratification to ripple-laminated beds.

FA 6 is interpreted as distributary channel deposits. Channel erosion is indicated by the scoured bases and the presence of a basal lag. Fining-upward units represent waning energy conditions following flood passage or as the channel is progressively filled. Sedimentary structures indicate unidirectional flow. Multiple fining-upward units suggest aggradational stacking of channel sandstones. Juxtaposition of FA 6 with shallow-marine or deltaic facies associations suggests that the channels were deltaic distributaries rather than fluvial channels.

Fining-upward packages 3–9 ft (1–3 m) in thickness represent relatively complete cycles of distributary channel deposition and abandonment; therefore, these thicknesses approximate paleodistributary channel depths. Thicker occurrences of FA 6 (i.e., up to 59 ft; 18 m) represent stacked distributary channel deposits. Where distributary channel deposits overlie FA 2, an anomalous facies break is indicated (shallow-water facies over deep-water facies). The absence of delta-front, distributary mouth bar, or shoreface deposits (i.e., FA 3, FA 4, FA 5) possibly indicate (1) a relative drop in sea level, (2) exceptional distributary channel progradation and scour, (3) slumping on an unstable delta front, or (4) some combination of these processes.

Facies Association 7 (Swamp, Marsh, Interdistributary Bay, Bay)

Dark- to medium-gray heterolithic claystone and siltstone and minor sandstone comprise FA 7 (Figure 19). FA 7 may range up to 20 ft (6 m) thick and caps either FA 4, FA 5, or FA 6. More commonly, FA 7 is sharp-based and 1–5 ft (0.3–1.5 m) thick. FA 7 can be gradationally overlain by FA 3 or FA 4 or erosively capped by FA 6 or FA 7.

Claystone to sandstone lithofacies are very thinly interbedded. Siltstones are commonly normally graded. Sandstones are symmetrically and asymmetrically ripple laminated and may form lenticular beds averaging 1 in. (2.5 cm) thick. Other features include small-scale loading, mud cracks, and syneresis cracks. Fractures are common. Rare trace fossils include *Arenicolites*.

FA 7 is interpreted as having been deposited in a shallow-water subtidal setting. The presence of starved symmetric- and asymmetric-ripple laminations suggests wave and tidal processes affected these areas. Syneresis cracks may indicate brackish conditions (Plummer and Gostin, 1981; Bhattacharya and Walker, 1992). The linkage with facies associations 4 and 6 suggests a muddy deltaic plain. Depositional environments could include interdistributary bays or larger bays fringing a delta lobe, poorly drained swamps, and marshes.

Facies Association 8 (Fluvial Channel)

This facies association comprises multiple, fining-upward units of medium- to fine-grained sandstones that individually average 10–15 ft (3–5 m) in thickness (Figure 20). Amalgamated units up to 42 ft (13 m) thick occur.

Fining-upward subunits have sharp to erosional bases commonly mantled by a lag of mudstone chips, siderite clasts, chert pebbles, and granules. Medium-grained sandstones are predominantly trough and planar-tabular cross-bedded in sets 1–3 ft (0.3–1 m) thick. Fine-grained sandstone commonly is cross-bedded to flat stratified. Laminated to asymmetric current-rippled very fine grained sandstone constitutes a minor proportion of FA 8. Carbonaceous material usually is absent. Thin units of siltstone and claystone may cap the fining-upward subunits.

FA 8 is most common in the middle and upper portions of the Romeo interval. It is distinguished from FA 6 by its greater proportion of medium-grained sandstone, the presence of chert granules and pebbles, and lack of carbonaceous material. FA 8 also occurs at a higher stratigraphic position. FA 8 commonly overlies FA 4, FA 6, or FA 7.

FA 8 is interpreted as a fluvial-channel deposit. Its coarse-grained texture and lack of association with deltaic deposits indicates a nonmarine depositional setting. The high proportion of sandstone, numerous scours, internal stratification, and the lack of inclined mudstone drapes (i.e., lateral accretion sets) suggest deposition in low-sinuosity, sandy, braided-river channels approximately 15 ft (5 m) deep.

Facies Association 9 (Fluvial Channel)

FA 9 consists of stacked, sharp to erosional based, fining-upward units of coarse- to fine-grained sandstone with interbedded pebbly sandstone and sandy conglomerate (Figure 21). It averages 10–20 ft (3–6 m) in thickness. The maximum thickness observed is 15 m (46 ft). Conglomerates are commonly poorly sorted and matrix-supported (medium-grained sandstone). Pebbly sandstone may be draped by ripple-laminated very fine grained sandstone, siltstone, and thin mudstone layers. Cobble-size material is rare.

Sandy conglomerates and pebbly sandstones are poorly stratified to cross-bedded. Pebbles are well rounded and maximum clast size is approximately 0.4 in. (1 cm). Cross sets ranging from a few to 11 in. (30 cm) thick contain normally graded avalanche beds, creating a distinct arrangement of conglomerate/sandstone couplets.

This facies association represents the coarse-grained pebbly deposits of fluvial channels. Thin conglomerates (pebble and clay clast) at the bottoms of sharp-based sandstone beds correspond to channel-lag deposits. Interbedded conglomerate, pebbly sandstone, and sandstone represent channel-bar deposits. Conglomerate-sandstone stratification is formed by bar migration and aggradation as sandy bed forms accrete onto conglomerate-armored bar margins.

Facies Association 10 (Fluvial Channel)

FA 10 comprises erosionally or sharp-based poorly stratified conglomerate and sandy conglomerate (Figure 21). Distinct bedding contacts are difficult to recognize owing to the large grain sizes. Pebbles are well rounded and comprise dense and microporous chert, and rock fragments (mostly sedimentary). Clast sizes approach 1 in. (3 cm) in diameter. FA 10 is a minor facies association restricted to the uppermost part of the Romeo interval. Erosional surfaces and coarse-grained textures suggest FA 10 represents coarse-grained channel and bar deposits.

Facies Association 11 (Abandoned Channel)

FA 11 comprises rare successions of gradationally fining-upward interbedded very fine grained sandstone, siltstone, and mudstone (Figure 22) that may reach 9 ft (3 m) in thickness. Claystone and siltstone constitute the majority of FA 11 with very fine grained sandstone and minor fine-grained sandstone comprising the remainder. Asymmetric-ripple laminae and soft-sediment deformation are common. FA 11 gradationally overlies facies associations 6, 8, 9, and, rarely, 10. FA 11 is most commonly associated with FA 6 and FA 8.

Based on both its fine-grained composition and the intimate and gradational relationship with underlying interpreted channel sandstones, this heterolithic facies association is interpreted as abandoned channel fill. Asymmetric- (current) ripple laminations and soft-sediment deformation are compatible with low-energy and fluctuating fluvial processes. Fining-upward textural trends imply progressively lower depositional energies as the channels were abandoned. Atkinson et al. (1988) noted that abandoned channel fills grade upward into flood-plain deposits (our FA 13).

Facies Association 12 (Crevasse Splay, Lacustrine Delta, Natural Levee, Bayhead Delta)

Interbedded lower coarse- to medium-grained sandstone, cross-stratified fine-grained sandstone, very fine grained asymmetric-ripple laminated sandstone, and siltstone and claystone comprise FA 12 (Figure 22). Sandstones also exhibit small-scale loading features. Occurrences may either coarsen or fine upward and reach 10 ft (3 m) in thickness.

The dominance of asymmetric- (current) ripple laminations and loading features and lack of wave-formed sedimentary structures and marine traces suggest rapid deposition from unidirectional flows in a nonmarine setting. Association with nonmarine to marginal marine shales suggests that these deposits represent overbank deposition on alluvial and deltaic plains such as natural-levee, crevasse-splay, lacustrine-delta, or bayhead deltaic environments.

Facies Association 13 (Alluvial Flood Plain)

FA 13 contains mudstone and siltstone with very minor sandstone (Figure 22). Thicknesses average 4.5 ft (1.4 m), but may reach 30 ft (9 m). The dominant lithofacies is laminated, green to brown mudstone that commonly passes upward into mudstone characterized by mud cracks, root mottling, swelling clay, slickensides, and diagenetic mottling. Mud cracks may be filled with siltstone or sandstone. Laminated to mottled units may form distinct cycles 10–20 ft (3–6 m) thick. Rarely, mudstones have a distinct red coloration. FA 13 commonly is intercalated with facies associations 8, 9, 10, and 12 and noticeably absent within the basal Ivishak.

FA 13 is nonmarine in origin. Well-laminated mudstones imply low-energy subaqueous deposition, probably in freshwater lakes. The transition into mudstones containing abundant swelling clays is interpreted as representing periods when the lakes were dried or filled and sediments were exposed to subaerial processes (e.g., pedogenesis). Thicknesses of laminated to mottled mudstone packages may bear some relationship to paleolake depths. Considering compaction, lakes were a few meters deep. Red coloration may indicate oxygenation during subaerial exposure. Atkinson et al. (1988) interpreted the mottled lithofacies as immature paleosols (gley to pseudogley) reflecting a flood plain characterized by high sedimentation rates and seasonal fluctuation in groundwater levels.

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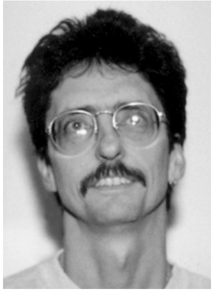
ABOUT THE AUTHORS

Robert S. Tye

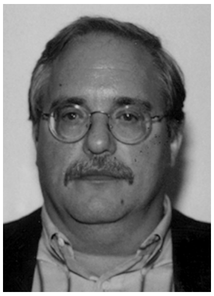


Bo Tye acquired his interest and passion for geology during his youth while exploring beaches and tidal rivers near Charleston, South Carolina. He holds degrees in geology, marine sciences, and environmental sciences from The College of Charleston, The University of South Carolina, Louisiana State University, and The University of Alaska-Anchorage. Presently, Bo is a principal research geologist with ARCO and, in addition to Alaska, has worked projects in Algeria, Ecuador, Indonesia, Mozambique, Turkey, and Venezuela. Previous employers include Cities Service Company and the Texas Bureau of Economic Geology. Bo is keenly interested in the application of stratigraphy and depositional systems analysis to reservoir characterization. He is a member of AAPG, SEPM, and the International Association of Sedimentologists.

Janok P. Bhattacharya

Janok P. Bhattacharya is associate professor at the University of Texas at Dallas. His research interests include deltaic sequence stratigraphy and the local control of structure on stratigraphy. He received his B.Sc. degree in 1981 from Memorial University of Newfoundland, Canada, and his Ph.D. in 1989 from McMaster University, Hamilton, Ontario, Canada. Following an NSERC postdoc at the Alberta Geological Survey in Edmonton, Janok worked for ARCO and then the Bureau of Economic Geology at Austin, Texas.

James A. Lorsong



James A. Lorsong is senior staff geologist at ARCO El-Djazair Company. He received a B.Sc. degree from the University of Toronto (1975) and a Ph.D. from the University of Cambridge (1979). He researched reservoir geology of heavy oil fields at the Saskatchewan Geological Survey before leaving to found petroleum consulting and mineral exploration companies in 1982. He continued as an independent for seven years while teaching stratigraphy and sedimentology part-time at the University of Regina and the University of Saskatchewan. In 1988 he joined ARCO's reservoir geology research group, where he spent six years working on projects mainly in the North Sea, Indonesia, and Alaska, including Prudhoe Bay. He then served as director of stratigraphic research before moving to international operations, where he is currently involved in redevelopment of a large field in North Africa.

Scott T. Sindelar

Scott graduated from Montana College of Mineral Science and Technology in 1988. He joined ARCO Alaska in July 1988. He has held several positions of increasing responsibility as reservoir engineer and operations/analytical engineer in the Kuparuk and Prudhoe Bay fields. Currently, Scott is working as an operations/analytical engineer in ARCO Alaska's exploration group.

Douglas G. Knock

Douglas G. Knock is a senior geologist at ARCO Alaska, Inc., in Anchorage, Alaska, with 11 years of oil industry experience. He has worked on several reservoir characterization projects involving the Kuparuk River and Prudhoe Bay oil fields. Currently, he is working on development of the newly discovered Alpine oil field on Alaska's North Slope. Doug holds a B.S. degree in geology from the University of Idaho and an M.S. degree in geology from the University of Alaska-Fairbanks.

David D. Puls

David graduated from California Lutheran University in 1982 (B.S. degree in geology) and from Northern Arizona University in 1986 (M.S. degree in geology). Since that time, he has worked for Exxon on exploration projects in Nevada, west Texas, and New Mexico. In 1990, he began work on Prudhoe Bay field and participated with ARCO and BP personnel on reservoir description and development studies. David is now located in Baku, Azerbaijan, where he works for Exxon Ventures (CIS) on exploration of the South Caspian Basin.

Richard A. Levinson

Richard A. Levinson received a B.A. degree in earth science from Drake University in 1974 and an M.S. degree in geology from the University of Wyoming in 1979. He spent most of his career with ARCO working a variety of Alaskan exploration and field development projects on the North Slope, Cook Inlet, Alaska Peninsula, and Bering Sea. Presently, he is a staff geologist with the Prudhoe Bay resource development group focusing on multidisciplinary reservoir studies and modeling.