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Wave-Influenced Estuarine Sand Body, Senlac Heavy Oil Pool, Saskatchewan, Canada

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Introduction

A review of several petroleum-producing basins has shown that significant volumes of hydrocarbons are contained in fluvial and estuarine facies deposited within incised paleovalley systems (Table 15-1). Few of these studies investigated the relationships between estuarine facies, their reservoir characteristics, and their production behavior. The absence of such information is at least in part attributable to the incomplete understanding of estuarine stratigraphy within paleovalley systems. The aims of this chapter, therefore, are (1) to present an overview of the facies distribution and diagnostic criteria of estuarine systems, with particular emphasis upon the wave-dominated estuarine complex, and (2) to relate the spatial distribution and vertical stacking of estuarine facies to trapping mechanism, reservoir characteristics, and production behavior.

The reservoir that will serve as the case study is the Senlac Heavy Oil Pool (hereafter termed the Senlac Pool), located in west-central Saskatchewan, Canada (Fig. 15-1). The Senlac Pool was previously interpreted as an estuarine sand plug located at the mouth of an incised paleovalley system (Zaitlin and Shultz, 1984). Additional study has resulted in a more detailed understanding of the relationship between facies architecture, reservoir characteristics, and reservoir behavior. However, since no comprehensive suite of stratigraphically applicable estuarine facies models now exists (Frey and Howard, 1986; Zaitlin, 1987), we will briefly summarize the estuarine depositional model as determined from the study of modern estuarine systems.

The Estuarine Model

An estuary was defined by Pritchard (1967) as "a semi-enclosed coastal body of water having a free connection with the open sea and within which seawater is measurably diluted by fresh water of river origin." The majority of classifications of modern estuarine systems are based on salinity variations (Rochford, 1951; Pritchard, 1967; Biggs, 1978). Salinity can remain depressed for considerable distances beyond the limit of active deposition; in addition, tidal flux can exert significant influence on depositional patterns headward of the limit of measurable salinity (Rochford, 1951; Journeau and Latouche, 1981; Zaitlin, 1987). Because it is difficult to resolve the effects of salinity variations on ancient sequences, geologists tend to define estuarine sequences as "the deposits found within drowned paleovalleys" (Curray, 1969). To resolve this ambiguity, Zaitlin (1987) proposed that an **estuarine complex** would include "all tidally influenced deposits, seaward from the limit of tidal marine influence to the major facies change with normal marine deposits, occurring within a constrained (paleo-) valley setting, affected by the mixing of marine and fresh waters."

An important characteristic of estuaries is that a significant percentage of their sedimentary fill con-

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Table 15-1. Examples of selected hydrocarbon-bearing formations/groups with interpreted estuarine facies as a major reservoir type.

Location	Formation/group	Age	References
Western Canada	Paddy Fm.	Upper Cretaceous	Leckie, 1988
			Leckie and Reinson, in press
	Viking Fm.	Middle Cretaceous	Reinson and others, 1988
	Lloydminster Fm.	Lower Cretaceous	Zaitlin and Shultz, 1984
	McMurray Fm.	Lower Cretaceous	Flach and Mossop, 1985
	General Petroleum and Rex Fms.	Lower Cretaceous	O'Connel and Benns, 1988
	Halfway Fm.	Triassic	Unpublished Data
	Kiskatinaw Fm.	Permo-Pennsylvanian	Unpublished Data
	Granite Wash	Devonian (?)	Unpublished Data
USA	Mesaverde Gp.	Upper Cretaceous	Lorenz and Rutledge, 1985
	Muddy Fm	Lower Cretaceous	Stone, 1972
			Mitchell, 1978
	Morrowan Fm.	Lower Pennsylvanian	Emery and Sutterlin, 1986
	Tyler Fm.	Lower Pennsylvanian	Maughan, 1984
			Barwis, this volume
	Simpson Gp.	Middle Ordovician	Esslinger, 1983
India	Gujarat Fm.	Eocene	Raju and Rao, 1975
Australia	Latrobe Gp.	Tertiary	Sloan, 1987
Libya	Marada Fm.	Miocene	El-Hawat, 1980

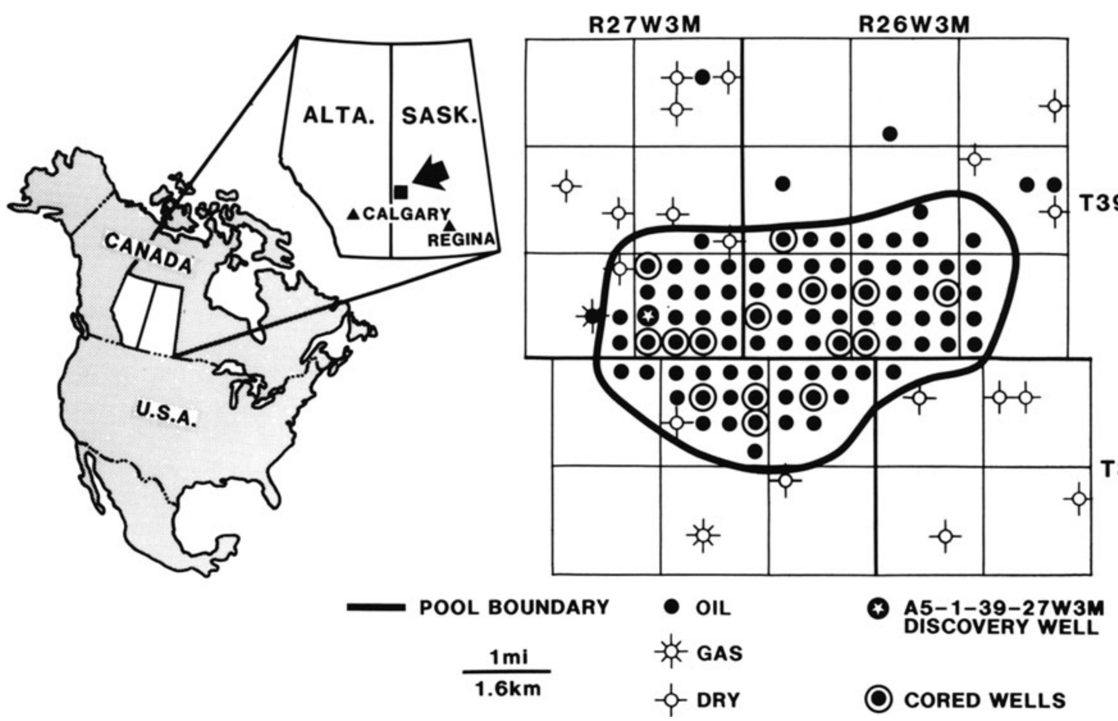


Fig. 15-1. Distribution of cored wells and location of the discovery well in the Saskoil-Gulf Senlac Pool. Arrow in inset map shows the location of the Senlac area (solid square) in west-central Saskatchewan. ALTA. = Alberta; SASK. = Saskatchewan.

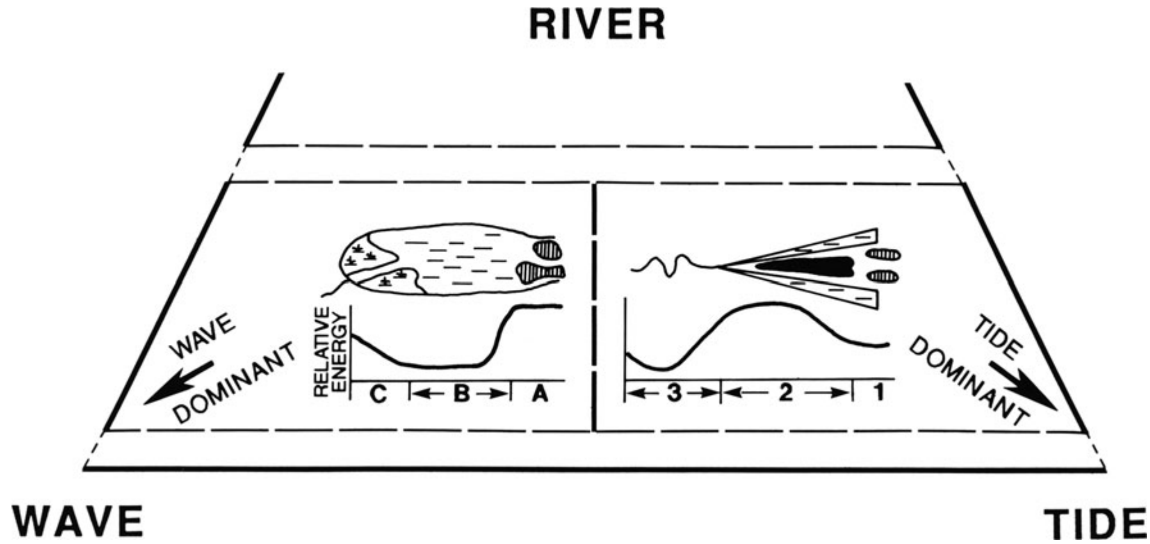


Fig. 15-2. Conceptual ternary diagram exhibiting the spatial distribution in plan view of depositional zones for wave- and tide-dominated estuarine complexes. Wave-dominated estuarine complexes are divisible (after Roy, 1984) into three zones: Zone A—seaward sand plug (vertical lines); Zone B— central basin (horizontal dashes); and Zone C (marsh symbols). The relative energy dissipated across each zone is shown below the inset diagrams. Tidally dominated estuarine complexes (after Dalrymple and Zaitlin, 1989) are fringed by intertidal to supratidal fine-grained deposits (horizontal dashes), and the axial facies is divisible into Zone 1—elongate tidal sandbars (horizontal lines); Zone 2—high-energy sand flats (solid); and Zone 3—tidal-fluvial deposits.

sists of sediment supplied from seaward of the incised valley mouth. This material is transported both along shore and onshore by nearshore coastal marine processes, until those processes (i.e., waves or tides), operating at the estuary's mouth, transport the material headwards into the lower reaches of the drowned valley. Sediment may also be supplied from the hinterland to the upper reaches of the estuary by rivers. Estuarine deposition is thus characterized by sediment filling the valley from two opposing directions: headward of the estuarine zone, valley fill is composed of a variety of fluvial deposits; at the seaward end of the estuarine zone, the incised valley fill consists of more open-marine deposits. The estuarine portion of the incised valley is unique, however, as it is the only area in the valley characterized by sedimentary fill sourced from opposing directions (land and sea). The estuarine portion of the incised valley is influenced by the interaction between marine and fluvial depositional processes redistributing this sediment. The resulting depositional response to this interaction is a complex longitudinal facies distribution along the axis of the valley, with possible compositional changes due to mixed provenance. These variations may have a major control on reservoir quality.

Investigations of modern estuarine facies (Clifton, 1982; Roy, 1984; Chappell and Woodroffe, 1985; Frey and Howard, 1986; Boyd et al., 1987; Zaitlin, 1987; Dalrymple and Zaitlin, 1989; Dalrymple et al., in press) have documented the nature of incised-valley fill. They have also considered a variety of sediment types (sand- vs. mud-dominated), sediment sources (headward vs. seaward), depositional process (wave-, tide-, or fluvial-dominated) and sea-level conditions (relative sea-level rise, fall, or stillstand; single or multiple cycles) in relation to the final incised-valley fill.

Estuarine complexes are characterized by a predictable facies architecture (Roy, 1984; Zaitlin, 1987; Dalrymple et al., in press). Variations in facies architecture, in the preserved vertical sequence, and in diagnostic sedimentological features result from the relative dominance of marine processes (waves versus tides) responsible for redistribution of sediment at the estuary mouth. A wave-dominated estuarine model (Fig. 15-2) developed from estuaries along the New South Wales coast of

Australia (Roy, 1984) and the eastern shore of Nova Scotia (Boyd et al., 1984) exhibits the following threefold zonation: (a) an outer estuarine sand plug, (b) a central basin, and (c) an inner tidal-fluvial zone. In contrast, tidally dominated estuaries similar to those studied in the Bay of Fundy (Dalrymple, 1977; Knight, 1977, 1980; Zaitlin, 1987; Dalrymple et al., in press), Western Australia (Wright et al., 1973, 1975), Queensland (Cook and Mayo, 1977), and the Northern Territory of Australia (Chappell and Woodroffe, 1985) are divisible into (a) a fringing intertidal to supratidal flat, and (b) an axial zone divisible longitudinally landwards into elongate bars, high-energy sand flats, and inner tidal-fluvial facies.

Variations in facies characteristics between wave- and tide-dominated estuarine complexes, particularly those near the estuary mouth (i.e., wave-dominated estuarine sand plug versus tidally dominated elongate bar-sand flats), can therefore be used to determine the relative position of any point along the estuarine portion of an incised valley system. These variations can also be used to infer regional paleogeographic changes along a shoreline or to predict the reservoir characteristics and continuity within an individual estuarine sand body. A brief summary of the spatial distribution, reservoir potential, and sealing characteristics of sandy, wave-dominated estuarine deposits is presented below. Detailed descriptions of tide-dominated estuarine complexes can be found in Cook and Mayo (1977), Chappell and Woodroffe (1985), Zaitlin (1987), Dalrymple and Zaitlin, (1989); and Dalrymple and others (in press).

Sandy Wave-Dominated Estuarine Systems

The distribution of facies within sandy, wave-dominated estuarine systems is controlled both by the effective dissipation of wave energy at the mouth of the complex and by the shape of the incised valley (Roy, 1984). Dissipation of wave energy and sand-plug development at the mouth of the system have been shown to differ slightly between shallow and deeply incised valley systems (Roy, 1984). The distinction between deep and shallow wave-dominated estuaries most probably depends on the actual depth of the valley relative to the amount of the sediment available to fill the system. Any estuary mouth would be "deep" at the time of initial flooding but will become "shallow" as additional sand is transported into the mouth of the system. As a result, subaqueous tidal-delta deposits initially develop at the mouth of deeply incised valley systems as the amount of available sediment is insufficient to fill up the valley mouth during the initial flooding. In such a system, the tidal delta is effective in only the partial dissipation of the marine processes (i.e., wave energy and tidal circulation), thus allowing for the free interchange of marine and fresh waters between the fluvial and the open-marine zones. In contrast, as the incised valley becomes shallow due to increased sediment input relative to its effective depth, a subaerial barrier or spit complex may develop across the mouth of the embayment. This restricts the free interchange of marine and fluvial waters, except through tidal inlets, and effectively dampens the wave energy between the inner estuary and the outer, open-marine area.

Wave-dominated estuarine complexes developed within shallow valley systems are divisible, after Roy (1984), into three major facies belts (Zones A, B, and C—Fig. 15-2), as follows:

Zone A consists of a wave-dominated composite sand plug (Fig. 15-3) across which wave energy is dissipated (Fig. 15-2). The facies geometry within a composite sand plug is dependent on the interplay of sediment supply and sea-level history. The sand plug is divisible into an inner transgressive core and an outer progradational sand body. The transgressive core consists of a barrier shoreface and/or spit complex cut by multiple, laterally migrating tidal inlets; the resulting vertical sequence is dominated by upward-fining tidal inlet deposits capped by upward-coarsening shoreface sequences. The transgressive core is developed during the initial stages of flooding as the result of transport of sediment headwards into the mouth of the valley. As the rate of sea-level rise decreases or as sediment supply is increased to the mouth of the system, sediment cannot be driven headward through the tidal inlet at sufficiently fast rates, thus resulting in the progradation of a sand body accreted onto the seaward side of the transgressive core. This progradational shoreline is dominated by an upward-coarsening shoreface sequence which may be dissected by a few relatively stationary tidal inlets with tidal deltas prograding into the central basin.

Zone B is a central basin zone containing the lowest-energy intertidal to shallow subtidal deposits in the complex (Figs. 15-2, 15-4). Zone B comprises fringing intertidal to supratidal flats and an axial subtidal area containing "lagoonal," interdistributary-bay and/or fluvial deposits. These Zone B facies are deposited behind the barrier con-

Fig. 15-3. An example of a modern Zone A sand plug displaying barrier, inlet, and tidal-delta deposits from the New South Wales coast of Australia. (Photo courtesy of A. Short, University of Sydney)

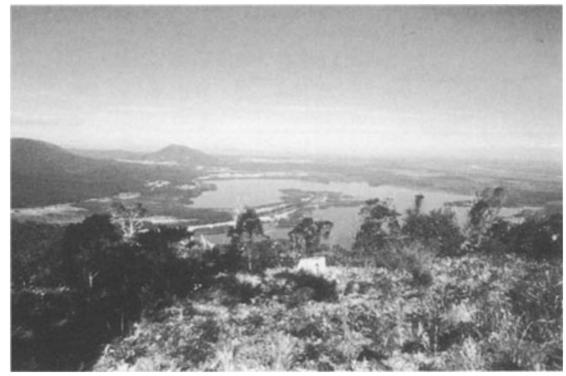


Fig. 15-4. An example of modern central basin and tidal-fluvial delta deposits from the New South Wales coast of Australia. (Photo courtesy of A. Short, University of Sydney)

structed in Zone A but are sourced predominantly from updip fluviodeltaic environments.

Zone C is the innermost zone consisting of tidal-fluvial channels and interdistributary-bay and overbank (delta-plain) deposits (Figs. 15-2, 15-4). Zone C sediments are transported from above the limit of tidal influence and are reworked to varying degrees by the tidal processes operating in the headward reaches of the estuarine system. Reworking by waves is minimal.

Reservoir Potential of Wave-Influenced Estuarine Complexes

The composite sand plug (Zone A) commonly has the best reservoir potential of the wave-dominated estuarine complex. The sand plug is usually oriented parallel to the coastline, its lateral extent being controlled by the geometry of the valley. The sand plug is restricted to the valley mouth along deeply embayed coastlines but may be more laterally continuous in low-relief coastal-plain settings where the sand bodies form more typical barrier-island/lagoonal systems (Rehkemper, 1969; Hayes, 1979; Davis and Hayes, 1984).

Facies of the tidal-fluvial zone (Zone C) may have moderate reservoir potential associated with tidally modified distributary channel-fill deposits oriented parallel to depositional dip. However, these "bayhead deltas" are typically immature and texturally and mineralogically very muddy because of their protected location and lack of reworking, so even the channel-fill and distributary mouth-bar sequences can be poor reservoirs (McEwen, 1969).

Finer-grained deposits are common within Zones B and C and are represented by interdistributary-bay, lagoonal, and coastal-plain facies. These facies have a variable spatial distribution and display poor reservoir quality because of their generally finer grain size. Fine-grained deposits within Zones B and C form effective lateral seals for reservoirs in Zones A and C. In addition, the quiet water, anoxic "lagoonal" facies of Zone B may, under certain conditions, be an excellent source of hydrocarbons (e.g., the Cretaceous Paddy Formation of western Canada; personal communication, J. Allan and S. Creaney, 1988). Top and bottom seals for wave-dominated estuarine reservoirs are controlled by the vertical stacking of backstepping parasequences due to either the stepped rise in relative sea level or fluctuations in sediment input. In a transgressive or backstepping sequence, the superposition of open-marine mudstones over the sand plug forms the seal. With progradation, the development of coastal-plain deposits over the reservoir sands forms the topseal.

Senlac Heavy Oil Pool

Reservoir Characteristics and Available Data

The Senlac Pool was discovered in 1980 with the drilling of Gulf-Saskoil Senlac A5-1-39-27W3M (Fig. 15-5). Production is from the Lloydminster

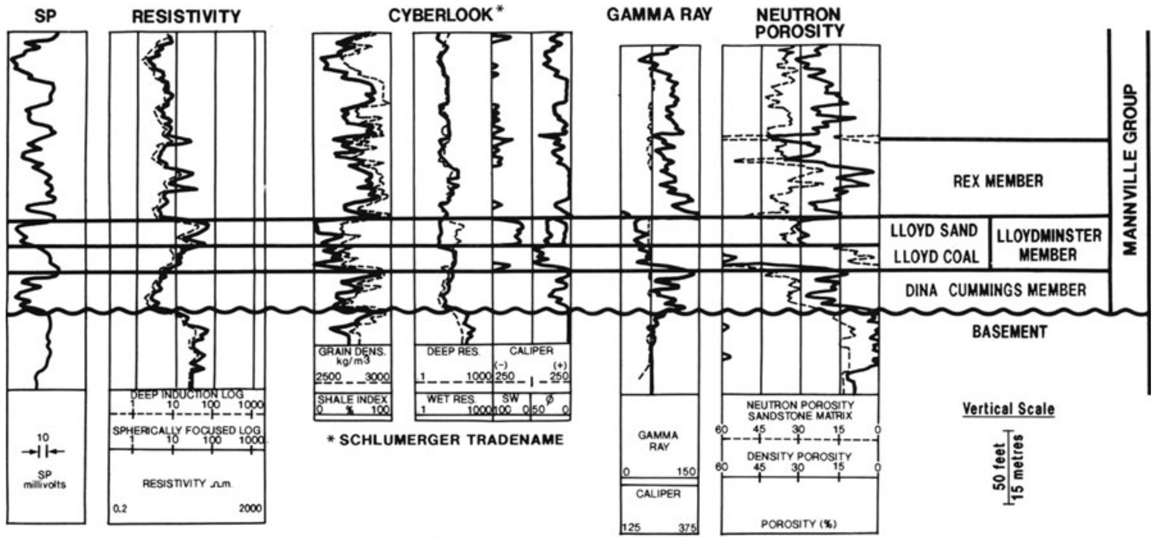


Fig. 15-5. Characteristic log responses from Gulf et al. Senlac A5-1-39-27W3M discovery well. LLOYD = Lloydminster.

Member of the Lower Cretaceous (Aptian to lower Albian) Mannville Group. Operatorship of the pool was transferred from Gulf Canada Resources to Saskatchewan Oil and Gas Corporation (Saskoil) in 1983. The Senlac Pool is estimated to contain 84.3 million barrels (1.3×10^7 m³) of 13° to 15° API gravity oil in place (OIP). A 7.5% recovery factor is predicted to yield an ultimate 6.4 million barrels (1.0×10^6 m³) of oil on primary recovery. The pool is presently on primary production but is being evaluated as a possible candidate for an in situ combustion (fire flood) enhanced oil recovery (EOR) project.

The data base from the Senlac Pool includes 98 wells (84 producing) on 40-acre (16.2-ha.) spacing distributed over an area of 4,818 acres (1,951 ha.)

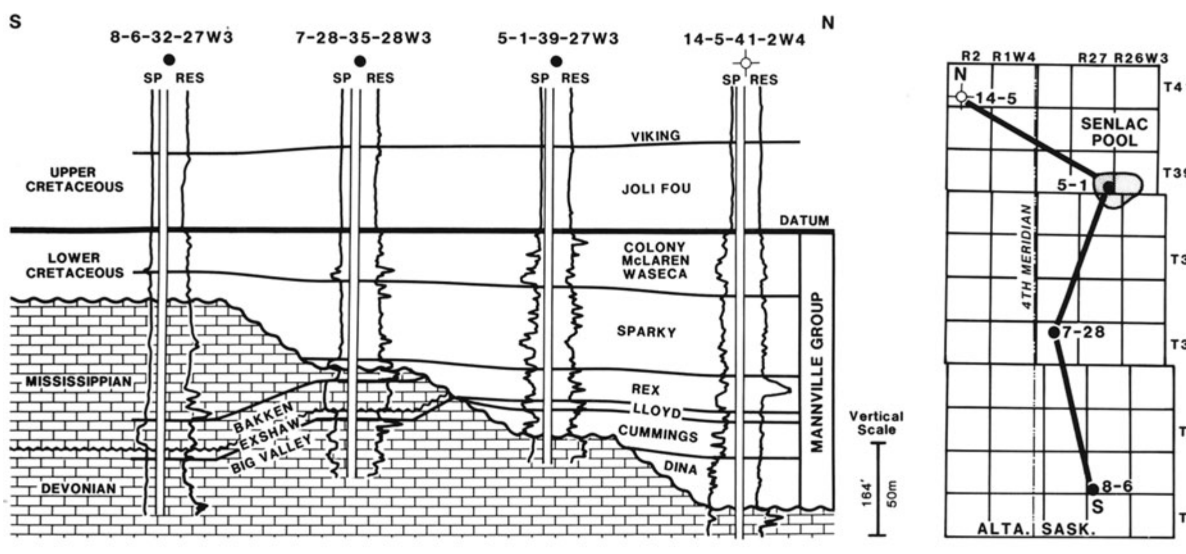


Fig. 15-6. Stratigraphic nomenclature and north-south cross section through the Senlac Pool in west-central Saskatchewan. LLOYD = Lloydminster Formation; ALTA. = Alberta; SASK. = Saskatchewan.

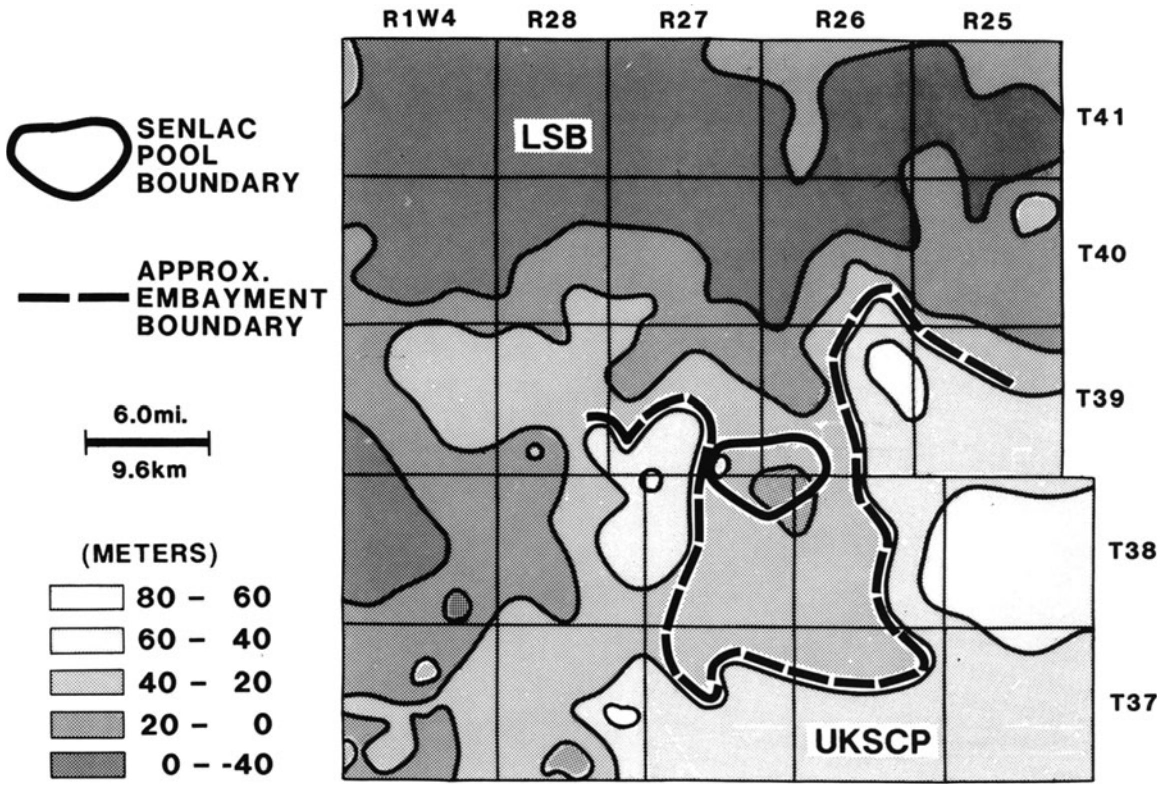


Fig. 15-7. Third-order structural residual map of the sub-Cretaceous erosional surface for the Senlac Pool and surrounding area contoured in meters. The embayment measures approximately 15 miles (24 km) N-S by 4 miles (6.4 km) E-W. LSB = Lloydminster sub-basin; UKSCP = Unity-Kindersley-Swift Current platform.

(Fig. 15-1). Fourteen of the wells that were cored penetrated the Lloydminster Member. All wells from the pool were examined and all cores were logged in detail. Surrounding wells in a three-township area (108 mi^2; 275 km^2) were also incorporated into the study in order to establish the Senlac Pool's general paleogeographic context.

Regional Stratigraphic and Structural Framework

The regional stratigraphic framework for west-central Saskatchewan is presented in Figure 15-6. Devonian and Mississippian carbonates and clastics are truncated by a regionally extensive sub-Cretaceous erosional surface. Overlying this unconformity is a complex northward-thickening wedge of flat-lying (Lower Cretaceous) Mannville Group terrestrial to shallow-marine clastic sediments. The Mannville Group is overlain by regionally extensive marine shale of the Upper Cretaceous Joli Fou Formation.

The Western Canada Sedimentary basin has undergone repetitive eustatic fluctuations in sea level. Tectonic activity to the west resulted in varying sediment supply to the basin; together these factors result in a composite stacking of transgressive-regressive cycles throughout the basin. Lower Cretaceous strata were deposited in a number of discrete mappable sub-basins controlled by the irregular sub-Cretaceous paleotopography (Ranger, 1983). The Senlac area is situated at the southern limit of one such area (Fig. 15-7), termed the Lloydminster sub-basin (Zaitlin and Shultz, 1984). The Senlac area straddles the boundary between this sub-basin and the northern edge of the Unity-Kindersley-Swift Current platform (Christopher, 1980; hereafter termed the Swift Current platform).

The Mannville Group, divided into nine members by Nauss (1945) and Vigrass (1977), is 590 to 755 feet (180–230 m) thick within the Lloydminster sub-basin and abruptly thins to 230 to 328 feet (70–100 m) over the Swift Current platform (Christopher, 1980). The Mannville Group isopach map exhibits thick-

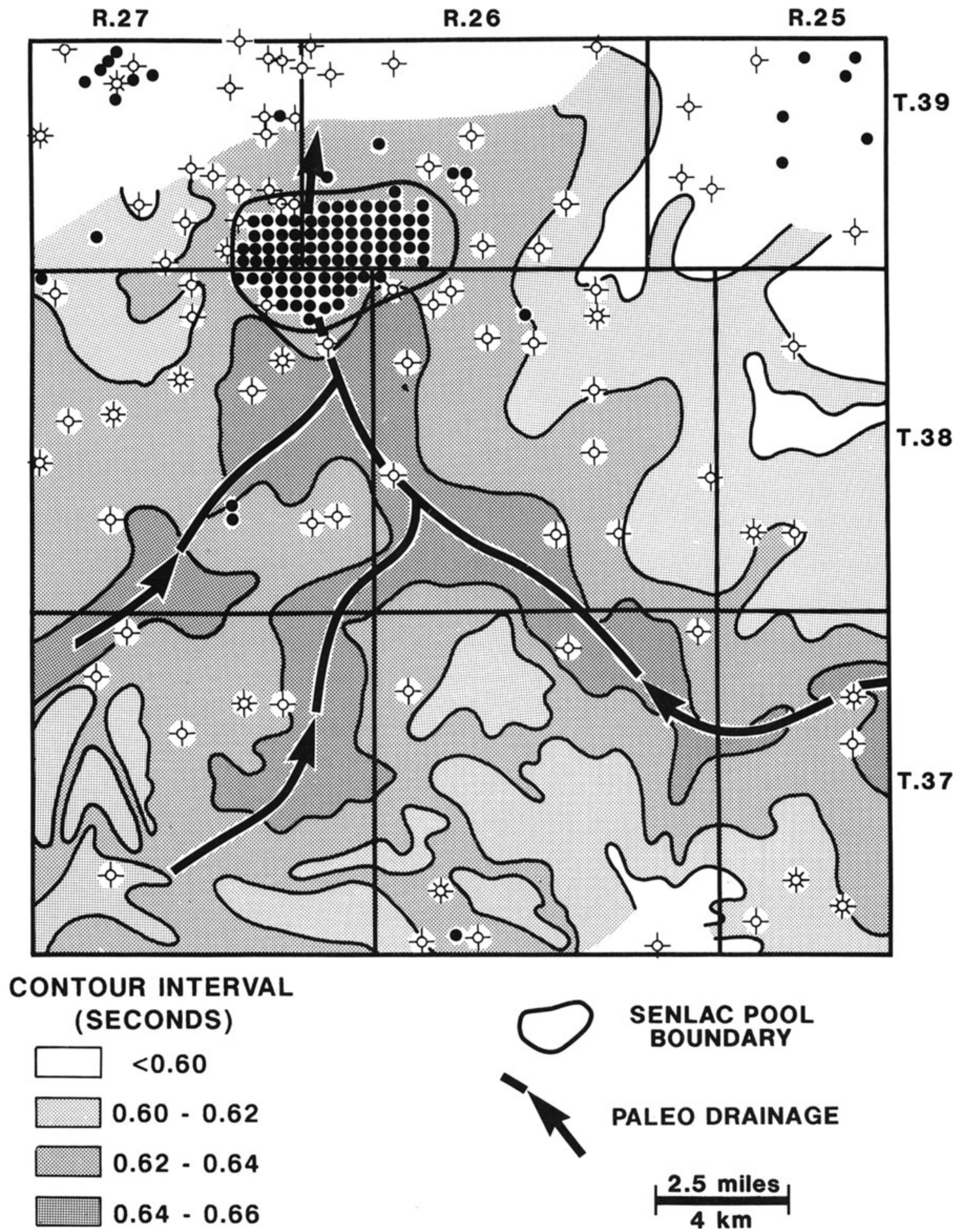
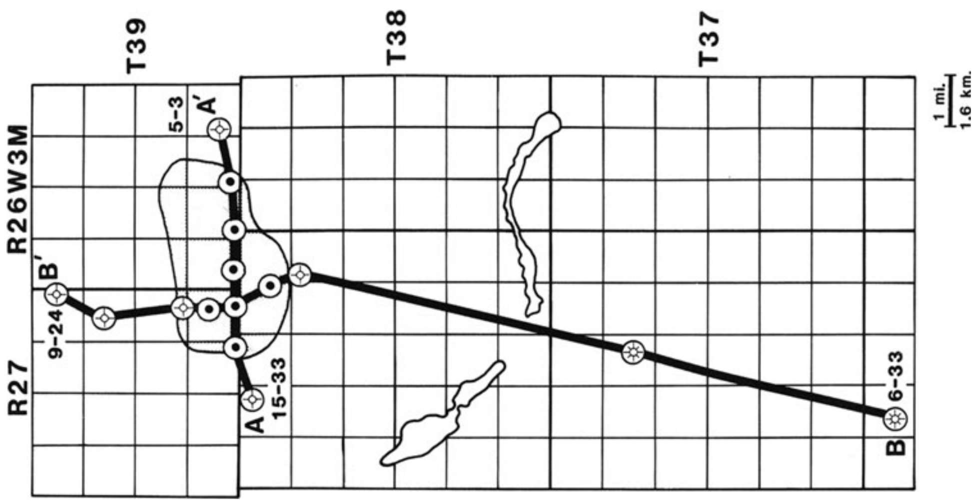


Fig. 15-8. Structural seismic interpretation on the sub-Cretaceous unconformity. Contour interval is 0.02 seconds using two-way travel time. Arrows indicate interpreted paleovalley trends and inferred paleodrainage directions.



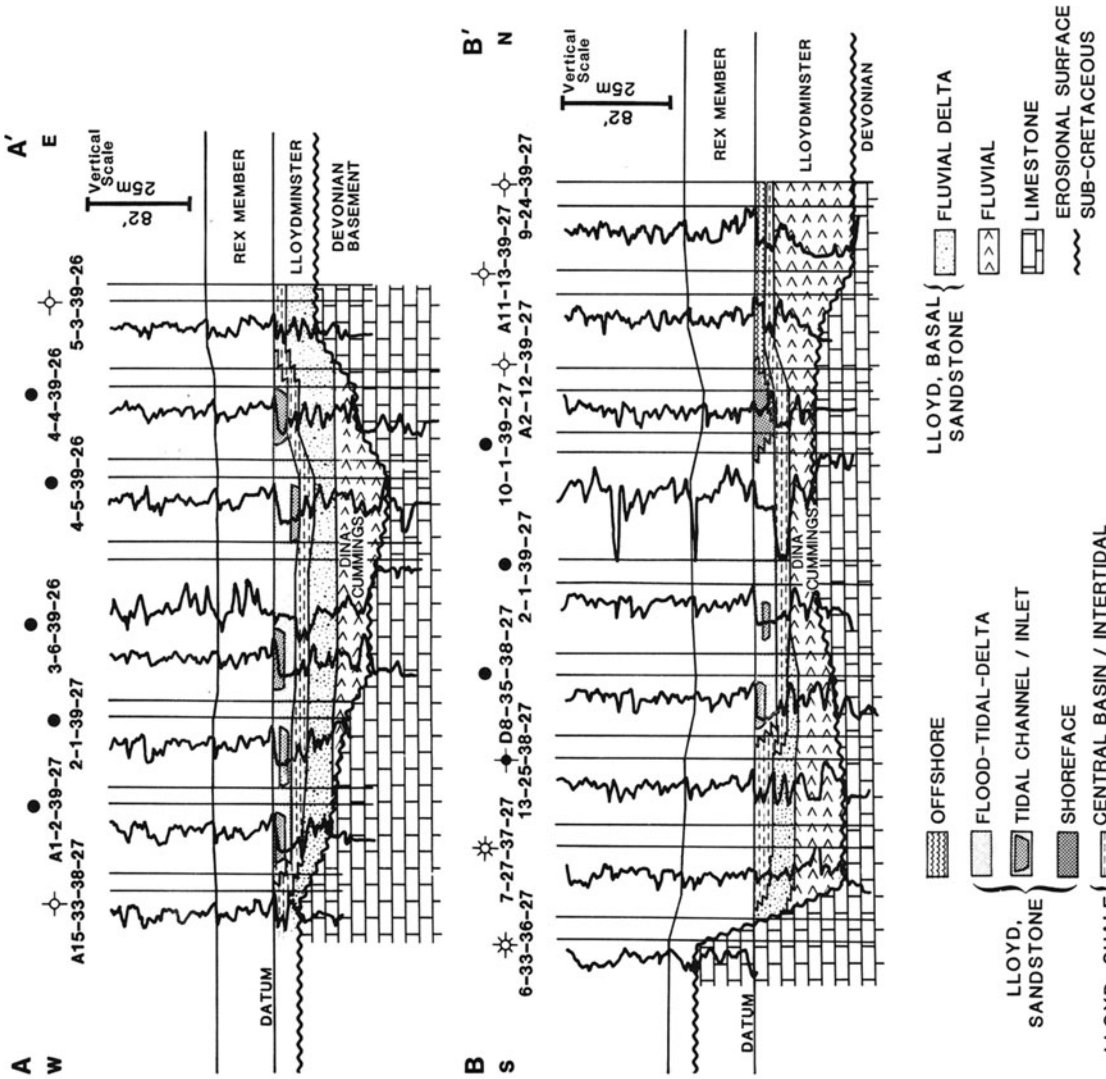


Fig. 15-9. Detailed east-west (A-A') and north-south (B-B') gamma-ray wireline-log correlations across the Senlac embayment. Datum is the major flooding surface above the Lloydminster Formation. LLOYD = Lloydminster.

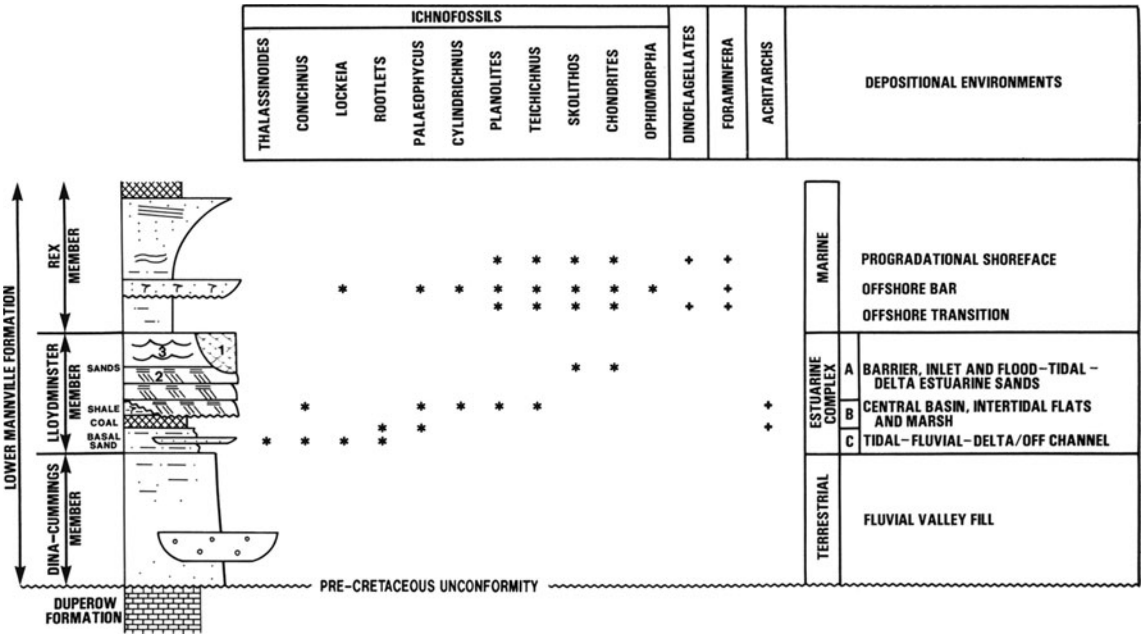


Fig. 15-10. Idealized vertical sequence of the Lower Mannville Group in the Senlac area. Ichnofossils (*) identified by G. Pemberton and micropaleontology (+) identified by Robertson Research and C. Vervoloet. A, B, and C refer to zones defined in Figure 15-2 for a wave-dominated estuarine complex. Numbers 1, 2, and 3 refer to sand types described in the chapter.

ening of more than 650 feet (200 m) in areas interpreted as incised paleovalleys associated with the sub-Cretaceous erosional surface. The third-order residual and structure maps (Figs. 15-7, 15-8) are observed to mimic closely the inferred paleotopography at the time of deposition. The residual map clearly shows the occurrence of a paleotopographic embayment in the edge of the Swift Current platform in the Senlac area. This incised paleovalley system is 15 miles (24 km) north-south by 4 miles (6.4 km) east-west and opens northwards into the Lloydminster sub-basin. This feature has been termed the Senlac embayment (Zaitlin and Shultz, 1984). Detailed correlations (Fig. 15-9) and third-order residual and structural mapping on the sub-Cretaceous unconformity (Figs. 15-7, 15-8) exhibit a localized depression with 65 to 130 feet (20–40 m) of topographic relief in the Senlac area. The depression is interpreted to represent a northward-draining paleovalley system on the sub-Cretaceous erosional surface at the edge of the Swift Current platform (Fig. 15-8). From detailed correlations, this depression can be shown to contain the localized development of Dina-Cummings and Lloydminster Members (Fig. 15-9). These units are absent from the surrounding paleotopographic highs.

Reservoir Characterization

Stratigraphy and Facies Description

Core-controlled correlations permit the development of a composite stratigraphic section of the Senlac embayment fill (Fig. 15-10). The documentation and interpretation of lithofacies in the Senlac area have been presented in Zaitlin and Shultz (1984) and are summarized briefly below. The composite vertical section constructed suggests a slow continuous sea-level rise with a resultant limited headward translation of facies belts. The composite section does not take into consideration local erosional events within the system.

Dina-Cummings Member. The undifferentiated Dina-Cummings Member is in erosional contact with underlying carbonates of the Devonian Duperow Formation (Figs. 15-6, 15-9, 15-10). The Dina-Cummings Member, where present, forms an

Fig. 15-11. Core photographs of Saskoil-Gulf Senlac B4-5-39-26W3M. Top of core is to upper right, base of core is to bottom left. Lloydminster basal sandstone (bs) is overlain by the carbonaceous shales of the Lloydminster coal (coal), which is overlain by Lloydminster shale (S) and the Lloydminster sand (sand). Rex Member siltstone and shale (rex) overlie Lloydminster Member deposits. Scale bar is 6 inches (15 cm).

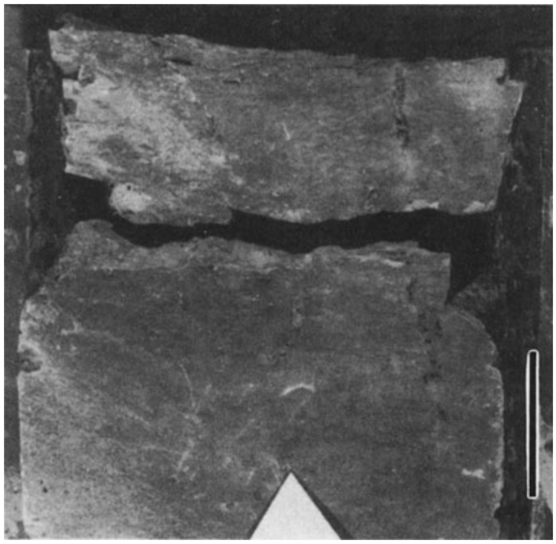


Fig. 15-12. Lloydminster basal sandstone (Gulf-Saskoil Senlac 1-6-39-26W3M) displaying carbonaceous root casts and a possible *Thalassinoides* burrow. Scale bar is 1 inch (2.5 cm).

overall upward-fining sequence, up to 100 feet (30 m) thick, composed of interbedded calcareous-cemented, cross-bedded sandstone and siltstone. The finer-grained facies contain pyritized rootlets but have yielded no recognizable micropaleontologic or palynologic material. This unit is interpreted to have been deposited as part of a fluvial-dominated valley-fill sequence prior to the flooding of the valley during Lloydminster time.

Lloydminster Member. The Lloydminster Member is divisible into four informal units (Figs. 15-10, 15-11): the basal sandstone, the Lloydminster coal, the Lloydminster shale, and the Lloydminster sands (Figs. 15-9, 15-10).

Basal sandstone. The basal sandstone ranges in thickness up to 16 feet (4.9 m) and appears to be in gradational contact with the underlying Dina-Cummings Member. This unit is characterized by calcite-cemented sandstone organized into repetitive upward-fining cycles ranging from 0.3 to 3.3 feet (0.1–1 m) thick. Each upward-fining cycle is composed of unstratified to cross-bedded sandstone, with ripple cross-laminae and flaser beds which grade into carbonaceous, rooted siltstone (Fig. 15-12). The siltstone contains an ichnofossil assemblage composed of *Palaeophycus herberti*, *Conichnus*, *Lockeia*, and *Thalassinoides* and has yielded a few undiagnostic acritarchs. Thin-section and core analyses reveal low porosity (< 5%) and no effective permeability (< 0.01 md). The basal sandstone is situated toward the south or headward reaches of the estuarine system (Fig. 15-9) and is interpreted to have been deposited as part of the sandy, tidal-fluvial and off-channel environments in the inner reaches of the estuarine complex (Fig. 15-13). The unit has little reservoir potential and, where higher permeability or porosity is present, is water-bearing due to the gentle southwest structural dip in the Senlac area.

Lloydminster Coal. The Lloydminster coal ranges in thickness up to 13 feet (4.0 m) and overlies the basal sandstone (Figs. 15-9, 15-10). The coal is interbedded with dark, carbonaceous shale and siltstone. The siltstone contains pinstripe bedding, lenticular and flaser bedding, and isolated rootlets. A sparse ichnofossil assemblage dominated by *P. herberti* is present. The coal and interbedded siltstone and shale are interpreted to represent the fringing upper intertidal to supratidal facies. The coal forms both within Zone C of the inner tidal-fluvial environments and within the Zone B central basin.

Lloydminster Shale. The Lloydminster shale occurs locally throughout the Senlac embayment and, where present, directly overlies the Lloydminster coal (Figs. 15-9, 15-10). The shale is less than 2.5 feet (0.8 m) thick and contains well-developed pinstripe, lenticular, and tidal bedding features (Fig. 15-14 A-D). The shale has yielded a few acritarchs and contains a suite of recognizable restricted shallow subtidal to intertidal ichnofossils (Fig. 15-10). The Lloydminster shale is interpreted to represent a variety of central basin-fringing tidal-flat, and shallow subtidal subenvironments (Zone B, e.g., lagoon, interdistributary bay, and prodelta).

Lloydminster Sands. The Lloydminster sands are developed near the mouth of the Senlac embayment. Based upon the examination of primary sedimentary structures, spatial distribution, production data, and reservoir characteristics, the hydrocarbon-saturated Lloydminster sands are divisible into three distinct sand types (Fig. 15-14 E-G). Subtle differences in the gamma-ray log signature, directly correlatable to the cored intervals, are discernible for each type. Porosity, permeability, and water/oil saturations also differ among the three types (Fig. 15-15).

Type 1 sands range in thickness up to 13 feet (4.0 m) and average 5 feet (1.5 m) thick. They are organized into 2-inch to 5-foot (5–150 cm) thick, repetitive upward-fining cycles. Each upward-fining cycle begins with a sharp, erosional basal contact (with or

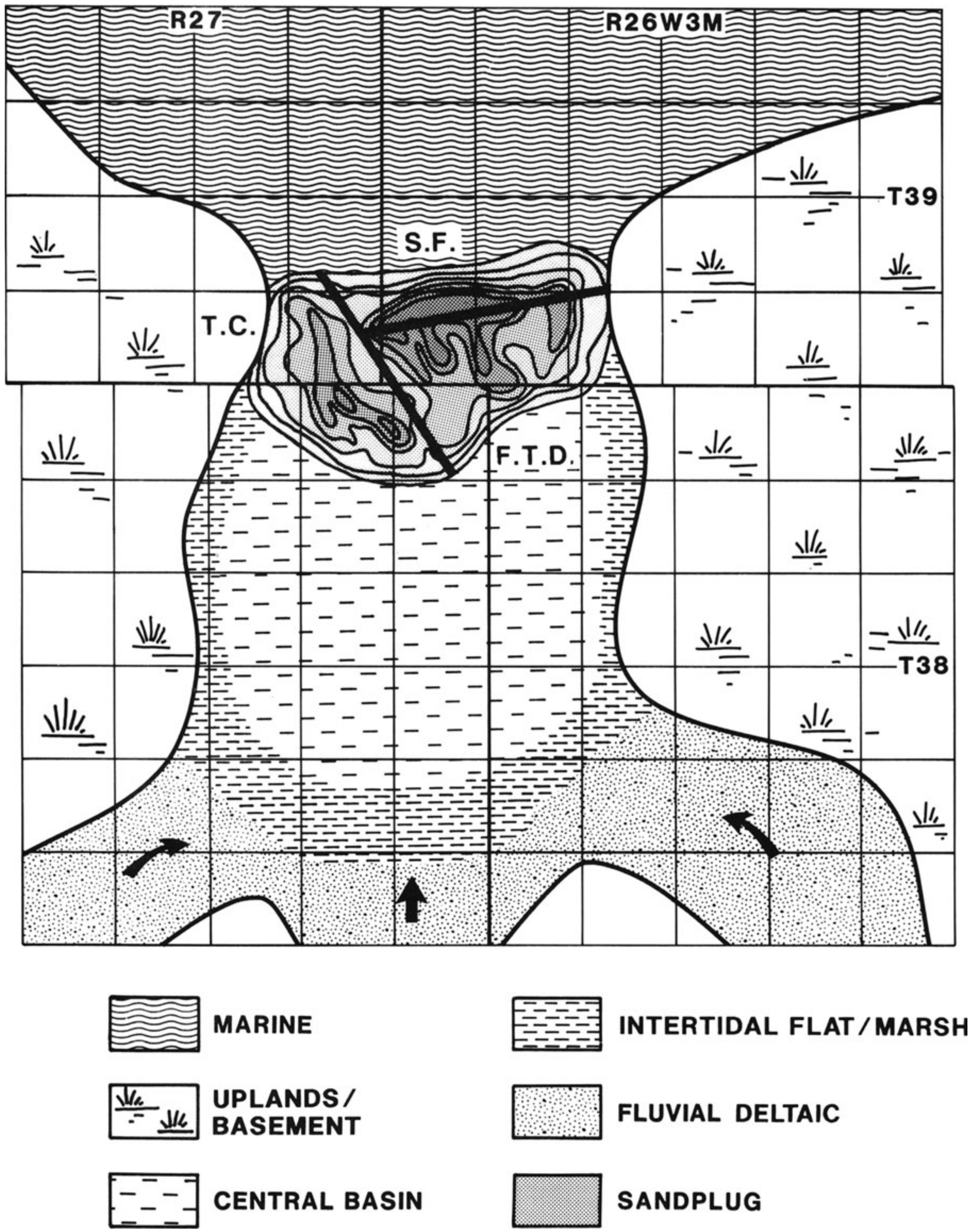


Fig. 15-13. Distribution of depositional environments during Lloydminster time in the Senlac embayment. S.F. = shoreface deposits; T.C. = tidal-channel deposits; F.T.D. = flood-tidal-delta deposits. Heavy black lines separate depositional environments. Arrows indicate paleodrainage directions in the fluviodeltaic environments.

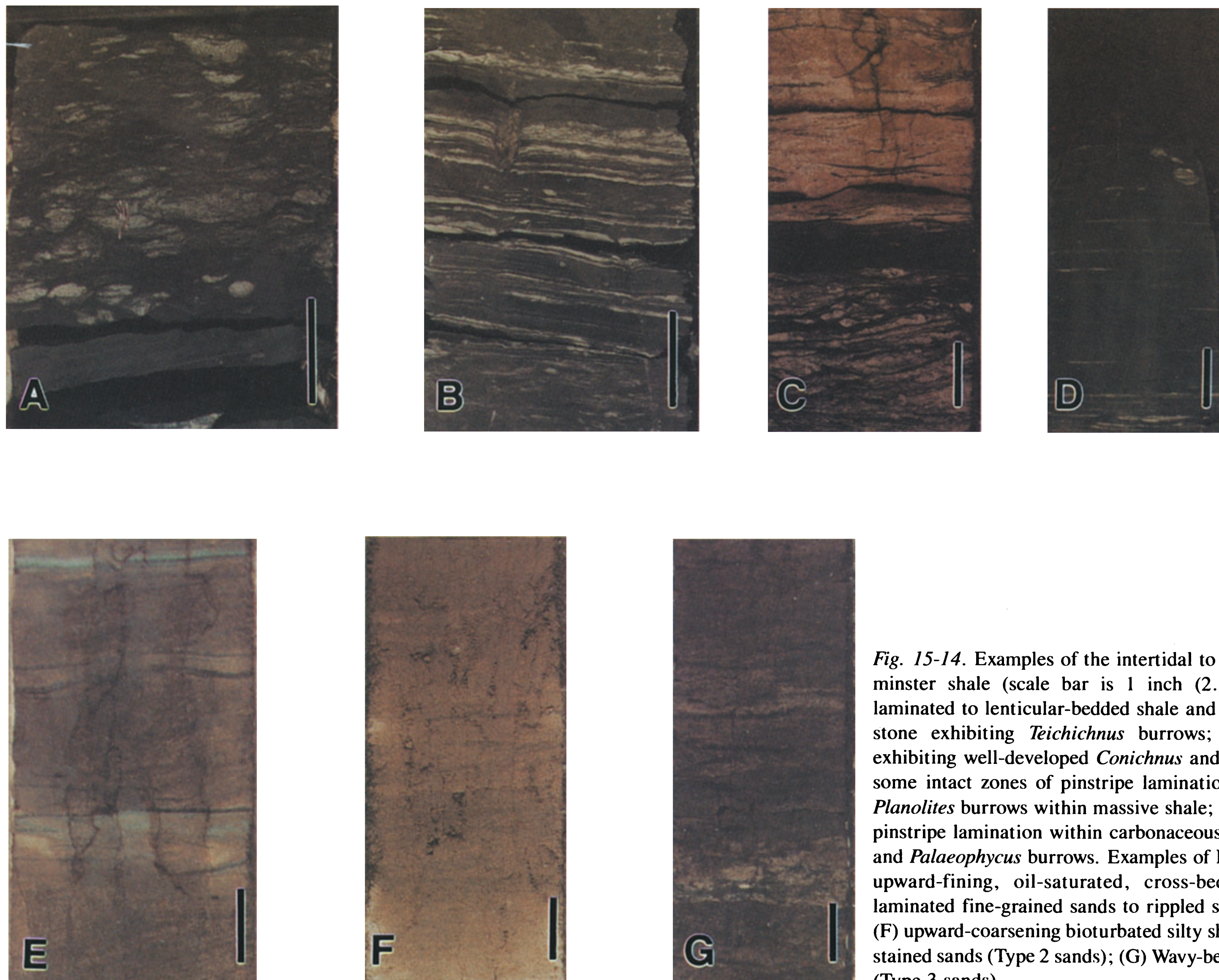
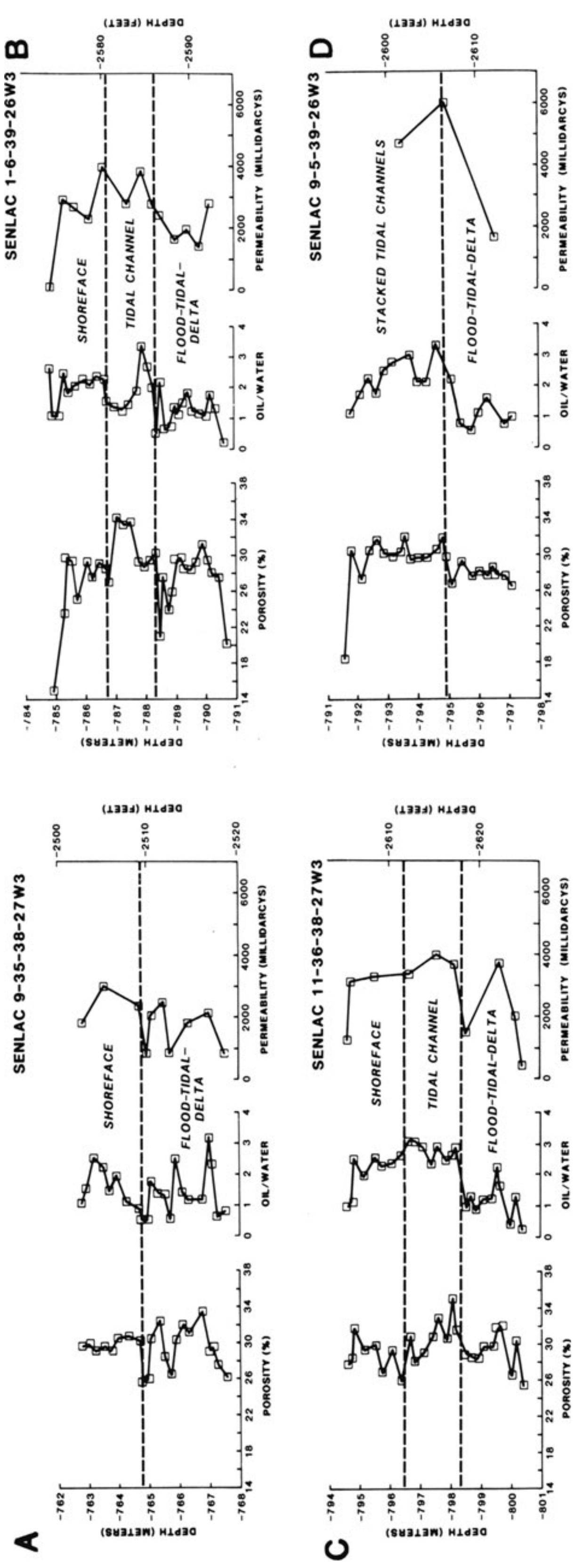
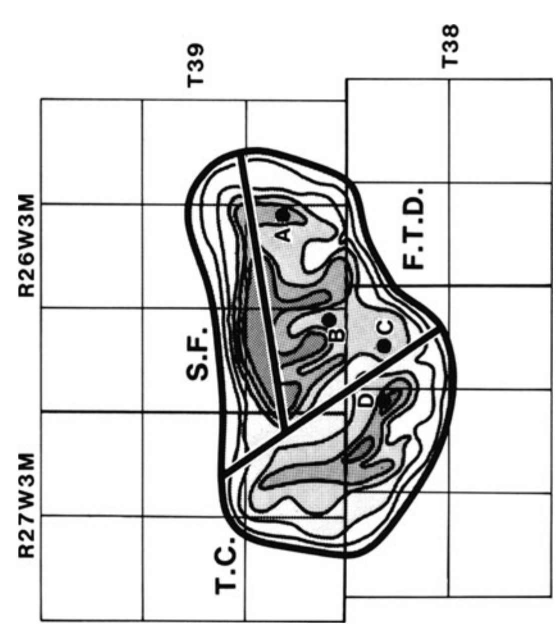


Fig. 15-14. Examples of the intertidal to shallow subtidal Lloydminster shale (scale bar is 1 inch (2.5 cm)): (A) Pinstripe-laminated to lenticular-bedded shale and very fine-grained sandstone exhibiting *Teichichnus* burrows; (B) bioturbated shale exhibiting well-developed *Conichnus* and *Planolites* burrows and some intact zones of pinstripe lamination; (C) *Teichichnus* and *Planolites* burrows within massive shale; (D) well-developed fine pinstripe lamination within carbonaceous shale with *Teichichnus* and *Palaeophycus* burrows. Examples of Lloydminster sands: (E) upward-fining, oil-saturated, cross-bedded to ripple cross-laminated fine-grained sands to rippled siltstone (Type 1 sands); (F) upward-coarsening bioturbated silty shale to cross-bedded oil-stained sands (Type 2 sands); (G) Wavy-bedded fine-grained sands (Type 3 sands).





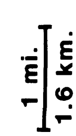


Fig. 15-15. Depth vs. porosity, oil/water ratio, and permeability profiles for the four wells (A-D) depicted in the inset isopach map of the Lloydminster sands (see Fig. 15-17). T.C. = Tidal-channel deposits; S.F. = Shoreface deposits; F.T.D. = Flood-tidal-delta deposits.

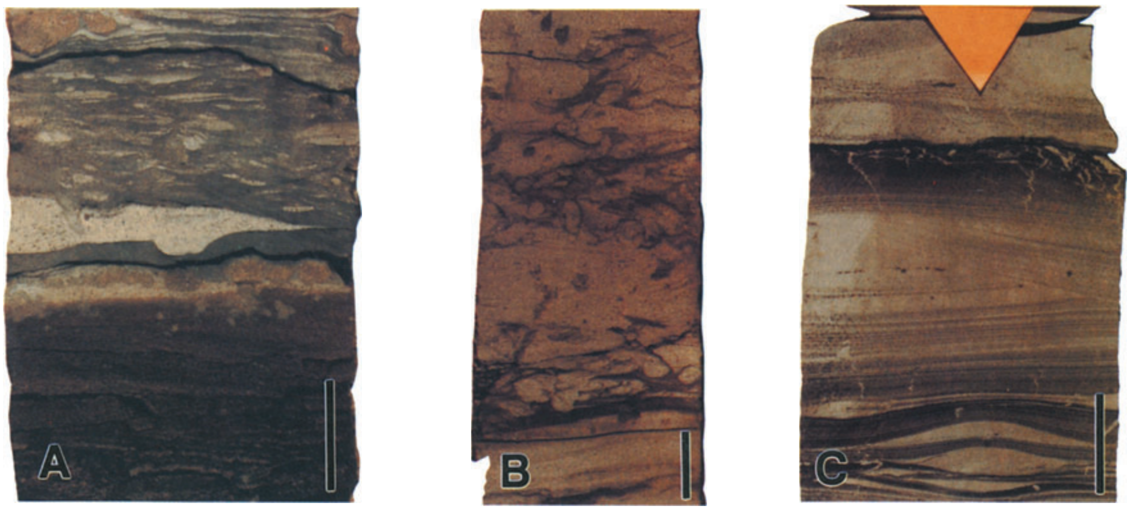


Fig. 15-16. (A) Bioturbated, starved ripple to lenticular bedded shale of the Rex Member, indicative of offshore transition to shelf deposits overlying Lloydminster sands. (B) Bioturbated shale and silty sandstone of the Rex Member, indicative of lower shoreface to offshore transition deposits. (C) Wave-ripple bedding within shale and sandstone of the Rex Member, indicative of lower shoreface deposits. (Scale bars are 1 inch (2.5 cm)).

without a gravel or shell lag) and overlain by cross-bedded, fine- to very fine-grained sandstone and ripple cross-laminated siltstone. Porosity values range from 25 to 30%, and permeability values are on the order of 3,000 to 4,000 md.

Type 2 sands range in thickness up to 21 feet (6.4 m) and are organized into upward-coarsening cycles that are 0.8 to 3.3 feet (0.25–1.0 m) thick. The lower part of each cycle generally consists of a bioturbated shale overlying a sharp contact and then coarsens upward into current-ripple cross-laminated siltstone and cross-bedded sandstone. *Chondrites* and *Skolithos lineraris* are present in the lower portions of each cycle. Porosity and permeability are variable, with maximum values on the order of 27 to 31% and 1,000 to 4,000 md developed near the top of each cycle. The basal bioturbated shale forms laterally restricted permeability barriers within the sand plug.

Type 3 sands range in thickness from 2 to 25 feet (0.6–7.6 m). They are fine- to medium-grained, undulatory, wavy-bedded, and cross-bedded and are organized into well-developed upward-coarsening cycles. Porosities range from 29 to 31%, and permeabilities are 2,000 to 3,500 md.

Rex Member. The Rex Member ranges in thickness from 16 to 33 feet (4.9–10.0 m) and directly overlies the Lloydminster Member (Figs. 15-9, 15-10). The Rex Member forms a well-developed upward-coarsening sequence, characterized by a basal carbonaceous pyritic shale (Fig. 15-16A). It is overlain by bioturbated shale, siltstone, and sandstone (Fig. 15-16B), with interbedded, 3 to 10 feet (0.9–3.0 m) thick, low-angle, wavy to hummocky cross-bedded sandstone (Fig. 15-16C). This upward-coarsening sequence is capped by a coal or carbonaceous shale. The lower shale contains a diverse open-marine ichnofossil assemblage and yields dinoflagellate cysts (Fig. 15-10).

Lloydminster Sands Distribution and Facies Interpretation. The Lloydminster gross-sandstone isopach map is presented in Figure 15-17 and describes a sand plug consisting of a 23-foot (7.0-m) thick lenticular sand body near the mouth of the embayment (Fig. 15-13). The sand body displays a north-south asymmetric profile, with the northern margin sloping steeply northward and the southern face tapering gently toward the south (Fig. 15-17). The Lloydminster sand undergoes a southward facies change, interfingering with the subtidal facies of the Lloydminster shale (Figs. 15-9, 15-10). Northward from the mouth of the paleovalley, the sands are not present and are replaced by open-marine shale and siltstone. To the east and west, the sand plug grades into fringing intertidal deposits of the Lloydminster shale, which in turn onlap the edge of the paleovalley.

Three distinct facies identified as the deposits of tidal channel (facies T.C.), flood-tidal delta (facies F.T.D), and shoreface (facies S.F.) are recognized within the sand plug (Figs. 15-13, 15-17).

The tidal-channel sequence is developed within a northwest-southeast trend along the western edge of the pool. Interpretation of core data and the gamma-log signature indicates that the sequence is dominated by Type 1 sands but may be capped to the north by a thin veneer of Type 2 and/or Type 3. Based on the dominant upward-fining profile, lack of bioturbation, and spatial distribution, this facies is interpreted to comprise composite, stacked tidal-channel deposits that cut across the sand plug.

The flood-tidal delta sequence is dominated by Type 2 sands and exhibits a number of north-south Type 1 sand trends. This facies ranges in thickness from 0 to 21 feet (0–6.4 m) and thins towards the south. The environmental interpretation is based upon its variable upward-coarsening profile, the thickness of the Type 2 sands, and the spatial distribution with respect to other facies.

Shoreface deposits are dominated by Type 3 sands, occur in an east-west trend, and display thicknesses extending to more than 23 feet (7.0 m). Their environmental interpretation is based upon their upward-coarsening profile, absence of crosscutting tidal-inlet fills, and sedimentary structures. The sequence formed on the seaward side of the Zone A sand plug.

Composition of the Lloydminster sands. The Lloydminster sands are dominated by quartz and chert (~85%), with accessory feldspar, carbonaceous material, rock fragments, and glauconite. No major compositional differences occur between the Type 1, 2, and 3 sands. A clay matrix (< 8% by weight) composed of kaolinite, minor illite, smectite, and traces of smectite-illite mixed-layer clays is present preferentially within Type 2 sands associated with the flood-tidal delta. The higher water saturations associated with the flood-tidal-delta facies are thought to be due to this higher interstitial clay content. This S_w criterion can be employed in uncored wells as an indicator of Type 2 sands.

Depositional Model And Trapping Mechanism

The Lower Mannville Group in the Senlac area is interpreted to represent the complex fill of an incised paleovalley system which evolved stratigraphically from fluvial through estuarine to open-marine deposits (Zaitlin and Shultz, 1984). Deposition is believed to have occurred during slow sea-level rise to stillstand conditions (Lloydminster Member), followed by a rapid sea-level rise and landward facies translation (Rex Member). The superposition of marine mudstone (Rex Member) over the Lloydminster Member sandstone forms the top seal of the Senlac reservoir (Figs. 15-9, 15-10).

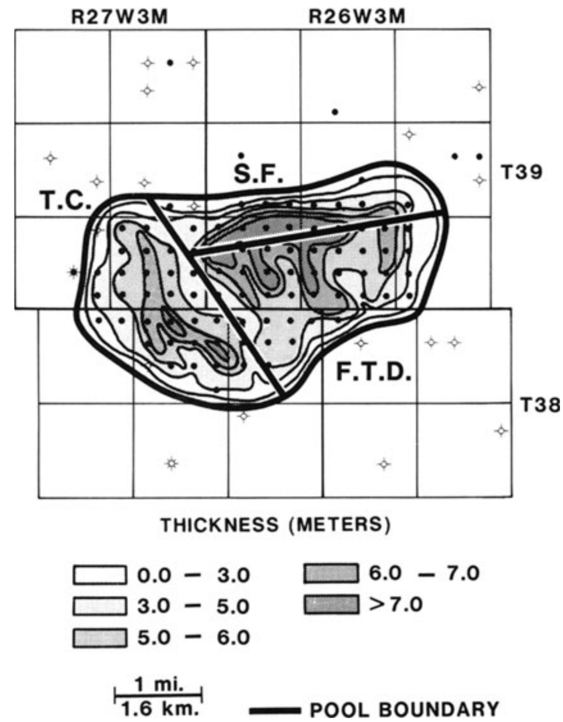


Fig. 15-17. Lloydminster gross-sandstone isopach map of the Senlac Pool. S.F. = shoreface; T.C. = tidal-channel; and F.T.D. = flood-tidal-delta.

The estuarine fill of the Lloydminster Formation in the Senlac area is characterized by facies deposited in three major environments (Fig. 15-13): (1) an outer composite sand plug composed of three distinct sand facies forming the reservoir; (2) a fine-grained central basin; and (3) an inner fluvially dominated, tidally modified delta, which grades headward into fluvial deposits. Figure 15-13 summarizes the interpreted paleogeography of the Senlac embayment at the time of Lloydminster deposition. Figure 15-3 is a modern example of a wave-dominated barrier sand plug from the east coast of Australia that is considered to be an analog to the Senlac area. Figure 15-10 summarizes the

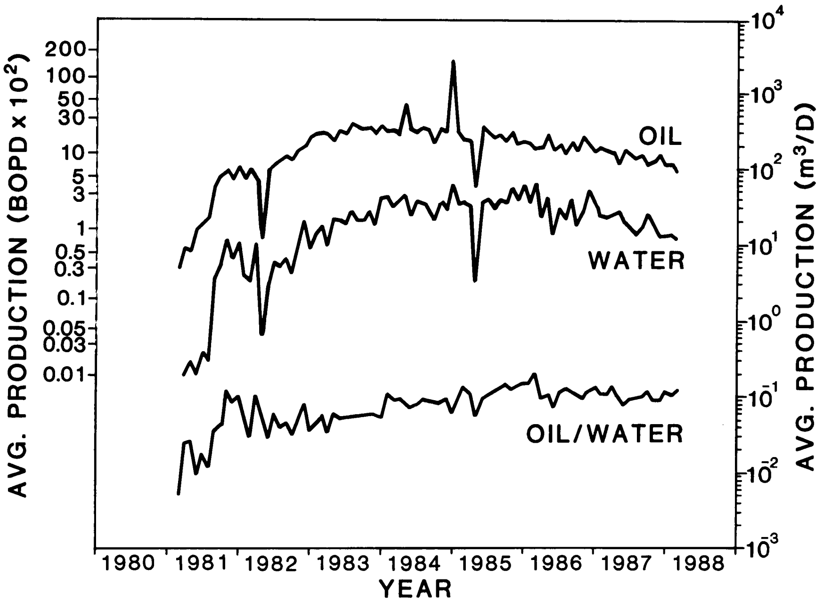


Fig. 15-18. Group summary of averaged fluid production from the Lloydminster sands, Senlac Pool. Data from the Alberta Energy Resources Conservation Board.

the idealized vertical sequence of the fill of the Senlac incised paleovalley.

The Lloydminster sand is a 3.5 by 2 mile (5.6 × 3.2 km) lenticular sandstone body situated near the mouth of the paleovalley (Fig. 15-13). The pool is a pure stratigraphic trap and is divisible into three major components represented by tidal-channel, flood-tidal-delta, and barrier/shoreface environments. The reservoir is encased within a variety of impermeable shales: (1) an updip seal formed by contemporaneous, open-marine shaly facies to the north (i.e., seaward) of the embayment mouth; (2) a top seal provided by the offshore deposits of the overlying Rex parasequence; (3) lateral seals to the east and west consisting of fringing intertidal-flat deposits; and (4) to the south by central estuary fine-grained deposits. Geochemical analysis of the biodegraded oil indicates that it was sourced from the Mississippian Exshaw Formation located to the southwest of the Senlac area (personal communication, S. Creaney and J. Allan, 1988) and subsequently migrated updip to the Senlac stratigraphic trap.

Production Characteristics

The Senlac Pool was discovered in 1980 with development drilling continuing until the end of 1986. Daily production peaked during late 1983 (Fig. 15-18), remained steady at a rate greater than 1,250 BOPD (200 m^3/D) between 1983 and 1985, and has slowly declined to 950 BOPD (150 m^3/D). Cumulative production exceeds 3.7 MMBO (5.9 × 10^5 m^3) (Fig. 15-19, inset).

Figure 15-20 presents the daily oil production averaged over the second 3,000 hours of production for each well in the pool. The wells were averaged by this method to eliminate erratic production during the initial period of well completion and production and to present a common datum from which to compare production across the reservoir. Daily oil production per well varies across the pool from less than 25 barrels (4.0 m^3) to more than 50 barrels (8.0 m^3).

Production rates are controlled by lithofacies. A strong correlation exists between the northwest-southeast-trending zone producing more than 50 BOPD (8.0 m^3/D) along the western edge of the sand plug, and the area interpreted as having been cut by tidal channels. In addition, the east-west-trending shoreface (Fig. 15-13) is characterized by production on the order of 37 BOPD (5.9 m^3/D) (Fig. 15-19). Production is erratic in the southeast portion of the pool in the area dominated by flood-tidal-delta deposits. The majority of the wells in this area are producing less than 25 BOPD (4.0 m^3/D) except in areas that are interpreted to be tidal channels, where rates are 50 BOPD (8.0 m^3/D). In areas where the relationship between depositional facies and production appears inconsistent, variations can be attributed to the differing percentages of each sand type in a particular well.

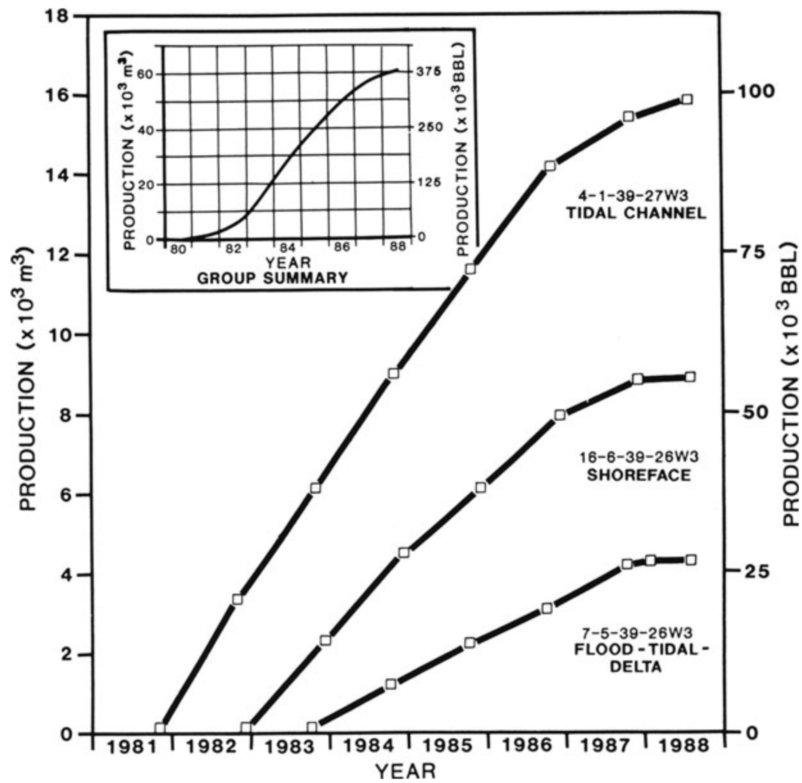


Fig. 15-19. Plot of cumulative oil production vs. time for three typical examples of wells completed in tidal-channel, shoreface, and flood-tidal-delta lithofacies. Inset—total cumulative oil production vs. time for the Senlac Pool. For well locations, see Figure 15-21. Data from the Alberta Energy Resources Conservation Board.

Figures 15-19 and 15-21 show the cumulative daily oil production for representative wells completed in sandstones of tidal channel, shoreface, and flood-tidal delta environments. Line breaks in Figure 15-21 signify temporary production shut-ins, most commonly due to well maintenance. The wells were chosen to exhibit the typical porosity, permeability, and water/oil ratios associated with each of the major depositional facies (Fig. 15-15). The tidal-channel sandstones average 50 to 63 BOPD (8.0–10.0 m^3/D); shoreface sandstones average between 37 and 50 BOPD (5.9–8.0 m^3/D); and the tidal-delta sandstones average between 12 and 25 BOPD (1.9–4.0 m^3/D). Cumulative production data for each depositional facies are shown in Figure 15-19 and vary significantly between facies. Thus, it is clear that the subfacies of the estuarine depositional environment

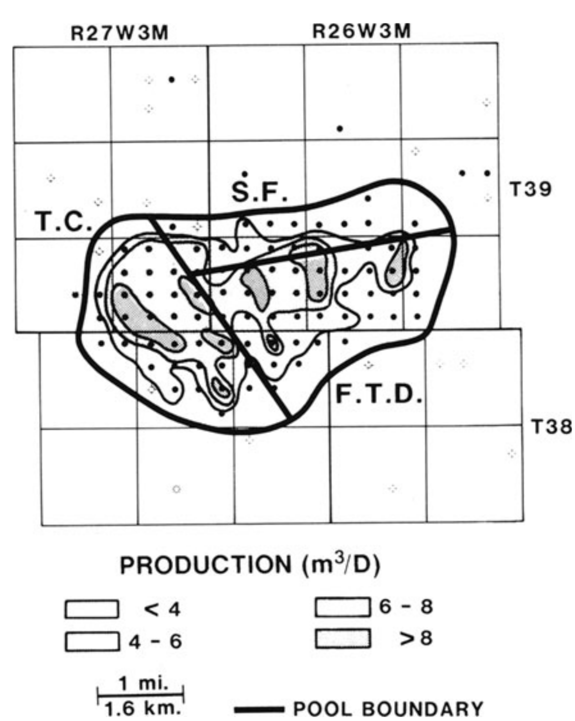


Fig. 15-20. Map of daily oil production (m^3/D) normalized to the second 3,000 hours of production from the Lloydminster sands, Senlac Pool. T.C. = tidal-channel; S.F. = shoreface; F.T.D. = flood-tidal-delta. Data from Alberta Energy Resources Conservation Board.

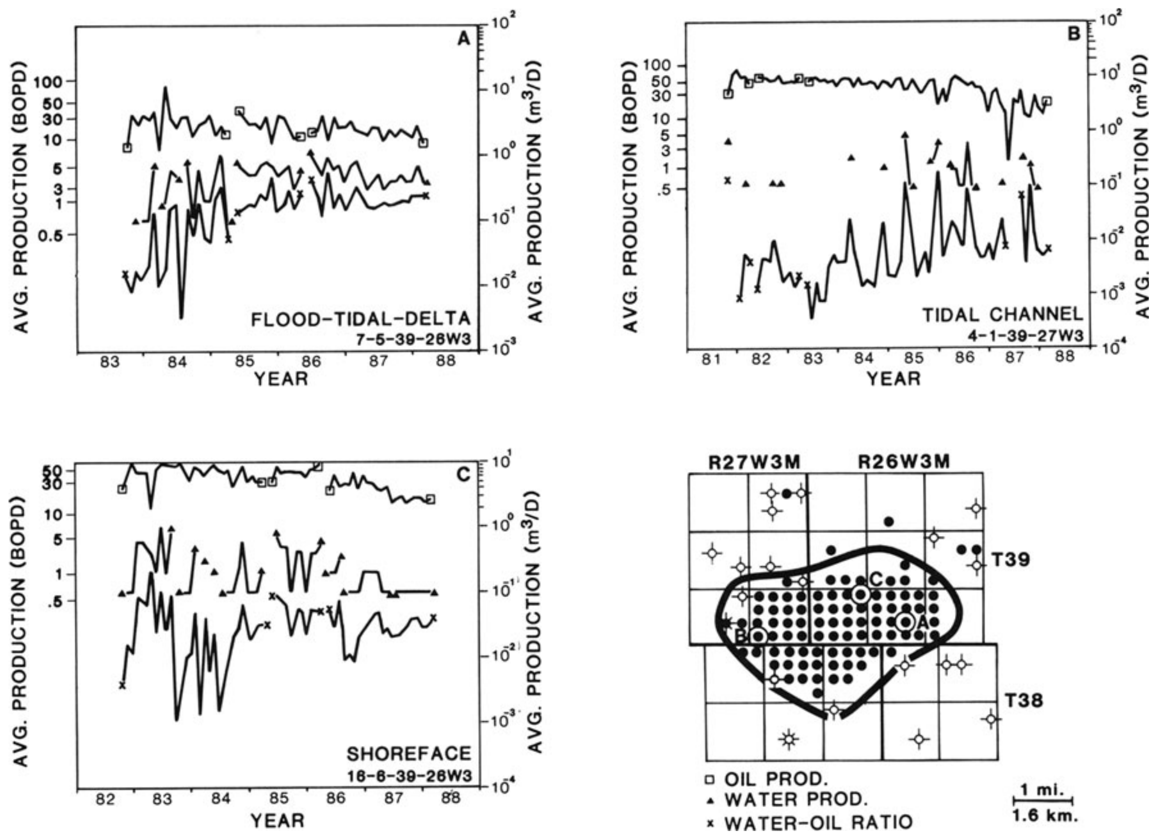


Fig. 15-21. Daily fluid production vs. time for typical examples of wells completed in flood-tidal-delta (A), tidal-channel (B), and shoreface (C) facies. Map shows well locations. Data from the Alberta Energy Resources Conservation Board.

provides the primary control to production characteristics of the Senlac Pool.

In addition, channel and shoreface sandstones produce increased volumes of water with time, whereas the oil/water ratio appears constant in wells which produce from flood-tidal-delta deposits (Fig. 15-21). This is confirmed by the variation between initial versus current water cuts (Figs. 15-22, 15-23). The initial water cut was based on the first three months average production for each well (Fig. 15-23). Water saturation is generally homogeneous across the pool; however, slightly higher water cuts exist in the southeastern portion of the pool. The current water cut is based on the last three months (January- March, 1988) average water production (Fig. 15-23). Higher volumes of water are being produced in the pool area interpreted to be dominated by the tidal-channel facies. A less obvious east-west trend associated with the shoreface deposits can also be detected by comparing Figures 15-22 and 15-23. Areas dominated by flood-tidal-delta deposits have not yielded large volumes of water. The tidal-channel and shoreface water cuts indicate a depleting reservoir in the vicinity of the wellbores. In these wells, water has begun to flow preferentially with respect to the oil. Although pressure data from these wells are not available to the authors, we believe that water is not being coned from the possible waterleg in the southeastern portion of the pool; rather it is the residual water in the vicinity of the wellbore which is being produced as the reservoir begins to deplete.

Exploration And Production Strategy

Exploration Strategy

Successful exploration for estuarine reservoirs within paleovalley systems depends on the ability to identify the distribution of incised paleovalleys in an area and determine the spatial distribution of reservoir facies within these systems.

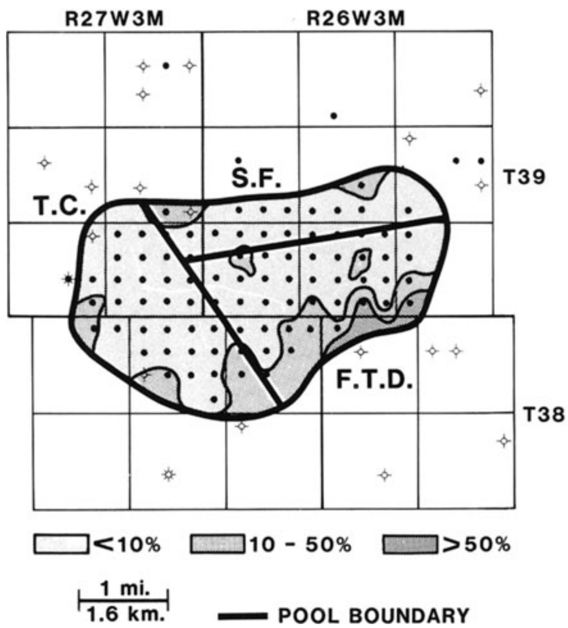


Fig. 15-22. Map of average initial water cut based on the first three months of production for each well in the Senlac Pool. T.C. = tidal-channel; S.F. = shoreface; F.T.D. = flood-tidal-delta. Data from the Alberta Energy Resources Conservation Board.

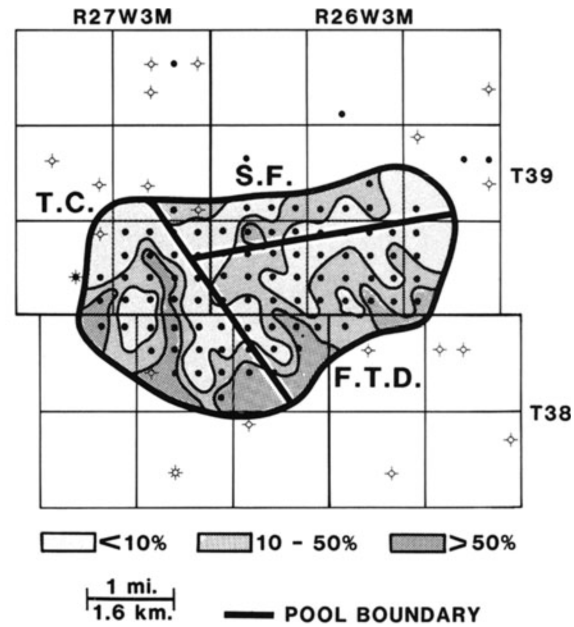


Fig. 15-23. Map of average current water cut based on the final three months of production, Senlac Pool. T.C. = tidal-channel; S.F. = shoreface; F.T.D. = flood-tidal-delta. Data from the Alberta Energy Resources Conservation Board.

To locate incised valley systems, it is critical to document the nature of the irregular paleotopographic surface and the direction of paleodrainage. A variety of techniques can be employed to map such a paleotopographic surface: seismic structural mapping; simple structural mapping of an erosional surface from well logs; and residual mapping of structural surfaces in areas that have undergone postdepositional structural tilting. Other methods that can be utilized to identify incised paleovalley systems include detailed isopach mapping to locate anomalously thick stratigraphic sections confined to paleotopographic lows; downward shift in facies; and detailed correlations to identify truncation of regionally extensive markers, thus defining the incision (Weimer, 1984).

Reservoir facies can be predicted with detailed core analysis calibrated to wireline logs. Because comprehensive estuarine facies models are not available to evaluate these cores (Frey and Howard, 1986; Zaitlin, 1987), the opportunity exists for effective depositional models to be constructed from subsurface data using log correlations and high-resolution seismic stratigraphy.

A regional understanding of parasequence stacking patterns can be applied within the paleovalley to predict the spatial distribution of reservoir facies throughout the system. Once the transgressive and regressive limits of the facies within a well-documented paleovalley have been determined, these can be extrapolated as fairways parallel to depositional strike; the intersection of these fairways with other paleovalley systems are areas of possible exploration potential.

Production Strategy

The ultimate aim of all development strategies is to maximize hydrocarbon recovery at the lowest unit cost in the shortest possible time. This can be achieved by reducing the number of wells required for primary production and by more efficient use of injectors during enhanced recovery operations. Both require a complete understanding of the reservoir facies architecture and its effect on fluid movement.

As demonstrated in this chapter, estuarine deposits contain a variety of possible reservoir facies. Wave-dominated estuarine systems can contain significant reservoir potential in the Zone C tidal-fluvial channels located at the head of the estuarine system (e.g., Crystal Viking Pool, Reinson et al., 1988; Reinson and Clark, this volume) or in the composite estuarine sand plug of Zone A. In each case, a different production strategy must be developed to account for the differences in reservoir geometry.

Zone C reservoirs are long, sinuous stacked channel-fill sandstones which may or may not be in reservoir communication. Zone A reservoirs, although in communication, are formed by a complex association of facies, each with different permeability and porosity characteristics. Evaluation of the production characteristics across the Senlac Pool indicated that lithofacies distribution is the primary control on reservoir behavior. Better production characteristics associated with the tidal-channel facies is a function of internal homogeneity, better lateral continuity, higher effective permeabilities, and coarser grain size. The upward-coarsening profiles of the shoreface deposits are characterized by textural inhomogeneities and variations in vertical porosity and permeability which result in decreased reservoir continuity. The flood-tidal-delta facies are also composed of repetitive coarsening-upward sequences and have the poorest production behavior. This poor production is interpreted to be a function of more internal permeability barriers, greater internal inhomogeneity, a higher proportion of fines, and lower reservoir continuity.

This complex arrangement of reservoir subfacies has an important control on fluid production response. As an example, Senlac Pool was characterized by an initial water cut that was uniform across the pool; however, after seven years of primary production, water cuts in the reservoir have become significantly more variable and will impact the combustion attributes for a potential fire flood of the pool.

Conclusions

The Saskoil Gulf-Senlac Heavy Oil Pool produces from the Lloydminster Member of the Lower Cretaceous Mannville Group. The distribution of facies within the Lloydminster Member in the Senlac area is interpreted to represent a wave-dominated sandy estuarine complex comprising a tidal-fluvial delta at the headward end, a middle central basin, and an estuarine sand plug at the seaward end. The Senlac reservoir is developed within the estuarine sand plug and is a composite feature dominated by tidal-channel, flood-tidal-delta, and shoreface sandstones. The reservoir body is a stratigraphic trap encased in fine-grained open-marine, central basin, and intertidal-flat deposits. The best production in the reservoir is associated with tidal-channel deposits; poorer production performance is associated with the shoreface deposits, and flood-tidal-delta deposits display the poorest production capabilities. Knowledge of the reservoir complexities of estuarine deposits and an understanding of the spectrum of estuarine depositional systems can significantly improve both exploration and production results.

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Reservoir Summary

Field: Senlac Heavy Oil Pool
Operators: Gulf Canada, Saskoil (Saskatchewan Oil & Gas)
Discovery: 1980
Location: West-central Saskatchewan, Canada
Basin: Western Canada sedimentary basin
Tectonic/Regional Paleosetting: Marginal to shallow epicontinental seaway (foreland basin)
Geologic Structure: Homoclinal dip

Trap Type: Stratigraphic pinch-out
Reservoir Drive Mechanism: Solution-gas drive
- **Original Reservoir Pressure:** NA

Reservoir Rocks
- **Age:** Early Cretaceous (Aptian to lower Albian)
- **Stratigraphic Unit:** Lloydminster Member, Mannville Group
- **Lithology:** Fine- to medium-grained sublitharenites
- **Depositional Environment:** Wave-dominated estuarine complex
- **Productive Facies:** Tidal-channel, shoreface, and tidal-delta of estuarine sand body
- **Petrophysics**
  - **Porosity Type:** Intergranular
  - **ϕ:** Tidal Channel—Average 27.5%, range 25 to 30% (cores/logs); Shoreface—Average 29.0%, range 27 to 31% (cores/logs); Flood-Tidal Delta—Average 30.0%, range 29 to 31% (cores/logs)
  - **k:** Tidal Channel—Average 3,000 md, range 3,000 to 4,000 md (cores); Shoreface—Average 2,500 md, range 1,000 to 4,000 md (cores); Flood-Tidal Delta—Average 2,700 md, range 2,000 to 4,000 md (cores)
  - **S_w:** 16 to 37% (logs)

Reservoir Dimensions
- **Depth:** 2,540 to 2,640 feet (775–805 m)
- **Areal Dimensions:** 3.5 by 2.0 miles (5.6 × 3.2 km)
- **Productive Area:** 4,818 acres (1,951 ha.)
- **Number of Reservoirs:** 1
- **Hydrocarbon Column Height:** NA
- **Fluid Contacts:** NA
- **Number of Pay Zones:** 1
- **Gross Sandstone Thickness:** 10 to 23 feet (3.0–7.0 m)
- **Net Sandstone Thickness:** 10 to 23 feet (3.0–7.0 m)
- **Net/Gross:** Approximately 1.0

Source Rocks
- **Stratigraphic Unit:** Basinal shales of the Exshaw Formation (Mississippian)
- **Time of Maturation:** Late Cretaceous (?)
- **Time of Trap Formation:** Early Cretaceous
- **Time of Migration:** Late Cretaceous (?)

Hydrocarbons
- **Type:** Oil
- **API Gravity:** 13 to 15°
- **FVF:** 1.11
- **Viscosity:** 1,245 to 3,959 cP ($1.2–4.0 \times 10^6$ Pa·s) at 77°F (25°C)

Volumetrics
- **In-Place:** 84.3 MMBO (1.3×10^7 m^6)
- **Cumulative Recovery:** 3.7 MMBO (5.9×10^5 m^3)
- **Ultimate Primary Recovery:** 6.4 MMBO (1.0×10^6 m^3)
- **Primary Recovery Efficiency:** 7.5%

Wells
- **Spacing:** 1,320 feet (400 m), 40 acres (16.2 ha.)
- **Total:** 94 (84 presently producing)
- **Dry Holes:** 7

Typical Well Production:
- **Cumulative Production:** NA
- **Average Daily:** Tidal Channel—50 to 63 BOPD (8.0–10.0 m^3/D); Shoreface—37 to 50 BOPD (5.9–8.0 m^3/D); Flood-Tidal Delta—12 to 25 BOPD (1.9–4.0 m^3/D)

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Key Words

Senlac Heavy Oil Pool, Saskatchewan, Canada, western Canada Sedimentary basin, Lloydminster Member, Mannville Group, Early Cretaceous; Aptian-lower Albian, estuarine facies, tidal-channel deposits, flood-tidal-delta deposits, incised paleovalley systems, in situ combustion, fire flood, EOR, heavy oil, progradational-shoreface deposits.