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AN ESTUARINE-EMBAYMENT FILL MODEL FROM THE LOWER CRETACEOUS MANNVILLE GROUP WEST-CENTRAL SASKATCHEWAN

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ABSTRACT

The Saskoil-Gulf Senlac Heavy Oil Pool, located in Townships 38-39, Ranges 26-27 W3M, west-central Saskatchewan, produces from the Lloydminster Member 'Sands' of the Lower Cretaceous Mannville Group. The Dina-Cummings Member unconformably overlies the Devonian Duperow Formation and is composed of a 10-30 m fining-upward sequence of sandstone, siltstone and shales containing pyritized rootlets and a restricted trace fossil assemblage (*Palaeophycus heberti, Conichnus, Lockeia* and *Thalassinoides*). The overlying Lloydminster Member consists of a basal 1-5 m thick coal, and acritarch-bearing, pinstripe laminated, tidal and lenticular bedded shales, containing a diverse ichnofossil suite (*P. heberti, P. tubularis, Planolites, Teichichnus, Conichnus* and *Cylindrichnus concentricus*), that underlie the 0-8 m thick Lloydminster Sand.

The Lloydminster Sand is divisible into two distinct lithofacies: Type 1 sand consists of a 2-5 m thick, unconsolidated, fine to very fine grained sand arranged in 5-150 cm fining-upward cycles. Each cycle is composed of a basal erosional surface overlain by medium angle, planar to trough crossbedded sands that grade upward through trough cross-laminated to rippled silts and silty shales, capped by thin carbonaceous shales. The Type 2 sand is 4-7 m thick, fine grained and exhibits undulating and ripple bedding, with minor amounts of flaser bedding. Bioturbated sandstone, siltstone and silty shales of the Rex Member containing dinoflagellate cysts, foraminifera and a wide diversity of ichnofossils (including *Ophiomorpha*), overlie the Lloydminster Member.

The Lower Mannville Dina-Cummings to Rex sediments in the Senlac area were deposited within a 25 km (N-S) by 6 km (E-W) northward opening paleo-topographic embayment. The sequence is interpreted, based upon its paleogeomorphic setting, vertical stratigraphic sequence and inferred lithofacies distribution, to represent the progressive change from terrestrial valley-fill deposits in inferred northward draining paleo-valley systems (Dina-Cummings), to estuarine-embayment fill deposits, with associated salt marsh, tidal flat, lagoonal and subtidal (channel and tidal delta/shoal) environments (Lloydminster), to marine deposits of the Rex Member, resulting from an Early to Mid-Albian transgressive event.

INTRODUCTION

An estuary is defined as a "semi-enclosed coastal body of water which has a free connection with the open sea, and within which seawater is measurably diluted with fresh water of river origin" (Pritchard, 1967). Modern classifications of estuaries are based on one, or a combination of the following parameters: 1) geomorphic setting (Pritchard, 1967); 2) residual circulation and stratification patterns (Pritchard, 1955; Pritchard and Carter, 1971); or, 3) tidal range (Davies, 1964; Hayes, 1975; Hayes and Kana, 1976). The distribution of sediments within an estuary is controlled by the interaction of tidal currents, wave energy, fluvial input, biogenic activity, type and source of detritus, and basin geometry. The type and geometry of the resulting estuarine lithofacies is a function of the sediment dispersal pattern within a basin (i.e. circulation) which is controlled ultimately by its geomorphic setting.

The identification of ancient, tidally-influenced estuarine deposits in the geologic record is tenuous due to the difficulty in the determination of: 1) the residual paleocirculation pattern; and 2) the presence or absence of density and/or salinity paleo-stratification within a basin due to the (paleo-fluvial) input of fresh water. Geologic interpretations of tidalite and/or tidal deposits have therefore been based on the distinct combination of sedimentary structures, vertical sequences, textures, lithofacies, and a suitable regional and stratigraphic setting (Klein, 1971; Ginsburg, 1975). Ginsburg suggested that the sedimentary structures needed to recognize a tidally influenced environment result from: A) the rapid reversal of depositing currents (e.g., herringbone cross-stratification, reactivation surfaces); B) small-scale alternations in slack water and strong current conditions (e.g., flaser, lenticular, and wavy bedding, mud drapes); C) intermittent subaerial exposure (e.g., mud cracks, rainprints, root traces, tracks and trails); and D) alternating erosional and depositional features (e.g., channels). Ginsburg also stated that, unless a sequence contained unequivocal examples of A, B and C (above), an interpretation of an ancient sequence to have been tidally deposited would be open to question. This combination of features, along with a brackish water fauna, would then be indicative of a tidally-influenced estuarine environment in outcrop.

In the subsurface further restrictions exist in the interpretation of ancient sequences as being deposited under tidal conditions. The lack of traceable lateral continuity of section, and the consequent inability to examine sedimentary structure in detail, in addition to the fact that wireline log correlations may at times be tenuous, may inhibit the recognition of specific depositional settings. Subsurface geological estuarine interpretations, therefore, must result from the study of the lithofacies distribution within, and the paleogeomorphic setting, of the depositional basin.

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Few studies to date have dealt with the sedimentology of Mannville Group deposits in west-central Saskatchewan. This paper will use the stratigraphic, structural, seismic, and sedimentological data from the lower third of the Mannville Group in the Senlac area to develop a model for a transgressive estuarine-embayment fill deposit. Such transgressive estuarine-embayment fill deposits have not yet, to the authors' knowledge, been reported from the subsurface.

Historical Background, Reservoir Characteristics and Data Base

The Saskoil-Gulf Senlac Heavy Oil Pool, located in Twps 38-39, Rges 26-27 W3M (Fig. 1) produces from the Lloydminster Member 'Sands' of the Lower Cretaceous Mannville Group (Zaitlin et al., 1983; Fig. 2). The Lloydminster 'Sand' is present at an average depth of 785 m, and is estimated to contain 13.6 x 10 m^3 initial oil in place. The pool was discovered in June 1980, with the drilling of Gulf-Saskoil Senlac A5-1-39-27 W3M (Fig. 3). The net pay reservoir boundary as presently mapped covers approximately 1870 ha (Fig. 4). The derived reservoir characteristics are presented in Fig. 5.

Fifteen of the sixty wells within the pool were cored, with fourteen of the cores penetrating the Lloydminster 'Sand' interval (Fig. 1). In addition to the logging of all core, the remaining pool and surrounding wells were investigated to place the Senlac area into its regional context.

Regional Stratigraphic and Structural Framework

The regional stratigraphic framework for west-central Saskatchewan is presented in Figure 2. Devonian and Mississipian carbonates and minor clastics of the Saskatchewan, Three Forks and Madison Groups compose the "Basement" (Vigrass, 1977; Christopher, 1980). A well developed regional unconformity (Late Jurassic-Early Cretaceous) truncates the gently southward dipping Paleozoic "Basement" and is overlain by a northward thickening wedge of Lower Cretaceous Mannville sediments. The Mannville Group is disconformably overlain by the Upper Cretaceous Colorado Group, which has been interpreted to represent deposits of the Upper Cretaceous Interior Epicontinental Seaway (Williams and Stelck, 1975).

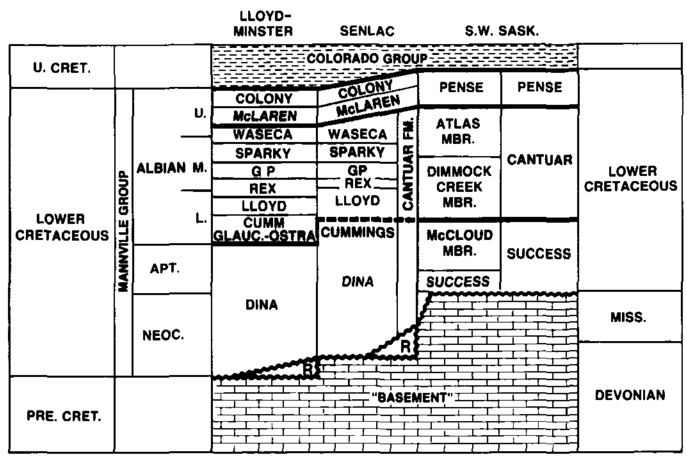

Fig. 2. Stratigraphic nomenclature used in this study, modified after Nauss (1945), Vigrass (1977) and Christopher (1980), for the Lloydminster, Senlac, and southwestern Saskatchewan (S.W. Sask.) area. Neo = Neocomian; Apt = Aptian; L, M, U = Lower, Middle, Upper; Glauc-Ostra = Glauconitic-Ostracod Zone; Cumm = Cummings; Lloyd = Lloydminster; R = Residual Zone; FM = Formation; Mbr = Member; Miss = Mississippian. "Basement" consists of the Saskatchewan, Three Forks and Madison Groups.

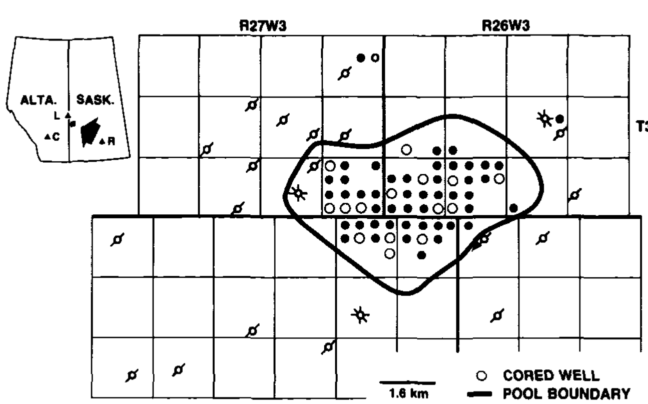

Fig. 1. Distribution of cored wells in the Saskoil Gulf Senlac Pool Area. Arrow in inset is toward the location of the Senlac area (Square) in west-central Saskatchewan (Twps 38-39, Rges 26-27 W3M). C = Calgary, L = Lloydminster, R = Regina.

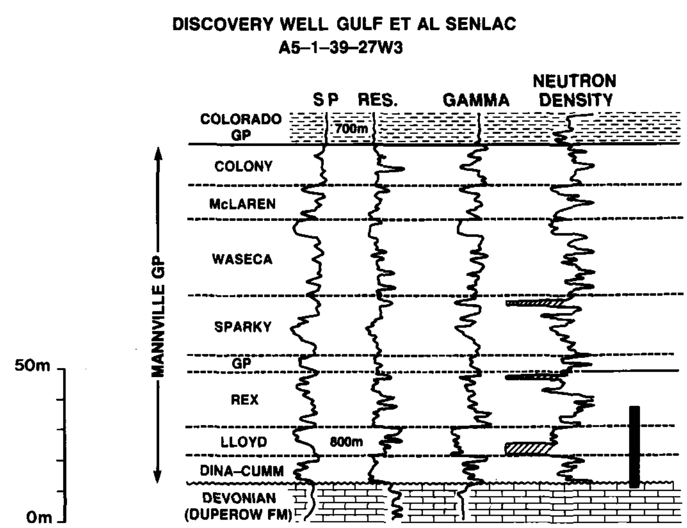

Fig. 3. Characteristic Log Response for the Gulf *et al.* Senlac A5-1-39-27 W3M discovery well. SP = spontaneous potential; RES = resisitivity. Hachured zones are coals. Bar indicates section studied in this paper.

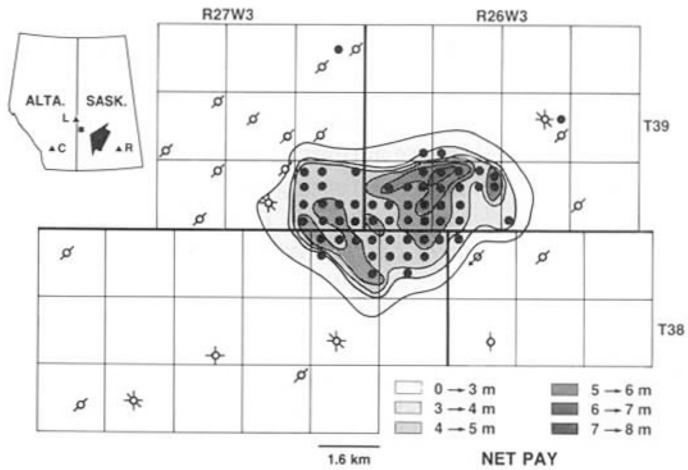

Fig. 4. Lloydminster Formation 'Sand' Net Pay map for the Senlac Area. Contour interval is 1 m net pay, with a 3 m economic cutoff (1982).

INITIAL OIL IN PLACE	**$13.6 \times 10^6 m^3$**	
POOL AREA	**1870 ha**	**(4620 ACRES)**
AVERAGE DEPTH	**775 – 805m**	
LLOYD SAND THICKNESS	**3.5 – 8.0m**	
LLOYD NET PAY	**3.0 – 7.5m**	
GRAIN SIZE	**2.82 – 3.34 ∅**	**(v.f–f. SAND)**
POROSITY (∅)	**27 – 32%**	**(29.2%)**
WATER SATURATION (Sw)	**16 – 37%**	**(25%)**
API GRAVITY	**13.0 – 15.0°**	
VISCOSITY (EST. DEAD OIL)	**1245 – 3950 mPa @ 25°C**	
PERMEABILITY	**2000 – 4000 md (APPROX)**	

Fig. 5. Saskoil Gulf Senlac Reservoir Characteristics.

The Mannville Group of the Vermilion-Lloydminster area has historically been divided into 9 Members/Formations (Nauss, 1945; Vigrass, 1977; Fig. 2). The confusion in Mannville Group nomenclature appears to result from the attempt to correlate units between mappable sub-basins (Ranger, 1983). Deposition within each sub-basin was controlled by the original Aptian-Lower Albian paleo-topographic surface. This irregular surface effectively formed a series of depositional sub-basins separated by paleotopographic highs (Ranger, 1983). Unique lithofacies belts would be expected to form within each sub-basin, dependent on local topography and the timing of transgressive/regressive events in the basin. For this reason, 'Lower Mannville' rock units in one geographic area may not be equivalent to those of another area. At Senlac we define the Lower Mannville to include the undifferentiated Dina-Cummings, the Lloydminster and the Rex intervals, as we interpret this sequence to have been deposited due to the first major transgressive event into the area.

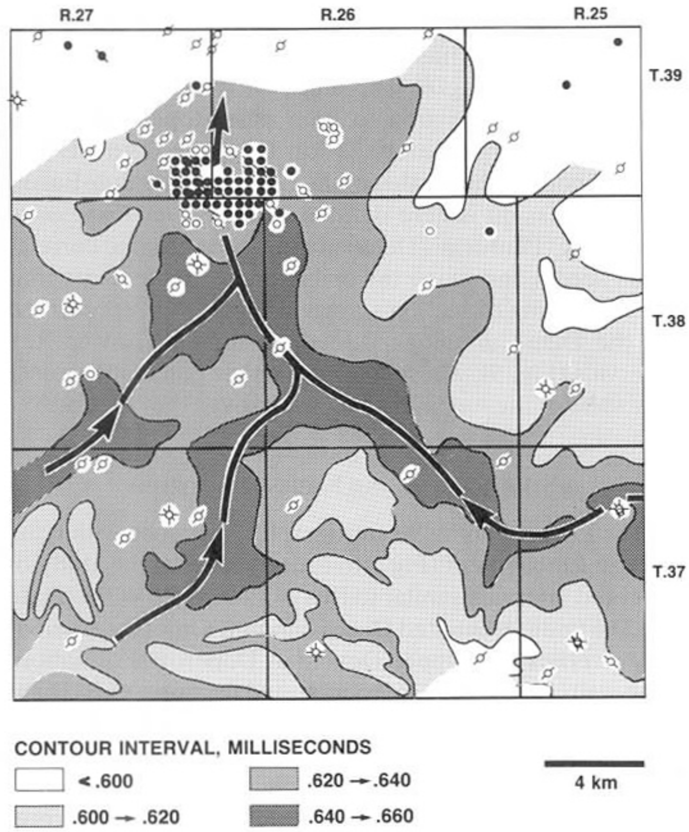

Fig. 6. *Structural seismic interpretation on the Sub-Cretaceous Unconformity. Contour interval .020 milliseconds. Datum - present day sea level. Arrows indicate paleo-valley trends and inferred drainage directions.*

The Senlac area is interpreted to have been situated at the southern limit of an Early Cretaceous depositional sub-basin, hereafter termed the 'Lloydminster Sub-Basin'. This sub-basin straddles the northern edge of the 'Unity-Kindersley-Swift Current Platform' paleotopographic high (Christopher, 1980; Ranger, 1983), hereafter termed the 'Platform'. The Mannville Group averages 180-230 m in thickness within the 'Lloydminster Sub-Basin', and abruptly thins to 70-100 m over the 'Platform' (Ranger, 1983). Mannville Group isopachs over areas of original Lower Cretaceous paleo-topographic lows within the 'Platform' can, however, exhibit an appreciable local thickening of section to more than 200 m.

A structural seismic map of the sub-Mannville erosional surface from the Senlac area reveals that a localized 10 to 30 millisecond depression exists across the pool (Fig. 6). This localized 10-30 millisecond dip is equivalent to 20-40 m of original paleotopographic relief. The Mannville Group isopach exhibits an equivalent increase in section within this low (Fig. 7). The magnitude of the east-west depressions increases southward to a maximum of 60 milliseconds, indicative of up to 80 m of relief. Overall the structure on the sub-Mannville erosional surface exhibits a present day southward dip.

A structural third order residual map of the sub-Mannville erosional surface has the net effect of removing post-depositional tilt (Fig. 8). This map clearly shows the depression in the Senlac area to be a paleo-topographic low measuring approximately 25 km (N-S) by 6 km (E-W), which opens to the north into the Lloydminster Sub-Basin. This depression is here defined as the *Senlac Embayment* within the 'Platform'. Detailed litho-stratigraphic correlations across and along the embayment axis indicate that the thickening of section shown in Figure 7 is represented by the Dina-Cummings, Lloydminster and Lower Rex intervals (Fig. 9). These intervals either pinch out against the walls of the embayment, or thin over the 'Platform'.

Stratigraphy and Facies Description

The Lower Mannville stratigraphic sequence within the Senlac Embayment (Fig. 10) is derived from the study of 15 cored intervals similar to that of 12-5-39-26 W3M (Plate 1). The undifferentiated Dina-Cummings interval erosionally overlies the Upper Devonian Duperow Formation. One well (1-6-39-26 W3M) penetrated the uppermost Dina-Cummings; cores exhibit well-cemented calcareous sandstones and siltstones containing pyritized rootlets (Plate 2a) and an ichnofossil assemblage consisting of *Palaeophycus heberti, Conichnus, Lockeia* and *Thalassinoides*. As interpreted from logs, the Dina-Cummings forms a 10-30 m fining upward sequence near the axis of the embayment, thinning toward the 'Platform' high.

The Lloydminster Coal overlies the Dina-Cummings and is taken to differentiate the Dina-Cummings from the Lloydminster "Sand". The coal sequence ranges in thickness from 1-5 m, and is composed of lignite coals with interbedded dark carbonaceous shales exhibiting minor pinstripe lamination, rootlets and *Palaeophycus heberti*.

The Lloydminster shale has a patchy distribution throughout the area, but where present directly overlies the coal. It ranges in thickness from 0 - .75 m and is characterized by well developed pinstripe, lenticular and tidal bedding (Plate 2). The shale yields rare acritarchs and a diverse suite of recognizable shallow burrowing and deposit feeding ichnofossils (*Palaeophycus heberti, P. tubularis, Planolites, Teichichnus, Conichnus, Cylindrichnus concentricus*).

The uppermost interval of the Lloydminster Member is composed of the Lloydminster "Sand", which can directly overlie either the shale or coal. The sand is divisible into two distinct lithofacies defined here as Type 1 and Type 2 sands. Type 1 is a 2-5 m thick, oil saturated, unconsolidated, fine- to very fine-grained sand, comprising repeated 5-150 cm fining-upward cycles (Plate 3a). Each Type 1 cycle can consist of an erosional basal surface that is overlain by medium angular, planar to trough cross-bedded sands which grade upward through cross-laminated to rippled silts to silty shales. The latter may, in turn, be overlain by horizontally laminated carbonaceous silty shales. The silt to silty shale package rarely comprises more than 5 percent of any one cycle. *Chondrites* and *Skolithos linearis* are present within the silty shales. Sharp (erosional) surfaces between cycles are sub-horizontal, bounding the slightly inclined cross-stratified to rippled units. Oil saturation decreases upward in each cycle.

Type 2 sands range in thickness from 4-7 m, are dominantly fine grained, and are moderately to well sorted. Type 2 sands exhibit extensive undulating to low angle planar and ripple bedding, with minor (>5 percent) siltstone and claystone flaser interbeds. No ichnofossil assemblage was recognized. Oil saturation is homogenous throughout this facies, and is significantly greater than the Type 1 facies (Figure 11).

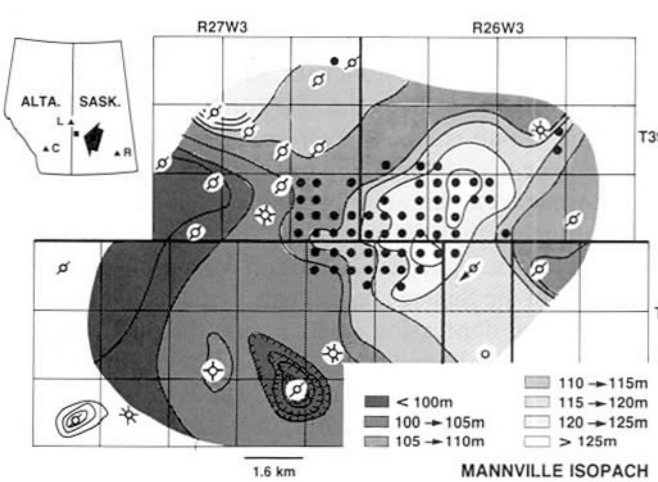

Fig. 7. Mannville Group Isopach from the Senlac Area, Saskatchewan. Contour Interval = 5 m.

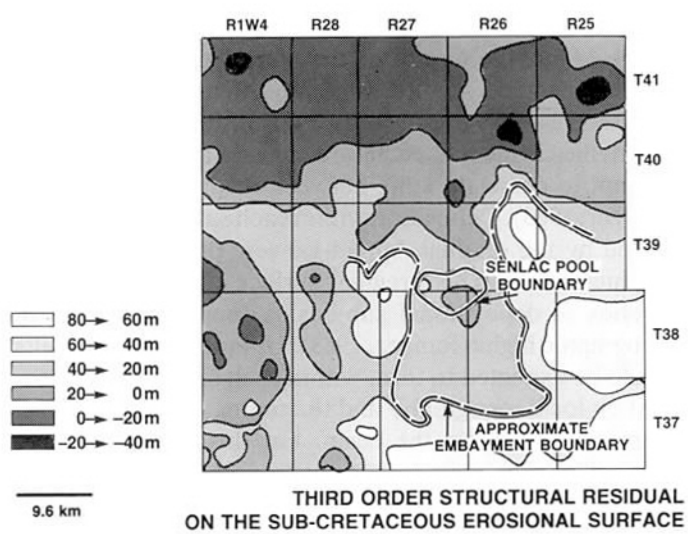

Fig. 8. Third Order Structural Residual map of the sub-Cretaceous Erosional Surface, Senlac and surrounding areas. Embayment (outlined by dashes) measures approximately 25 km (N-S) by 6 km (E-W).

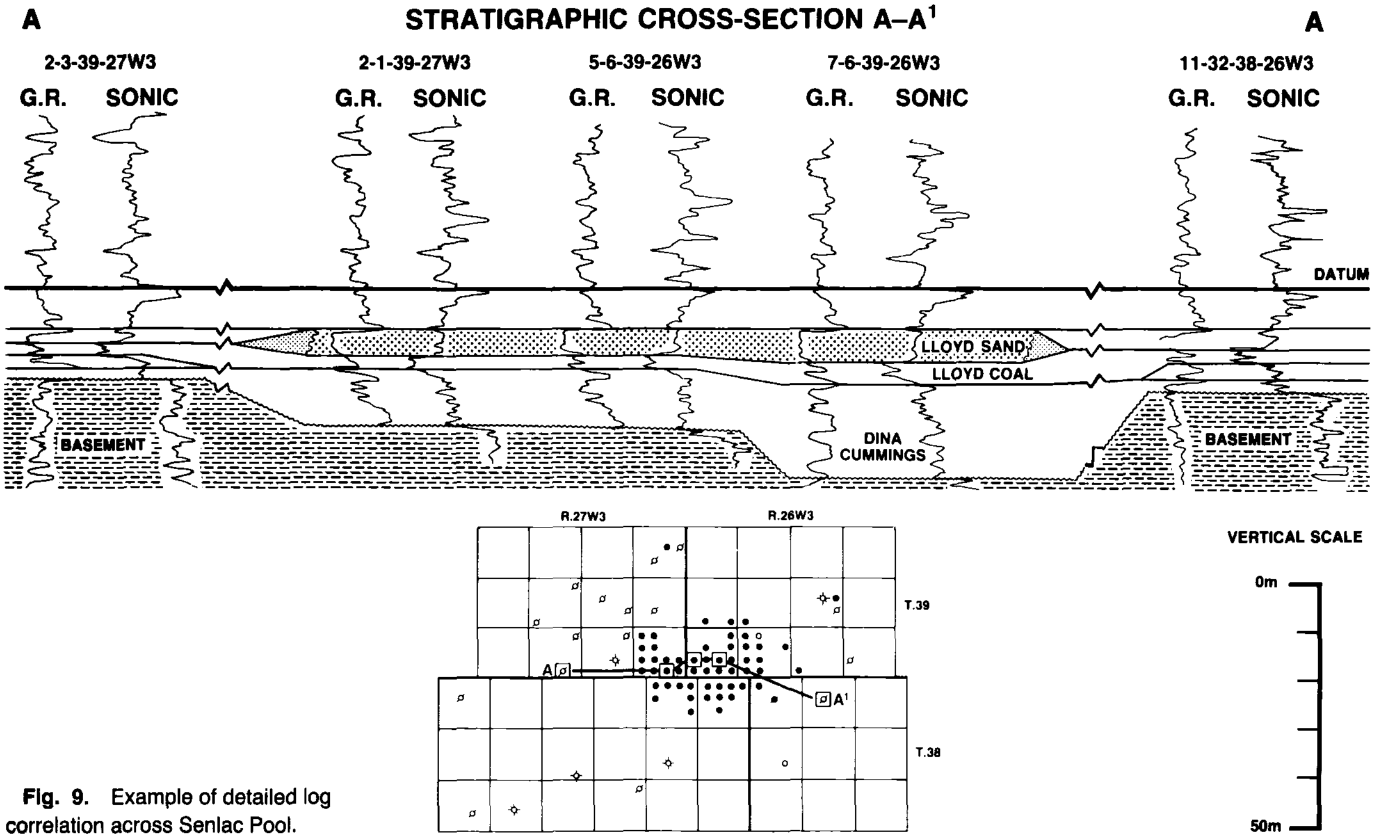

Fig. 9. Example of detailed log correlation across Senlac Pool.

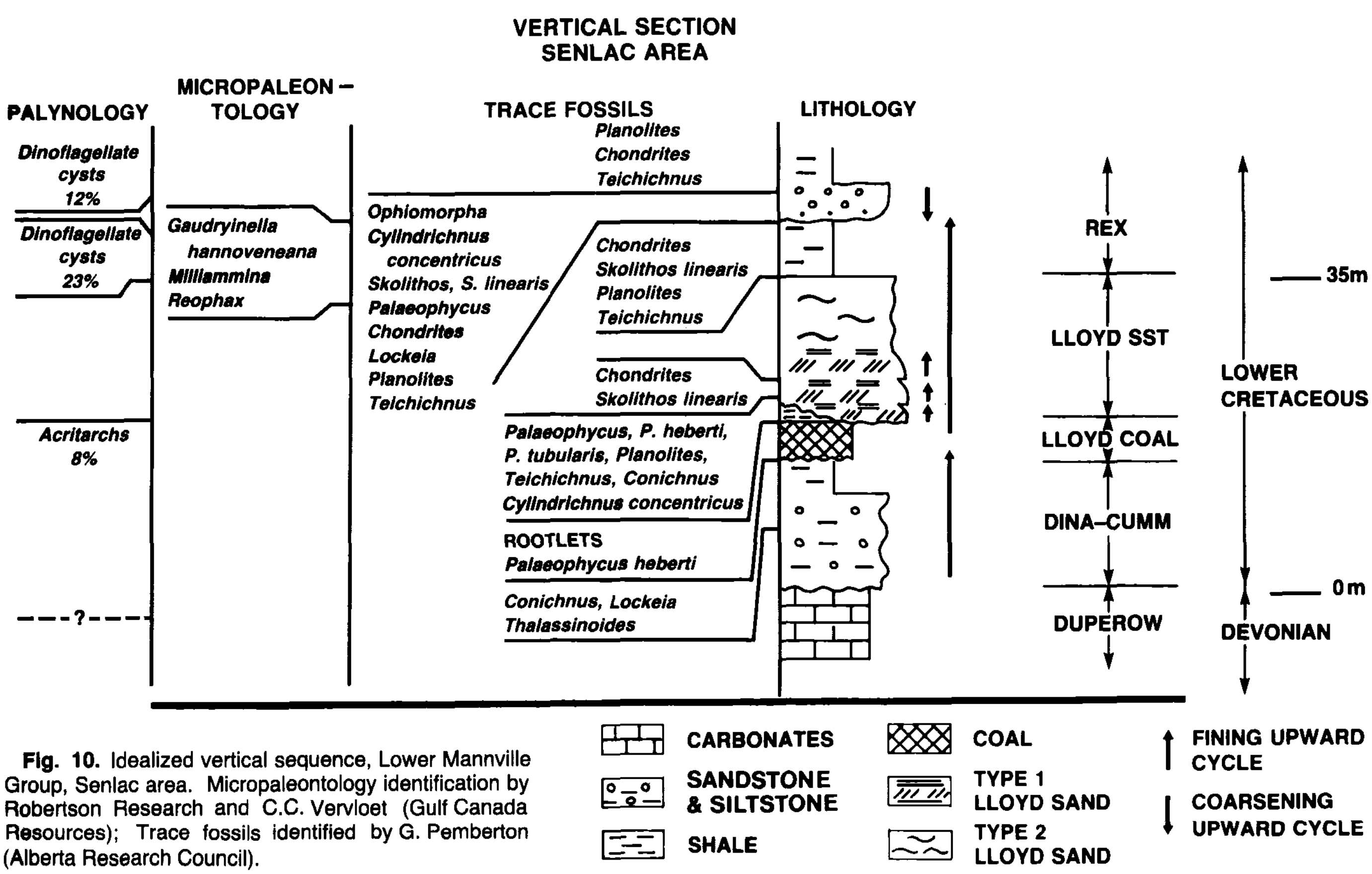

Fig. 10. Idealized vertical sequence, Lower Mannville Group, Senlac area. Micropaleontology identification by Robertson Research and C.C. Vervloet (Gulf Canada Resources); Trace fossils identified by G. Pemberton (Alberta Research Council).

Type 1 and 2 sands are not discernible by log signature from conventionally run wireline tools. The two lithofacies are easily detectable, however, in core and on dipmeter or micro-resistivity logs by the repetitive cyclic appearance of Type 1 sand contrasted with the blocky appearance of Type 2 sand. Due to the scarcity of dipmeter and micro-resistivity logs in the study area, and the lack of internal marker beds, however, it was considered not possible to present lithofacies distribution maps for Type 1 and 2 sands.

Petrographic studies have not been completed on the Lloydminster Sands. Initial work indicates that Type 1 and Type 2 sands are both compositionally sublitharenites, dominated by quartz and chert, with accessory feldspar, carbonaceous material, rock fragments and traces of glauconite. A clay matrix (<8 percent by weight), composed of kaolinite, with minor illite, smectite, and traces of smectite-illite mixed layer clays are present. Based on visual examination of the core, and the higher water content of Type 1 sand, it appears that Type 1 sand contains a higher interstitial clay content (Fig. 11).

The Rex Member abruptly overlies the Lloydminster Member and ranges in thickness from 5-10 m. The Rex forms a coarsening upward sequence, with a basal carbonaceous pyritic shale containing an ichnofossil suite of *Chondrites, Skolithos linearis, Planolites* and *Teichichnus*, that is overlain by bioturbated silty sands. The bioturbated sands have a patchy distribution, and contain dinoflagellate cysts, *Gaudryinella hannoveneana, Miliammina, Reophax,* and an ichnofossil assemblage containing *Ophiomorpha, Cylindrichnus concentricus, Skolithos, S. linearis, Palaeophycus, Chondrites, Lockeia, Planolites* and *Teichichnus*. A subfacies of the Rex consists of graded low angle (<10°) bedded and trough cross-laminated sandstone overlain by shales containing dinoflagellate cysts and *Planolites, Chondrites* and *Teichichnus* traces (Plate 4). The General Petroleums (GP) Member is interpreted from logs to overlie the Rex Member at the first appearance of coal stratigraphically above the Lloydminster Coal.

Distribution of Lloydminster Sands

The geometry and distribution of the Lloydminster Gross 'Sand' isolith for the Senlac Area is presented in Figure 12. Zone A is a NW-SE trending zone of thickened sand along the western edge of the pool. Type 1 sand appears to be dominant, with an approximate Type 1:Type 2 sand ratio of 1.5:1, obtained from visual examination of the core. Zone B is an arcuate E-W trending sand wedge, with an apparently steeply dipping northern edge, tapering off to the south, cut by a N-S trending sand. From core, Zone B is dominated by Type 2 sand (Type 1:Type 2 sand ratio = 1:3). Core from the eastern portion of Zone B consists of interbedded Type 1 and 2 sands, but in all cases the top sand is of Type 2. The intervening areas have Type 2 sand overlying Type 1 sand in varying proportions across the embayment, averaging 4-5 m in total thickness.

It is inferred from log and seismic data that the Lloydminster Sand continues southward along the embayment axis, where it is structurally lower and wet. The Lloydminster Sand appears to undergo a facies change near the head of the embayment into a laterally equivalent shale facies averaging 1-2 m in thickness. A 5-10 m thick sequence of bioturbated shales, siltstones and silty/shales of the Rex Member abruptly overlies the Lloydminster interval; the entire sequence overlying the Lloydminster Coal.

The two schematic stratigraphic cross-sections of the facies distribution presented in Figure 13 were constructed from detailed log correlations across the pool (Fig. 9) Consistent gamma ray log signatures were used to deter-

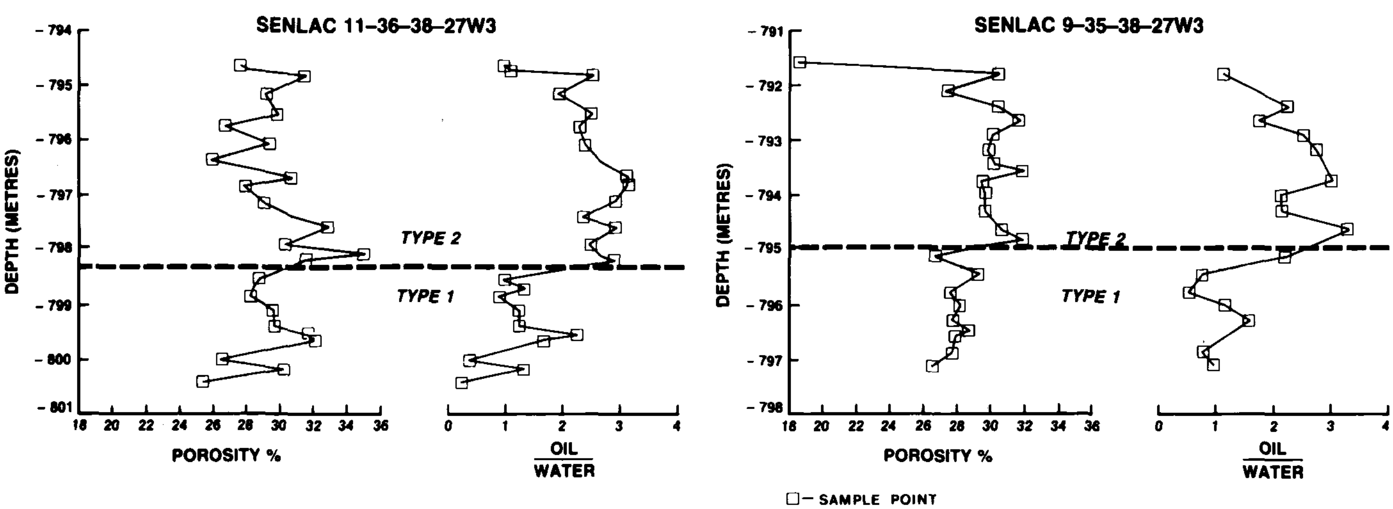

Fig. 11. Examples of porosity (Ø) and Oil:Water vs. depth for 9-35-38-27 W3M and 11-36-38-27 W3M. Note the significant change in Oil: Water between Type 1 and Type 2 sands.

mine relative sand thicknesses (Fig. 3). The base of the Lloydminster Coal was used as the datum, with its approximate paleo-depositional dip derived from the 3rd order residual map (Fig. 8). The cross-section (Fig. 13a) runs parallel to the original northward dip of the embayment axis. The underlying Dina-Cummings interval pinches out to the south against the 'Platform', except where present within the paleo-valleys that fed northward into the embayment (Fig. 6). The Dina-Cummings is absent or appreciably thinned on the 'Platform' high. The overlying Lloydminster Coal maintains a relatively uniform thickness down the axis of the embayment (Fig. 13a), pinching out to the south against the 'Platform'. The overlying (undifferentiated) Lloydminster Sand forms a lensoid body, with an apparent steep slope toward the north. The sand is absent beyond the embayment mouth. If equivalent sand is present to the north, it would occur as isolated bodies with no connection to the Senlac Lloydminster sand. The sand is interpreted to taper off to the south as a result of the facies change from sands to shales which, in turn, pinch out against the head of the embayment. The Rex Member (Plate 4) would overlie this sequence, draping over the Lloydminster interval.

The E-W schematic stratigraphic cross-section (Fig. 13b) is constructed perpendicular to the axis of the embayment and exhibits (exaggerated) paleo-topographic relief associated with the sub-Cretaceous erosional surface. The Dina-Cummings interval is thickest along the embayment axis, and either thins over, or pinches out against the embayment (paleo-valley) walls. The basal Lloydminster Coal mimics the original paleo-topographic surface, but exhibits much more subdued relief. The coal dips slightly northward and pinches out to the east and west against the embayment walls. The Lloydminster Sand and Shale sequence is deposited over the coal as a pod shaped body, confined by the embayment (paleo-valley) walls. The sand thickens toward the northeast and undergoes a lateral facies change east and west into the Lloydminster Shale. Although sands on the sub-Cretaceous highs appear to be stratigraphically equivalent to the Lloydminster sand in the embayment, they are considered distinct due to 1) slight difference in log signature, 2) lack of oil saturation, and 3) facies changes from sandstone to siltstone to shale. These Lloydminster shale parallels the embayment margins. The Lloydminster sequence is mantled by the shales, siltstones and sandstones of the Rex interval.

INTERPRETATION

Correlation of wireline logs indicate that the Dina-Cummings forms a 10-30 m fining-upward sequence restricted to the paleo-valleys. Core of the uppermost part of the Dina-Cummings sequence exhibits well cemented sandstones and siltstones containing pyritized rootlets (Plate 2a) and an ichnofossil assemblage consisting of *Palaeophycus heberti*, *Conichnus*, *Lockeia*, and *Thalassinoides* (Figure 10).

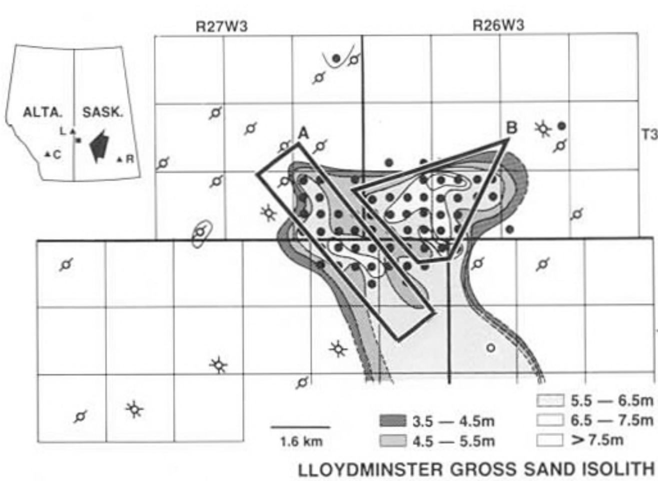

Fig. 12. Lloydminster Gross Sand Isolith, Senlac area, Saskatchewan. Zone A is dominated by Type 1 sands; Zone B by Type 2 sands. Contour interval = 1 m.

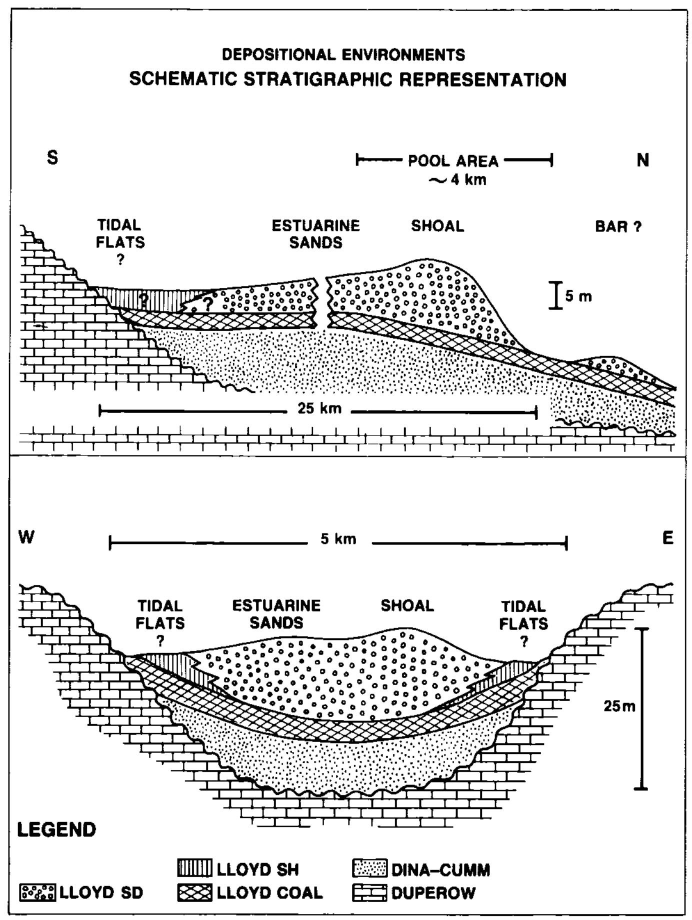

Fig. 13. Schematic stratigraphic representation of the Lloydminster Sand, with the interpreted distribution of depositional environments. 13A = N-S Section; 13B = E-W Section; Lloyd = Lloydminster; SD = Sand; SH = Shale; Dina-Cumm = Dina Cummings.

Based on its stratigraphic position and fining-upward sedimentary characteristics, the lower portion of the Dina-Cummings interval is interpreted to represent a paleo-valley fill within the incised sub-Cretaceous erosional surface. Study of the same interval in adjacent areas indicates that the first depositional interval above the sub-Cretaceous unconformity is usually fluviatile. The orientation of interpreted paleo-valleys from the seismic structural map (Fig. 6) and the 3rd order residual map on the sub-Cretaceous surface (Fig. 9) indicate that local drainage was from south to north. The introduction of a brackish shallow marine ichnofossil suite near the top of the sequence suggests the beginning of the slow southward flooding of the paleo-valley and the tidally-influenced rivers at the end of Dina-Cummings time, similar to estuarine fills described by Oomkens and Terwindt (1960).

The Lloydminster Coal, Shale and Sands that overlie the Dina-Cummings interval are interpreted to represent the deposits of a major marine transgression (flooding) of the paleo-valley/embayment. Paleo-valleys to the south would still be expected to flow from S-N, and would be a source of fresh water input into the embayment. If this was the case, it would fulfill the classical definition of an estuary (Pritchard, 1967).

The 'Coal' and associated interbedded carbonaceous shales that fringe the embayment are interpreted to represent extensive salt marsh/peat swamp conditions. The pinstripe-laminated, lenticular and tidally bedded Lloydminster Shale encircles the embayment. The shale contains rare acritarchs and a diverse suite of recognizable shallow burrowing and deposit feeding ichnofossil traces (*Palaeophycus heberti, P. tubularis, Planolites, Teichichnus, Conichnus, Cylindrichnus concentricus*). The pinstripe, tidal and lenticular laminations, ichnofossil suite, and its stratigraphic position rimming the embayment suggests a low energy, brackish (intertidal to shallow subtidal?) mud-dominated environment similar to those of modern mud to mixed tidal flat deposits (Terwindt, 1981; Reineck, 1975; Kraft, 1971; Kraft and Allen, 1975; Greer, 1975).

The Lloydminster Sand erosionally overlies the Lloydminster Shale and Coal along the axis of the embayment. The dominance of Type 1 sand in Zone A (Fig. 12) suggests that strong currents were operative along the western margin of the embayment. Sparse dipmeter analysis from this zone, correlated to the core, appears to indicate dominant SE to NW transport. The scale of the fining upward cycles (5-150 cm), and the sequence of sedimentary structures, with erosional and bounding (reactivation?) surfaces between cross-stratified units, can be interpreted to represent the migration of large scale bedforms (mega-ripples and/or sand waves) in sub-tidal channels (Hayes, 1975; Hayes and Kana, 1976; Dalrymple et al., 1978; Terwindt, 1981; Evans, 1975; Elliott and Gardiner, 1981). The presence of a restricted trace fossil assemblage (*Chondrites* and *Skolithos linearis*) within the laminated to rippled silty shales of Type 1 sand may be the result of brackish water conditions.

Zone B (Fig. 12) contains a thickened sand body which has an apparent abrupt northern edge and tapers off to the south. A north-south trend of thickened sand cuts through the sand wedge. The complex is dominated by Type 2 sands with wavy and flaser bedded sands. The geometry and distribution of sand lithofacies can be interpreted to represent a shoal or (flood) tidal delta cut by tidal channels (Hayes, 1975; Hayes and Kana, 1976).

The Lloydminster interval is abruptly overlain by the bioturbated shales, siltstones and silty sandstones of the Rex interval (Fig. 10; Plate 4); which contain abundant dinoflagellate cysts, foraminifera (*Gaudryinella hannoveneana, Miliammina and Reophax*), in addition to a large diversity of ichnofossils (including *Ophiomorpha*), which, when taken together, strongly suggests less restricted marine conditions.

The spatial distribution of depositional environments thought to have developed during latest Lloydminster time in the Senlac area is presented in Figure 14.

Discussion

The Lower Mannville vertical sequence in the Senlac Area (Fig. 10), when taken in context with the paleogeomorphic setting of a northward opening embayment within the Platform, is interpreted to represent a progressive change from fluviatile deposition in northward draining paleo-valleys incised during a Jurassic-Lower Cretaceous erosional event, to an estuarine-embayment paleo-valley fill during the early Albian transgressive event of the northern Boreal Sea. The estuarine fill is characterized by the transition down the axis of the embayment from supratidal salt marsh/peat swamp to intertidal, lagoonal mud

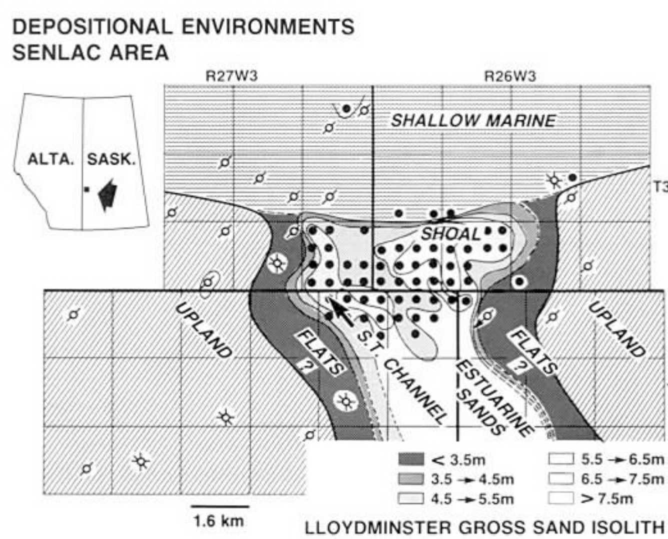

Fig. 14. Distribution of depositional environments, Late Lloydminster time, Senlac area. S.T. Channel = Sub-tidal Channel.

and mixed flats, to sub-tidal sands (with tidal channels, shoals and tidal delta sub-environments). The entire sequence is capped by less restricted shallow marine deposits.

The northern limit of estuarine sand deposition during latest Lloydminster time appears to have been controlled by the position of the embayment mouth (Fig. 6). North of the mouth, isolated sand accumulations may have been deposited, but sand appears to have been effectively removed from the area (by longshore currents?).

The elongated northwest to southeast trending Zone A is composed of repeated fining upward cycles of sand to shale that were apparently deposited by strong currents. Zone B is asymmetric north to south, with a gently southward dipping ramp and a steep northern margin. The entire complex can be interpreted to represent a flood tidal delta cut by a migrating network of ebb tidal channels. Deposition in the low energy back delta/shoal area would explain the relative high proportion of fines contained in the upper portions of Type 1 sands.

The configuration of the Lloydminster sub-basin, and the location of the Senlac area at the southern end of this sub-basin, may have amplified any tidal influence associated with the transgressing epicontinental sea. The asymmetric distribution of shoal/tidal delta and tidal channel environments within the embayment would appear to have resulted from an asymmetric, tidally influenced circulation pattern, or wave dominated area, that was operative within the embayment. The high energy nature of the northeast portion of the estuarine fill, with planar and low angle stratification of Zone B, may have developed due to wave reworking and/or asymmetric circulation. Depositional environments would be expected to migrate headward as the transgression progressed. If the transgression occurred at a sufficiently rapid rate, then one would expect similar depositional sequences to be "preserved" southward along the embayment.

Trapping Mechanism

The approximate boundary of the Senlac Pool (Fig. 15) shows the inferred oil/water contact running north-east to south-west along the southern edge of the pool. In wells to the south the Lloydminster Sand is water wet. Initial and produced water cuts indicate encroachment of water in the southeast part of the pool. Consequently, the Senlac Pool is interpreted to be a combined stratigraphic/structural trap. Initial sand deposition was controlled by the paleogeomorphology of the embayment. The northern limit of the pool is controlled by the absence of sand due to non-deposition. The eastern and western limits of the reservoir are controlled by a combined stratigraphic/structural trap due to the sand deposit pinching out laterally. This is a result of facies change from the estuarine sands to mudflats. The southern limit, however, is controlled by post depositional southward tilt of the area and updip migration (and subsequent degradation) of hydrocarbons (Fig. 16).

Comparison of the Senlac Model with Other Tidal Deposits

The Senlac Embayment fill developed within a pre-existing north-south trending drowned paleo-valley due to the southward transgression of a migrating epicontinental sea. The Senlac model is similar to those of Kraft (1971) and Kraft and Allen (1975), in which Holocene tidally influenced coastal sediments transgress over an incised pre-Holocene landscape along the New England coast. Kraft and Allen (1975) documented vertical sequences similar to those in the Senlac field, where sediments infilled embayments. A composite network of tidal deltas, subtidal channels, estuarine sands, and fringing salt marsh formed along the leading edge of the transgressive unit. In some of

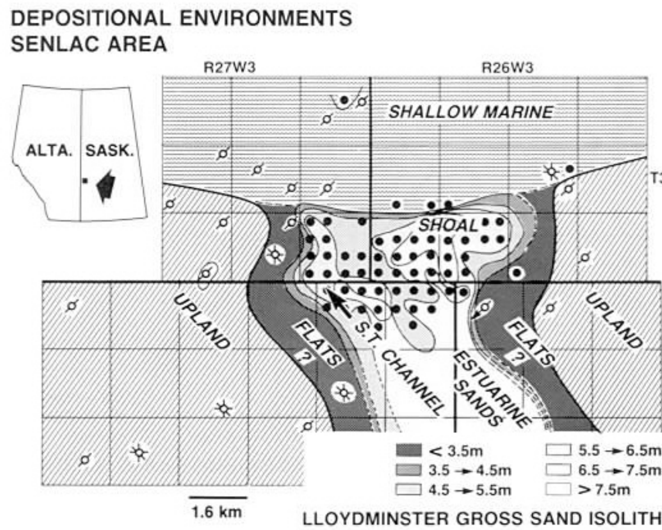

Fig. 15. Trapping mechanisms, boundaries and oil water contact superimposed on Late Lloydminster depositional environment distribution, Senlac area, Saskatchewan. S.T. Channel = sub-tidal channel; Arrows indicate inferred major flow directions.

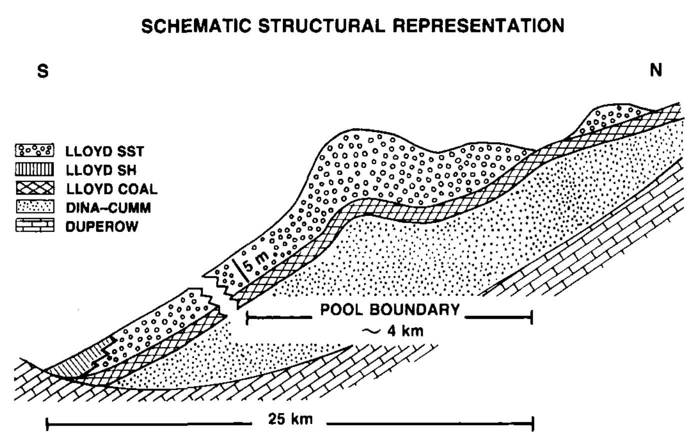

Fig. 16. Schematic structural representation of the Lloydminster Sand with present oil-water contact. Lloyd = Lloydminster, Dina-Cumm = Dina-Cummings, SD = Sand, SH = Shale.

the New England examples, the embayment mouth was controlled by a bay-mouth barrier, but either continued transgression, reworking, lack of sediment supply, or sufficient time to reach equilibrium with sea level, may eventually alter and erode the barrier unit, so that a shoal or tidal delta similar to that at Senlac may remain.

The above described estuarine fill mechanism is presently operating along the eastern shore of Nova Scotia (R. Boyd, per comm. 1983). There the estuarine sand complexes are expected to be preserved in areas where the controlling paleo-valleys have suitable topographic relief to 'capture' the estuarine lithofacies within the embayment. If transgression continues at a low rate, wave base will intersect the sediment surface and effectively remove and transport sediment headwards in the embayment. However, if transgression continues at a high rate, with a resultant increase in water depth, the sand would not be transported but would be preserved in the embayment system. In this case marine shales would directly overlie the estuarine sand facies. The latter mechanism appears to adequately describe the depositional sequence for the Lower Mannville in the Senlac area. Therefore, the vertical sequence and distribution of lithofacies in the New England and Nova Scotia transgressive models are considered to be good modern analogues to the ancient estuarine embayment fill in the Senlac Area.

Conclusions

The Saskoil-Gulf Senlac reservoir produces from the sand of the Lloydminster Member of the Lower Cretaceous Mannville Group. The Dina-Cummings to Lower Rex vertical sequence (approximately 20-40 m) is interpreted to represent the progressive change from fluviatile-paleo-valley infill (Dina-Cummings) to estuarine embayment (Lloydminster), to open marine conditions (Rex), within a 25 km (N-S) by 6 km (E-W) embayment. The transgressive vertical lateral distribution of lithofacies is similar to those reported along the New England and Nova Scotia coasts, and is one of the few transgressive estuarine-embayment fill sequences interpreted from the subsurface.

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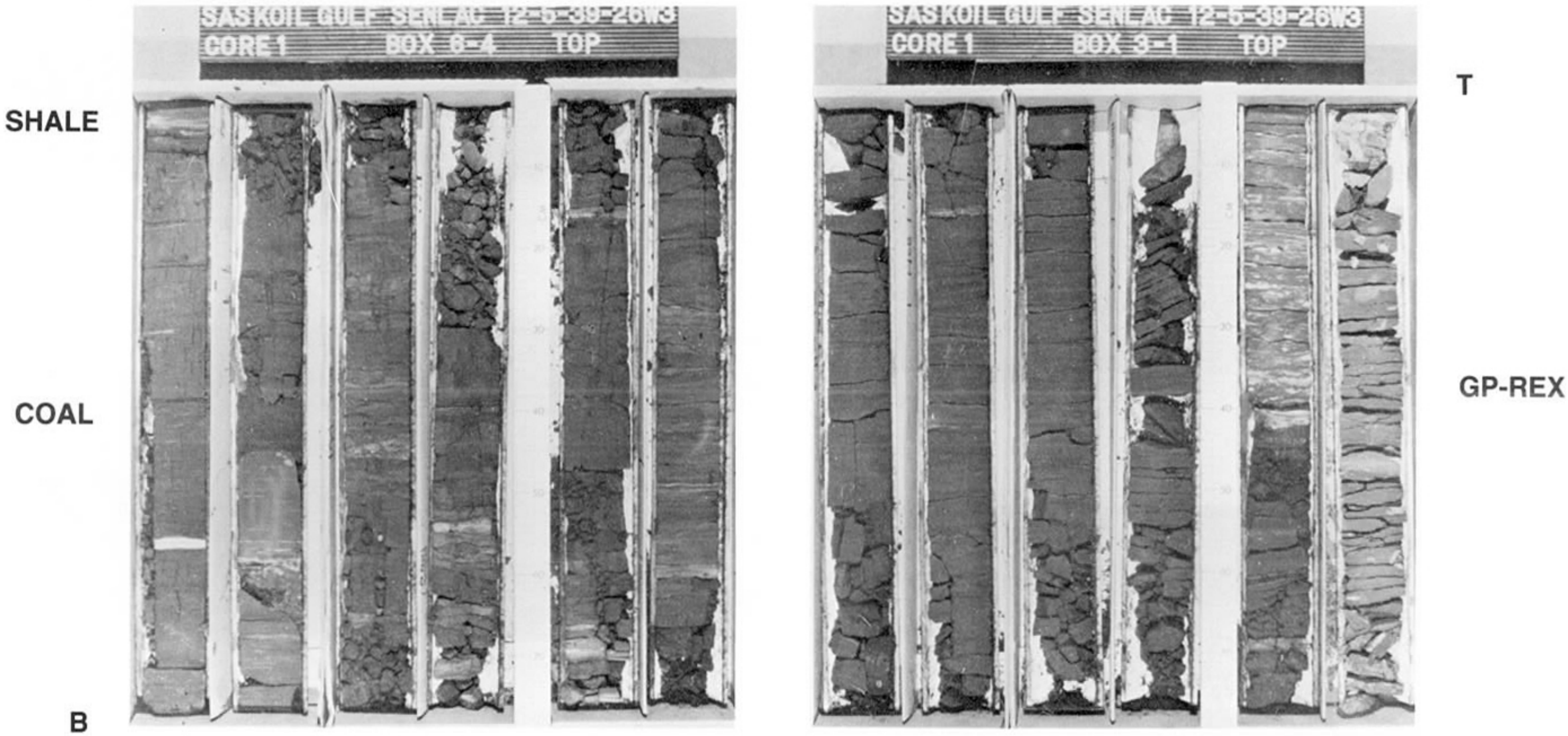
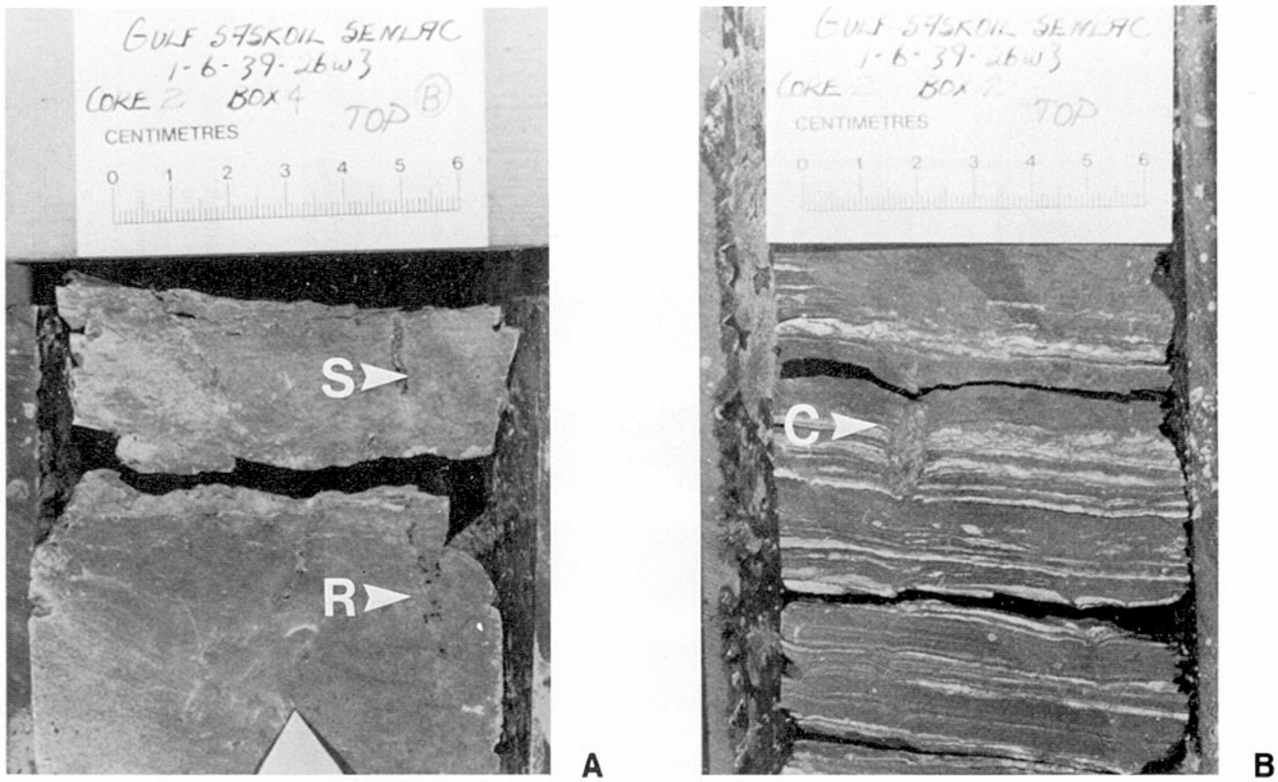


Plate 1. Full core photograph of Saskoil Gulf Senlac 12-5-39-26W3M (773.5-782.5 m). Top of core is to upper right (T), base of core is to bottom left (B). Lloydminster *Coal* (*COAL*) is abruptly overlain by the pinstripe laminated to lenticular bedded Lloydminster Shale (Shale). The Lloydminster Sand erosionally overlies the Shale, and is divisible into Type 1 and Type 2 sands, based on changing oil saturation. Repetitive fining-upward cycles (Type 1), overlain by wavy to undulating, homogenous oil saturated sands (Type 2). The Rex siltstones, bioturbated sandstones and shale overlie the Lloydminster Sand.



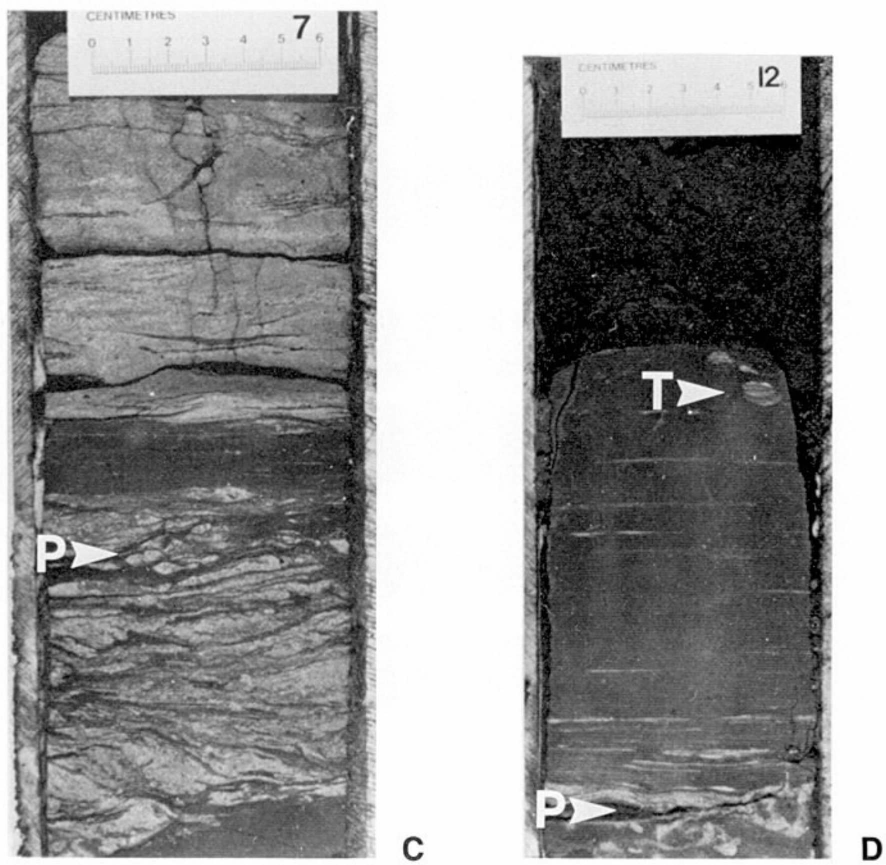


Plate 2.

a) Upper Dina-Cummings Member displaying pyritized rootlets (R), and *Skolithos* (S). (Gulf Saskoil Senlac 1-6-39-26W3M);
b) Pinstripe laminated to lenticular bedded shales and fine-grained sandstone. Well developed *Conichnus* (C) is present (Lloydminster Shale, Gulf Senlac 1-6-39-26W3M);
c) Bioturbated Lloydminster Shale, exhibiting abundant *Planolites* (P) with some intact zones of prinstripe lamination, overlain by lightly oil stained silty sandstone (Lloydminster Type 2 sand). (Saskoil Gulf Senlac 11-36-38-27W3M);
d) Well developed fine pinstripe laminations within Lloydminster carbonaceous shale, exhibiting *Teichnicus* (T) and *Palaeophycus* (P), erosionally overlain by Lloydminster Shale (Gulf Saskoil Senlac 12-5-39-26 W3M).

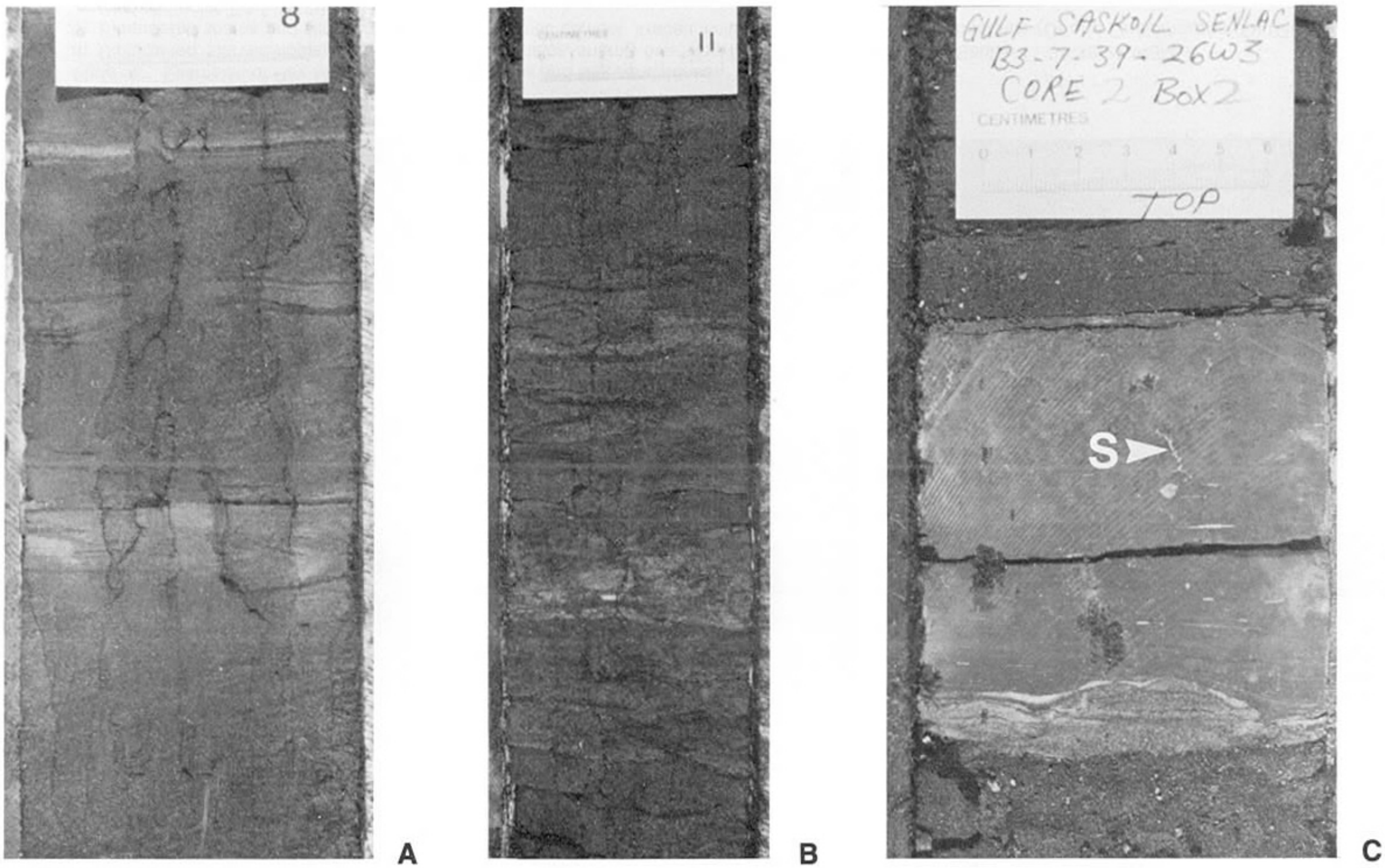


Plate 3.

a) Example of Type 1 Sand. Note 6-8 cm thick cycles of erosional surface-low angle planar (<10°) -trough cross-lamination-erosional surface (Saskoil Gulf Senlac 11-36-38-27 W3M).

b) Example of wavy bedded Lloydminster Type 2 Sand, with minor amount of flaser bedding (Saskoil Gulf Senlac 12-5-39-26 W3M).

c) Example of Lloydminster Shale within Type 1 Sand, with pin-stripe lamination and compressed shrinkage cracks (S) (Gulf Saskoil Senlac B3-7-39-26 W3M).

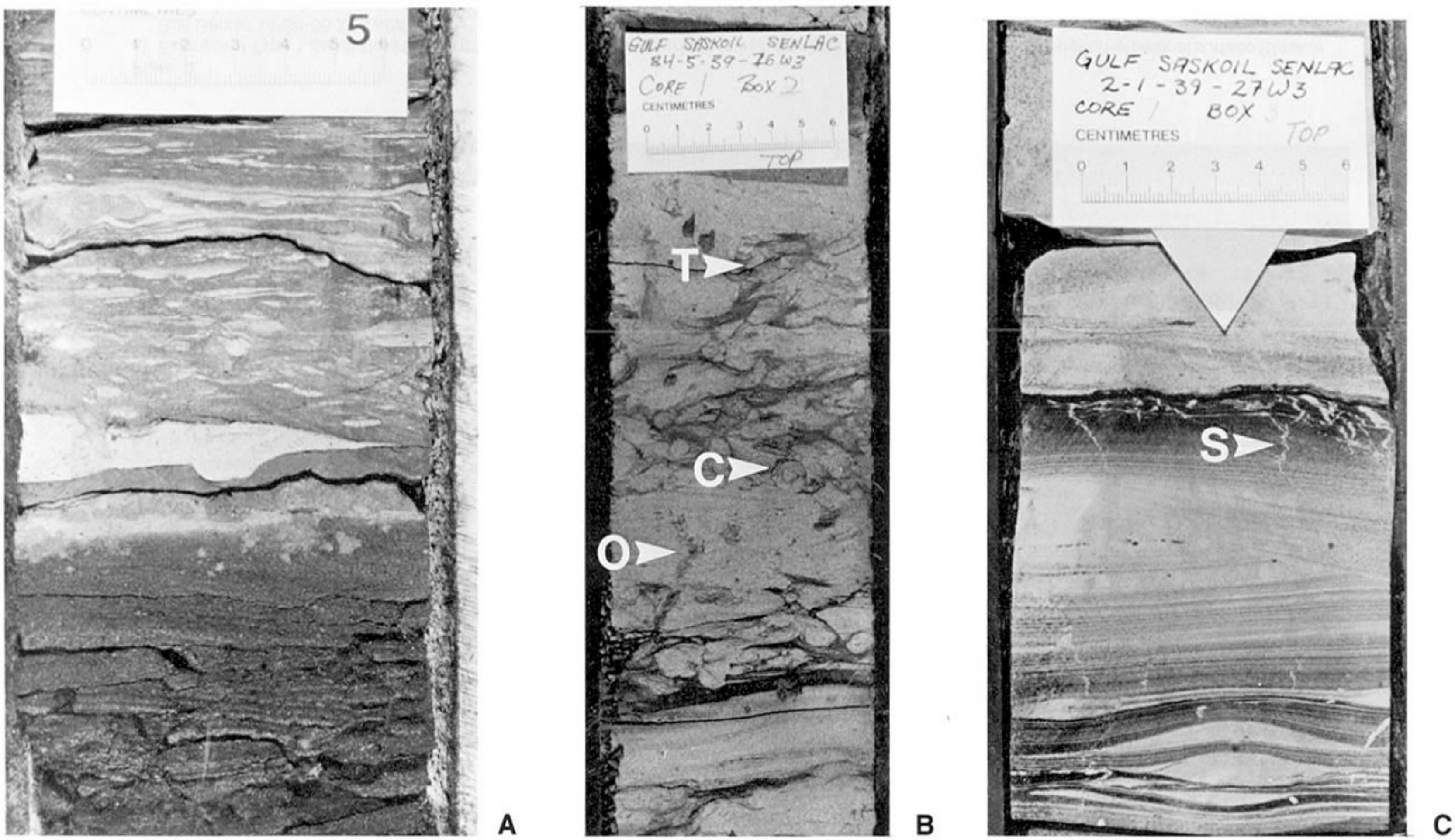


Plate 4. Examples of Rex Member shales, siltstones and silty sandstones.
a) Bioturbated, starved rippled to lenticular bedded shales, sharply overlying Type 2 sand. (Gulf Saskoil Senlac 11-36-38-27 W3M);
b) Bioturbated shales and silty sandstones with sideritic cement. Traces include *Teichichnus* (T), *Cylindrichnus* (C) and *Ophiomorpha* (O) (Gulf Saskoil Senlac B4-5-39-26 W3M);
c) Graded bedding, low angle planar and trough cross laminations cut by erosional surfaces, with well developed syneresis cracks (S) within the shales. (Gulf Saskoil Senlac 2-1-39-27 W3M).

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