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PETROLEUM GEOLOGY OF PIKES PEAK HEAVY OIL FIELD, WASECA FORMATION, LOWER CRETACEOUS, SASKATCHEWAN

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Abstract

The Pikes Peak heavy oil field is situated 40 km east of Lloydminster and is presently the site of a steam stimulation pilot project, producing from sands that are part of a major channel system within the Waseca Formation (Lower Cretaceous Mannville Group). Viscous oil (15,000 mpa.s at 21°C) is trapped in sand bodies up to 35 m thick within this north-south oriented channel system at a depth of approximately 500 m. The pilot project is located on a structural high axis created by solution of Devonian salt and much of the site contains no bottom water.

The stratigraphy and sedimentology of the Waseca Formation in the Pikes Peak field are reviewed with the aid of geophysical well logs and 24 cores. The channel facies of the formation are informally subdivided into three successive units: (A) the Homogeneous Sand Unit, the main reservoir sand, at the base; (B) the Interbedded Sand and Shale Unit, which flanks and overlies the main reservoir sand; and (C) the Sideritic Shale Unit capping the Interbedded and Homogeneous Units.

The quartzose, medium to fine grained reservoir sands are well sorted, laminated and planar cross bedded. The dominant clay is authigenic kaolinite. The sands are generally unconsolidated, but are occasionally cemented by calcite and siderite. Reservoir quality decreases upward.

The degree of bioturbation, type of microfauna and stratigraphic relationships suggest that the Waseca reservoir sand is tidal/estuarine in origin.

Introduction

The Pikes Peak field produces heavy oil from thick sands (15-25 m) of the Waseca Formation of the Lower Cretaceous Mannville Group. A portion of the Pikes Peak field has been selected by Husky Oil Operations for a pilot study to evaluate enhanced oil recovery (EOR) by cyclic steam injection in thick sands with high viscosity oil. The pilot area is situated 40 km east of the city of Lloydminster (Fig. 1).

The two major producing horizons in the Pikes Peak field are the General Petroleums Formation (GP) and the Waseca Formation. This paper discusses only the Waseca oil sands and reviews their stratigraphy, trapping mechanisms and reservoir quality.

Sandstone reservoirs of the Waseca Formation are well developed in the eastern part of the Lloydminster area. The Waseca Formation produces heavy oil, mostly by conventional methods, from a thin, 2-4 m, sheet-like sand in the Golden Lake, Gully Lake, Lashburn-Low Lake and Celtic-Westhazel fields. The geometry of the areally extensive sheet sands is very different from that of the thick sands of the stratigraphically equivalent Pikes Peak reservoir which have been interpreted to be channel sands (Putnam, 1980; MacEachern, 1982). The depositional environment of the two sand types is not well understood. Lorsong (1980, 1982) concluded, from a detailed sedimentological study of the Celtic area, that the thin sheet-like Waseca sands were deposited in a nearshore environment. Putnam (1980, 1982) interpreted the Waseca in the same area as having been deposited in a fluvial environment.

Geologic analysis of the pilot area is based on log, core and seismic studies in the 960 acre (384 ha) area where Husky operates its project. Channel wells have been studied in an area 20 km north and south of the pilot area.

Field History

The oil field is located in Township 50, Range 23 and 24, W3M (Fig. 2), 2 km south of the hamlet of Pikes Peak. The Pikes Peak field is a relatively new discovery and earlier wells, now abandoned, were drilled during 1965 to 1970 on road allowances. The wells mostly encountered shaly sections or water-bearing sands in the Waseca Formation. Only one producing well, in the General Petroleums Formation, A9-1-50-24W3, resulted from this program. The channel sand in the Waseca Formation is relatively thin in the A9-1 well and the potential of the Waseca was only realized after 1978, when the GP was delineated. The Pikes Peak Waseca reservoir was then drilled on a 40 acre (9.8 ha) spacing and many cores were cut. Enhanced Oil Recovery (EOR) development commenced in 1980 with steam stimulation. Approximately forty five wells have been drilled on a 1 ha spacing in the EOR pilot, which comprises an East area (Sec. 6 T50 R23W4) and a West area (Sec. 1 T50 R24W4).

Structure

Sediments of the Mannville Group overlie a pre-Cretaceous unconformity developed on gently southwesterly-dipping Paleozoic strata. Post-Mannville tilting to the southwest has enhanced the structural dip on the subcropping Paleozoic strata in the Lloydminster area (Orr et al., 1977).

The structural relief of the Mannville Group in the study area is complicated by dissolution of Middle Devonian Prairie Evaporite salt beds (Orr et al., op. cit.). Structural relief on the top of the Waseca indicates post-Mannville leaching of the upper part of the Prairie Evaporite northeast of the Pikes Peak field, which caused a northeast dip in the normally southwest-dipping strata (Fig. 3, 3A). The Pikes Peak field is situated on part of the resulting antiform

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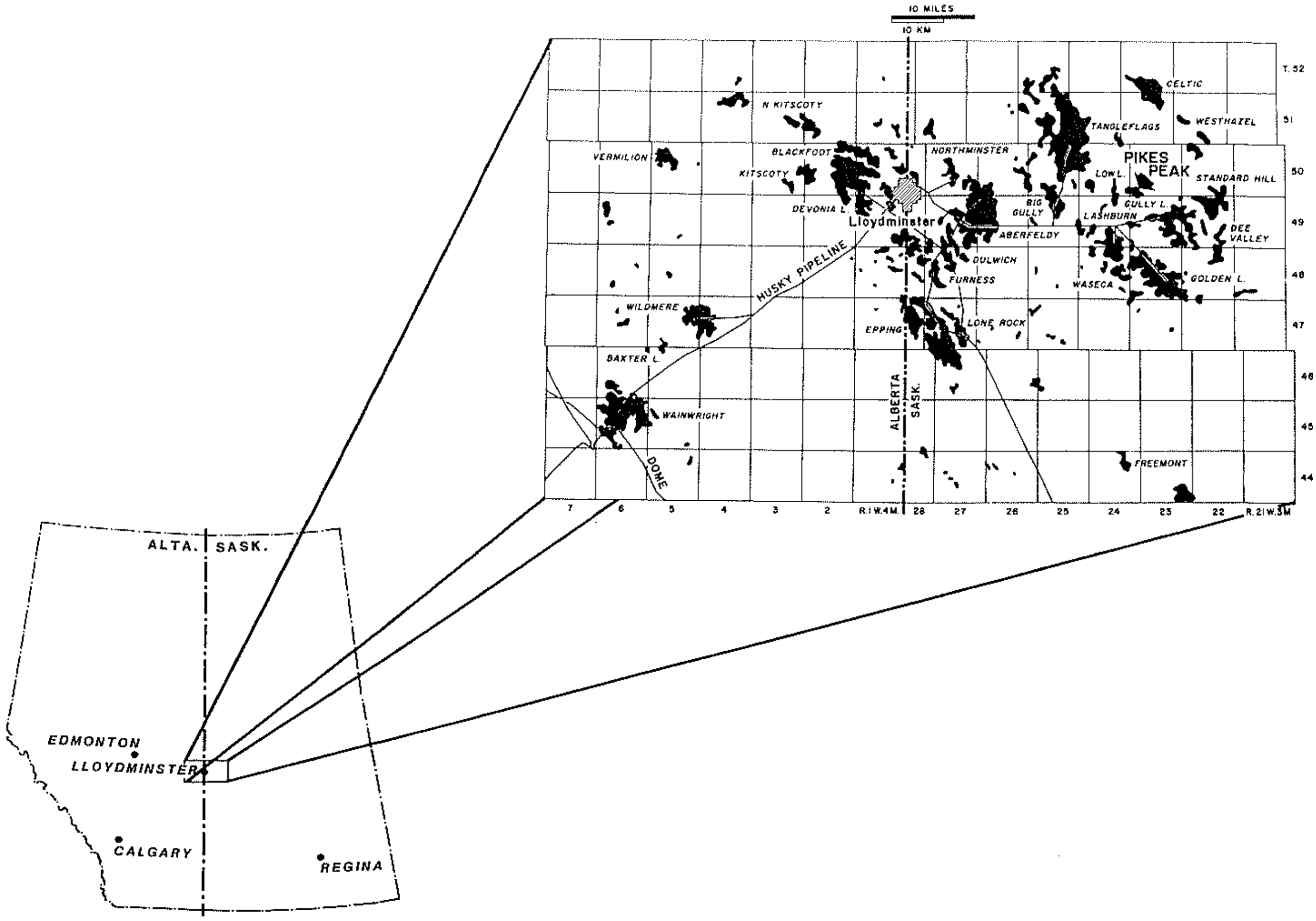

Fig. 1. Index map showing the location of the Pikes Peak field and other oil fields in the Lloydminster area of Alberta and Saskatchewan.

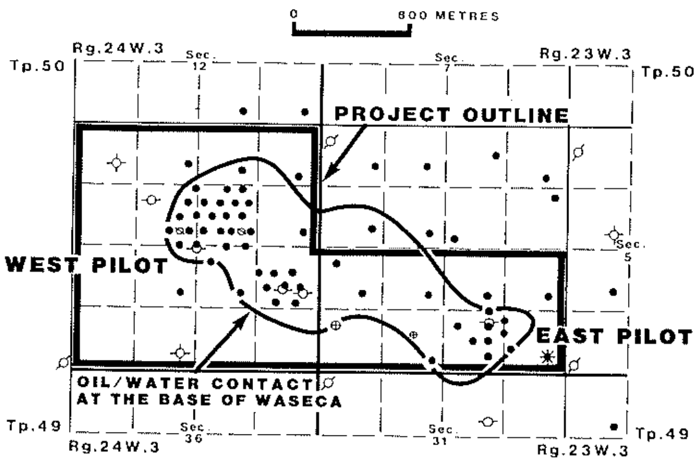

Fig. 2. Pikes Peak cyclic steam pilot. Outline of the project. Based on drilling density, the pilot is arbitrarily subdivided into an East and West area according to the section line between sections 1 and 6. The oil/water contact is related to the structure at the base (Fig. 5) and defines the present operational boundary of the pilot.

(Fig. 4), a large structure that trends northwest towards the Tangleflags field. A second anticlinal structure, parallel to the Tangleflags - Pikes Peak structural high, is present a few kilometres to the northeast in the area of the Celtic-Westhazel field. The Prairie Evaporite has been subject to complete dissolution northeast of this field. Dip reversal created by regional leaching and collapse created extensive oil traps in Cretaceous sediments in the Celtic-Westhazel, Standard Hill and the Tangleflags fields.

The anticlinal structure centered in the Pikes Peak field consists of a series of closed structural highs. A structural high in the Waseca Formation at the pilot location resulted in an area with little or no bottom water in the reservoir (Fig. 5). A map of the oil-water contact in the pilot area shows that this contact is tilted and warped; up to 10 m of structural relief is present in the closely spaced wells. The oil-water contact is 5 m structurally higher along the northeast edge of the pilot compared to the southwest side (Fig. 5). Cause of the tilting of the oil-water contact is unknown, but is possibly related to structural movement combined with the viscosity of the oil (15,000 mpa.s) or the presence of an active aquifier.

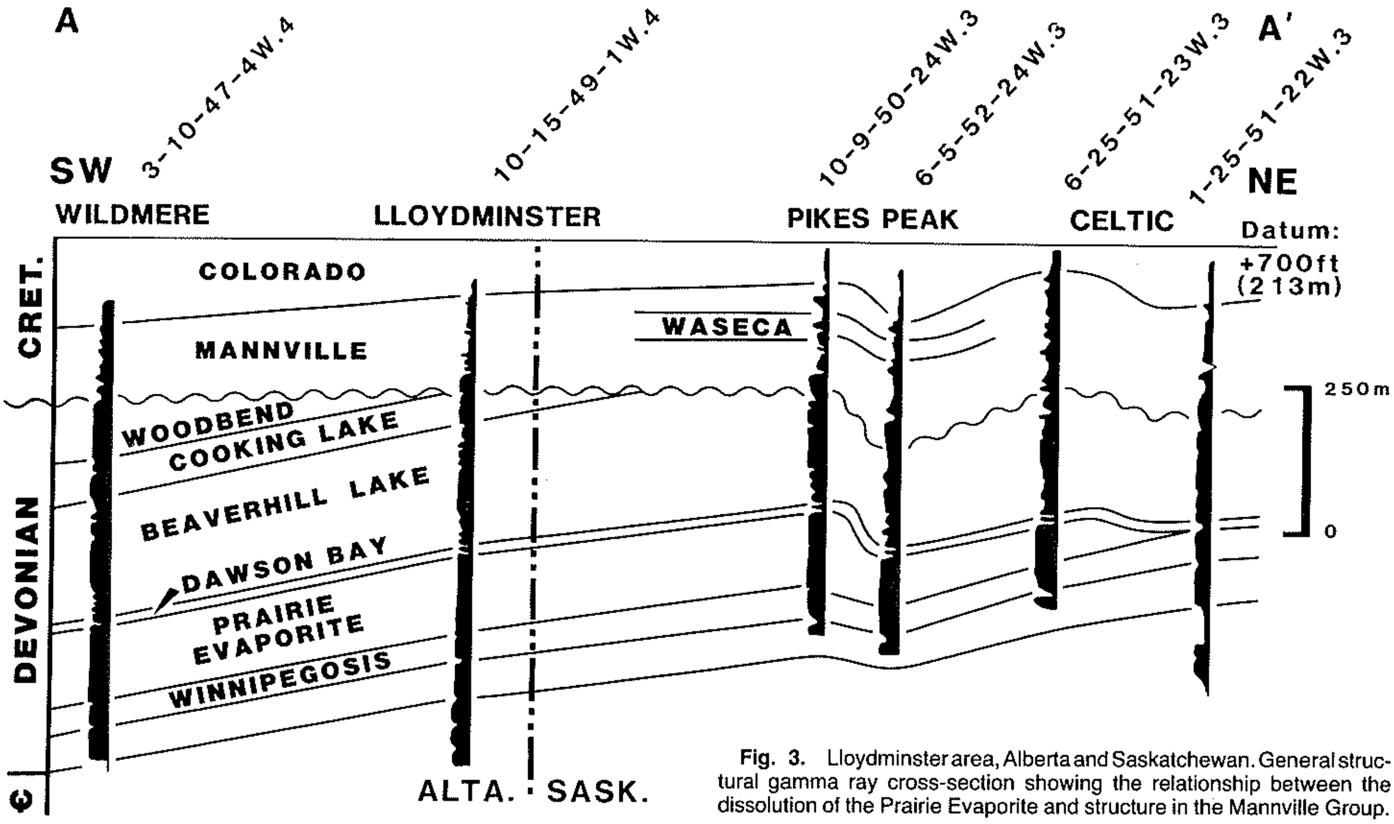

Fig. 3. Lloydminster area, Alberta and Saskatchewan. General structural gamma ray cross-section showing the relationship between the dissolution of the Prairie Evaporite and structure in the Mannville Group.

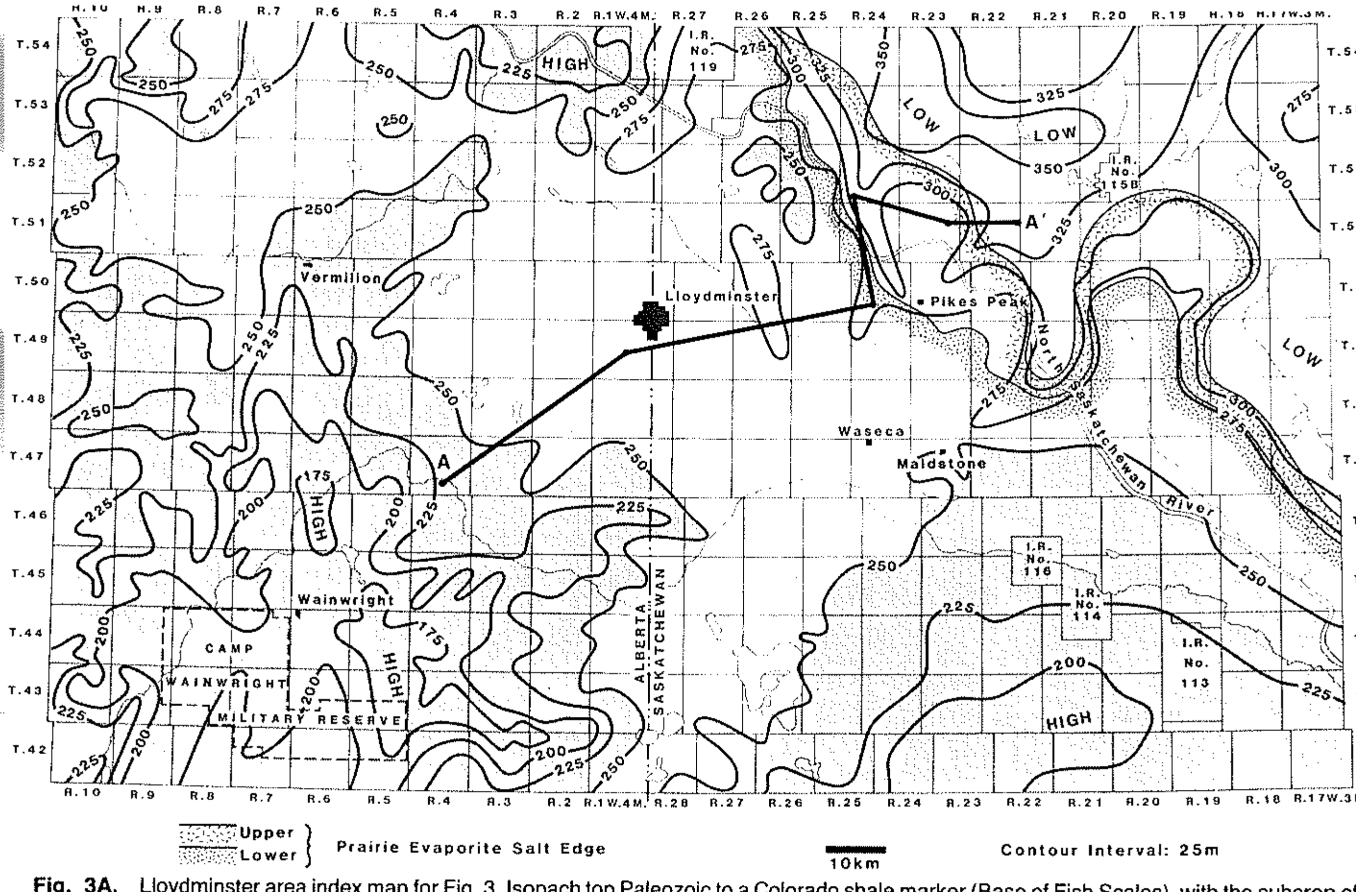

Fig. 3A. Lloydminster area index map for Fig. 3. Isopach top Paleozoic to a Colorado shale marker (Base of Fish Scales), with the subcrop of the upper and the main Prairie Evaporite salt edge indicated (after Orr et al., 1977). The map shows an overall thickening towards the northeast. It is interpreted that during Mannville deposition a high was present in the southwest and a low in the northeast.

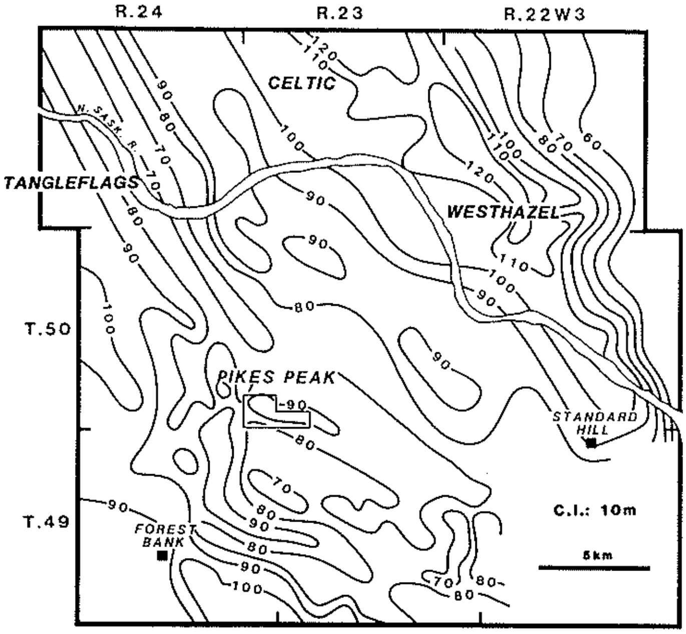

Fig. 4. Pikes Peak area. Structure on the top of the Sparky Formation, base Waseca. Depressions northeast of the oilfields in Tangleflags, Pikes Peak, Standard Hill and Celtic-Westhazel are formed by salt dissolution (see Fig. 3A, 9A).

Stratigraphy

General

The nomenclature for the Mannville Group as used in this paper is derived from Vigrass (1977) and Orr et al. (1977). The Mannville Group type well proposed by Vigrass (1977) shows the major subdivisions of the group (Fig. 6). The formations are based on a number of more or less correlatable sand and shale cycles that can be traced across the area. The Mannville Group is interpreted to be of Albian age (Vigrass, 1977; McLean and Wall, 1981), but the lack of index fossils precludes precise dating.

Early drilling in the area was concentrated around the town of Lloydminster. All of the units in the upper part of the Mannville were called Colony (Fig. 7) in the early nomenclature (Edmunds, 1948; Kent, 1959) and were named after gas zones near the town of Lloydminster. Oil bearing horizons are not common in the upper part of the Mannville on the Alberta side of the border but were discovered in the eastern part of the Lloydminster area as drilling activity expanded. One of the oil-bearing horizons occurring in the Upper Mannville was named after the

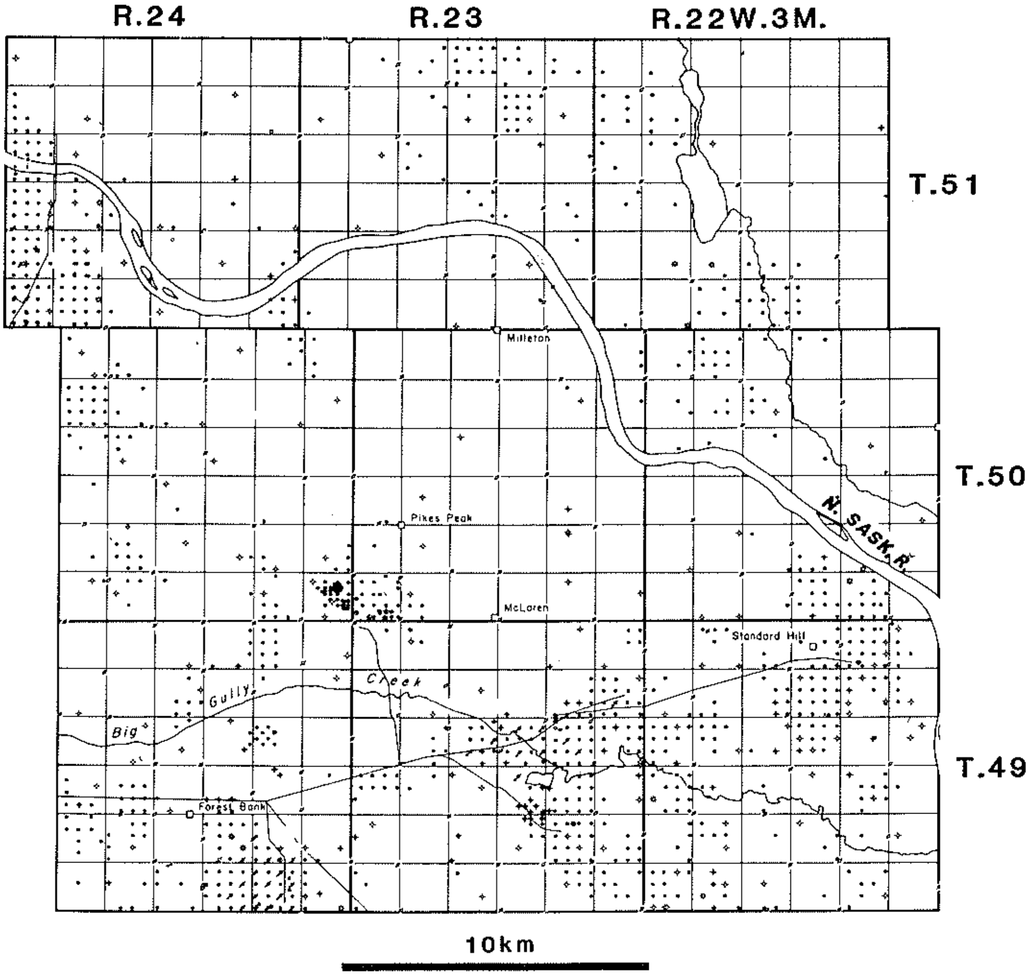

Fig. 4A. Index map for Figs. 4 and 9 showing the distribution of wells that have been used for detailed study of the Waseca.

town of Waseca, approximately 40 km east of Lloydminster. The first reference to the formation is found in Brown (1965). Formal description of the formation was given by Fuglem (1970). The Waseca Formation is overlain by the McLaren and underlain by the Sparky Formations.

Waseca Stratigraphy

The Waseca Formation displays two different facies types, a regional facies and an areally restricted channel facies. The channel facies is present in the Pikes Peak field and will be discussed later in detail.

The easily correlatable regional facies of the Waseca is characterized by approximately 15 - 20 m of silt and shale overlain by two 1-4 m sands. The regional facies of the Waseca Formation is illustrated from the type well (Fig. 6). A facies description of the regional Waseca is given in Lorsong (1980), correlations in Haidl (1980). The Waseca channel facies was described by Putnam (1980), McEachern (1981) and Lorsong (1982). Waseca production comes primarily from the thin sheet sands in the upper part of the regional facies.

In the following facies descriptions, the term shale is applied to mudstones with varying amounts of silt and clay sized material. The shales consist of variable percentages of quartz, feldspar, carbonate (siderite) and clay minerals (illite, kaolinite) and do not form potential reservoir units.

Regional Facies

Widespread markers can be used to correlate the regional facies across the eastern part of the Lloydminster area. The lower boundary of the Waseca occurs at the top of the 1 m thick Sparky coal which is correlative across most of the Lloydminster area. Between the sands of the Upper Waseca and the McLaren there is a shale, up to 7 m thick. Ironstone in this shale is used to define the boundary between the McLaren and Waseca.

The regional facies of the Waseca consists of a thick (15-20 m) basal unit of interbedded siltstone and shale, overlain by two thin (3-6 m) correlatable sands which are separated by a thin (1 m) shale (Fig. 8). This shale grades into a coal in some areas. An ironstone bed marker forms the top of the upper, thin shale unit. The two sand beds are informally designated as the Upper and Lower Waseca. The Lower Waseca is the main oil producing horizon and generally has the best reservoir quality. Observations of Golden Lake field cores for both the Upper and the Lower Waseca indicate that these sands generally display a fining upward sequence, with typical median grain size values

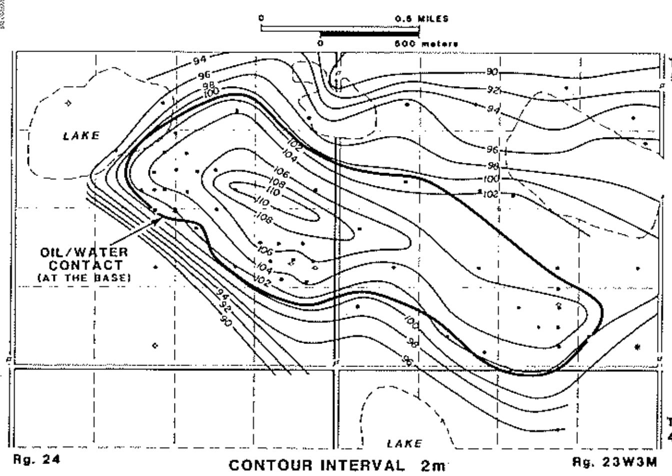

Fig. 5. Pikes Peak cyclic steam pilot. Structure at the base of the channel sand reservoir. The oil water contact at the base is very important to predict the performance of the wells. The oil water contact is significantly higher in the northeast of the pilot, compared to the southwest.

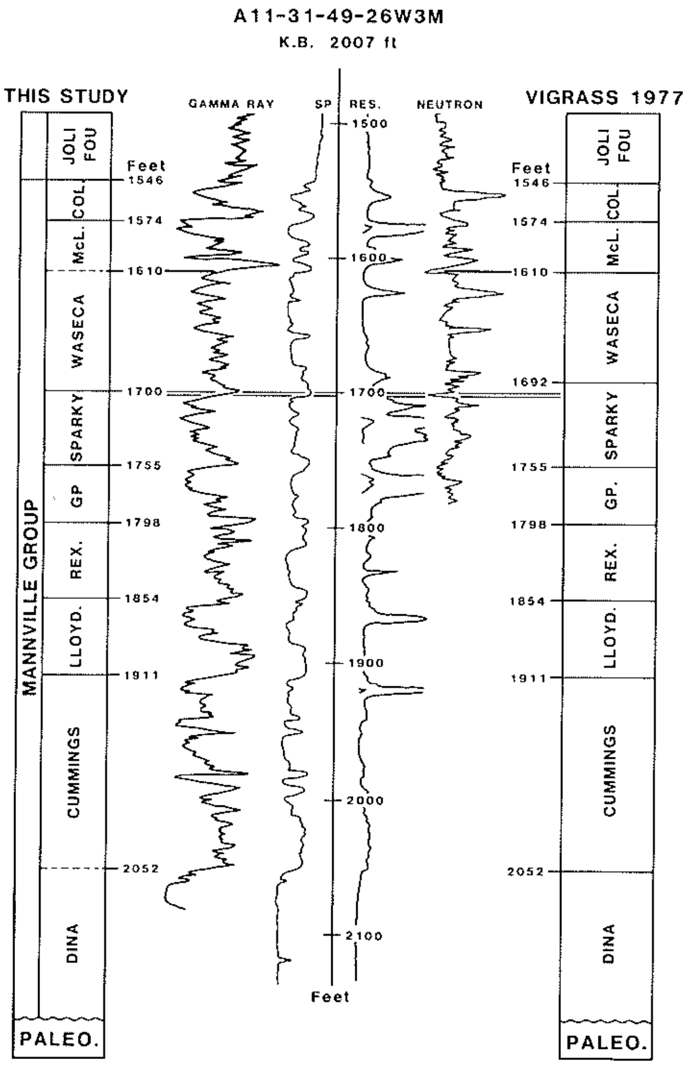

Fig. 6. Stratigraphical type log for the Lloydminster area. (Modified after Vigrass, 1977). A cased hole Neutron-Gamma ray log run on this well shows the Sparky coal to be slightly below where Vigrass (op. cit.) had picked the top of the Sparky. This log was not available to him during his study. Dashed lines indicate uncertain boundaries. (Col - Colony; McLaren; GP - General Petroleums; Lloyd Lloydminster; Paleo - undifferentiated Paleozoic).

around 3.5 phi. Structures are dominantly laminations and, rarely, trough cross-laminations (Lorsong, 1980). The basal part of the formation is generally silty, shaly or cemented and does not form an effective reservoir.

Channel Facies

General

Log correlations show that the regional Waseca sands are absent in a narrow band from at least 15 km to the north (Celtic, Tp 52, Rg 23) to 20 km south of the Pikes Peak pilot (Golden Lake, Tp 47, Rg 22). They are replaced by the herein described channel facies (Fig. 9). Three mappable rock units are identified in cores of the Pikes Peak channel facies (Fig. 8, 10, 12):

A. The Homogeneous Sand Unit,
B. The Interbedded Sand and Shale Unit, and
C. The Sideritic Silty Shale Unit.

A. The Homogeneous Sand Unit

The unit consists of clean sandstones up to 30 m thick. The sands are fine to medium grained, and well sorted (Fig. 13, 14). The percentage of fines (greater than 4.5 phi) ranges from 2 to 10 weight percent. The sands are quartzose and contain a few percent feldspar and traces of heavy minerals. Sideritic mudstone fragments are common. Clay percentages range from 1 to 3 percent. Plant debris and glauconite are rarely observed in thin sections.

The sand unit has a massive appearance in core because heavy oil saturation obscures sedimentary structures. Single shale clasts (cm-size) or mud balls are infrequently present throughout the section. The most common observable sedimentary structure in the lower part of the unit is planar crossbeds with a set height of 30 to 110 cm. Concentrations of small (cm to mm) shale pebbles form lag deposits at the base of sets of planar crossbeds and are increasingly abundant up-section. Parallel laminations are more common up-section.

Diagenesis in the sands consists of compaction, dissolution of unstable components and precipitation of widespread kaolinite and local carbonate. The sands are slightly to moderately compacted, as observed in SEM photos. The sands are locally cemented by porosity-occluding siderite or calcium-magnesium carbonates. The lateral extent of 1-2 m thick tight streaks can be over 100 m (Fig. 15).

Reservoir quality generally is very good, with porosity ranging from 30 to 35 percent and permeability from 5 to 10 Darcy's (Fig. 13). The reservoir quality, however, decreases

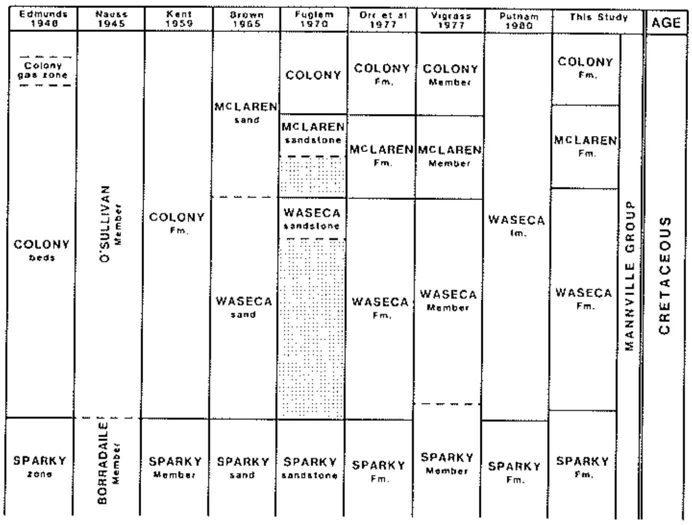

Fig. 7. Stratigraphical correlations of the Upper Mannville in the Lloydminster area, illustrating the development of the nomenclature in the past 35 years. The difference in position of the formation boundaries is due to the use of different lithologic breaks by the various authors. Dashed lines indicate uncertain boundaries.

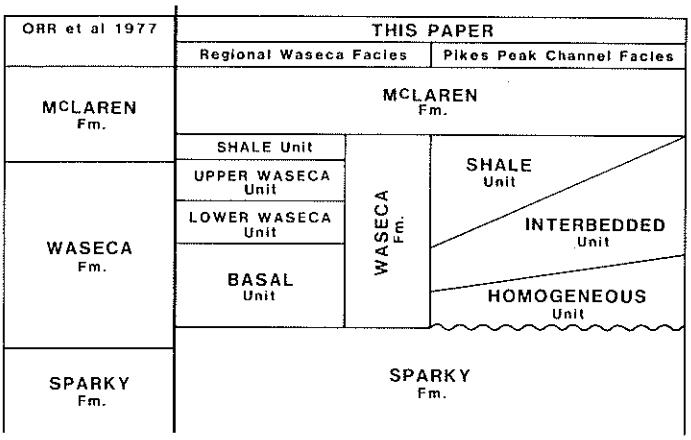

Fig. 8. The stratigraphic relationship between the regional and the channel facies of the Waseca formation. The boundaries in this study are different from Orr et al. (1977). MacCallum (1979) has been followed in the present study in using marker beds such as regional shales and coals for formation boundaries and not the top of sands.

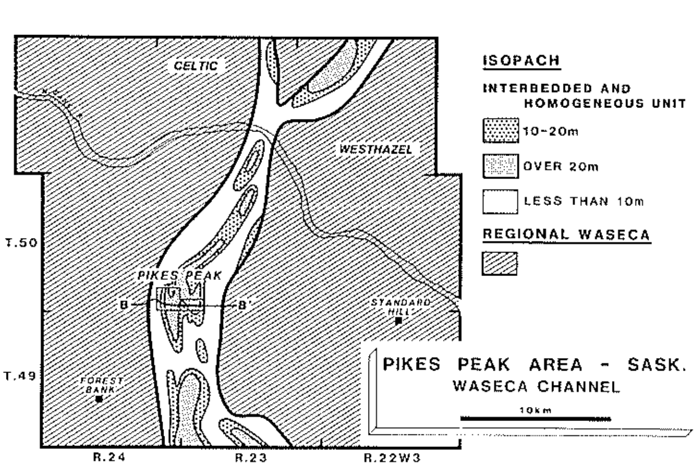

Fig. 9. Outline of the Waseca channel in the Pikes Peak area. B-B' indicates the location of the cross section of Fig. 10. The location of the oilfields in Celtic-Westhazel is indicated. For other oilfields in the area; see Fig. 1 and 9A.

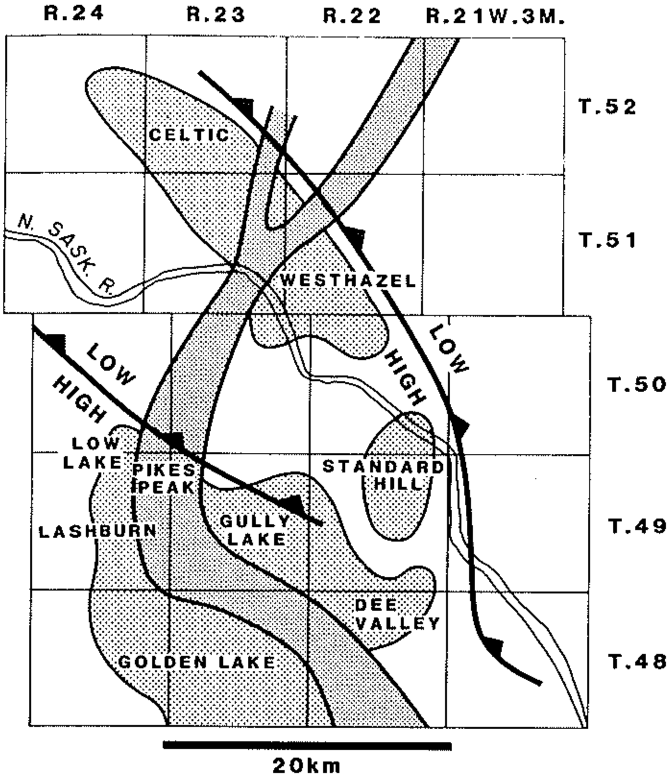

Fig. 9A. Pikes Peak area, showing the most important Waseca oilfields in the Lloydminster area and the outline of the Pikes Peak channel. Illustrates the apparent relationship between channel and regional Waseca.

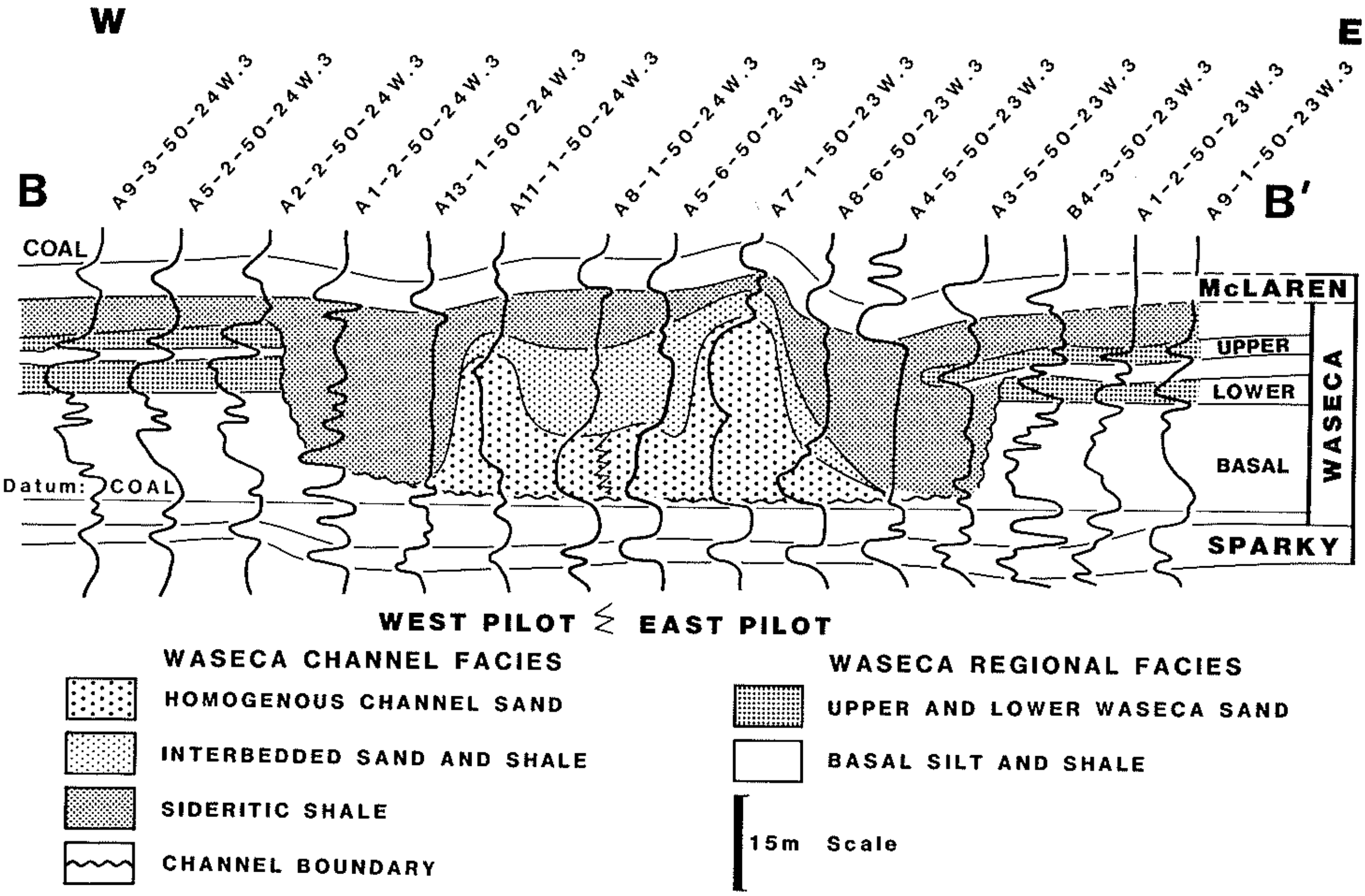

Fig. 10. Stratigraphical SP cross-section of the Waseca Formation in the Pikes Peak area illustrating the relationship between channel and regional facies.

upwards in the sand beds and is significantly better in the East pilot than in the West pilot (Fig. 14).

Infrequent beds of shale breccia occur within the Homogeneous Unit. The beds are from 10 cm to a few metres thick and consist of more than 20 percent angular to subrounded shale rip-up clasts, varying from cm to dm in size, floating in a sand matrix. The shale seems to be similar to the shales of unit type B and C and is characterized by sideritic nodules. The shale breccias most commonly occur in the West Pilot at the base of the Homogeneous Sand Unit and occur rarely in the East pilot at the top of the unit at the boundary with the Interbedded Unit (Fig. 16).

Lag deposits, consisting of well rounded siderite clasts and pieces of coal floating in a sand matrix, occur at the base of the Homogeneous Sandstone Unit. The clasts are similar to those in the shale breccia but are more rounded. These facies overlie regional Waseca shales or the top part of the Sparky with an interpreted erosional contact. Frequently the Sparky Coal directly underlies the channel facies and it is interesting to speculate that the coal forms a horizon resistive to channel erosion. Smaller pieces of coal found in the lag are possibly from the Sparky and can be several centimetres in length. Larger pieces are derived from trees. This coal is not typical of the Sparky. The sand matrix of the lag in places is indurated by a sideritic cement.

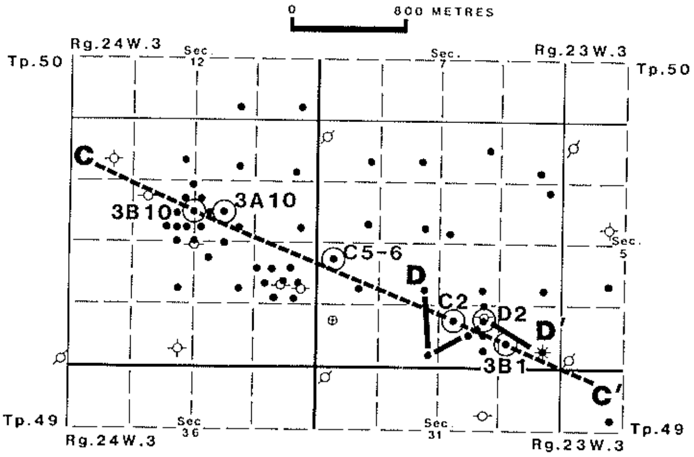

Fig. 11. Pikes Peak cyclic steam pilot — index map. Indicating the location of the cross sections and the well of Fig. 12, 13, 15 and 16.

B. The Interbedded Sand and Shale Unit

This unit is a few metres to as much as 15 m thick. It is characterized by cm to dm thick sand beds alternating with cm to dm thick mudstone beds (Fig. 16). The unit can be subdivided in core on the basis of bioturbation, thickness and frequency of shale beds.

The sands are fine to very fine grained and well sorted, but less so than the sands of the unit below (Fig. 13). The percentage of fines rarely exceeds 10 percent. The composition of the sand portion of the Interbedded unit is similar to the sands in the Homogeneous Sand Unit, but contain a few percent more feldspar and a similar, or somewhat higher, clay content.

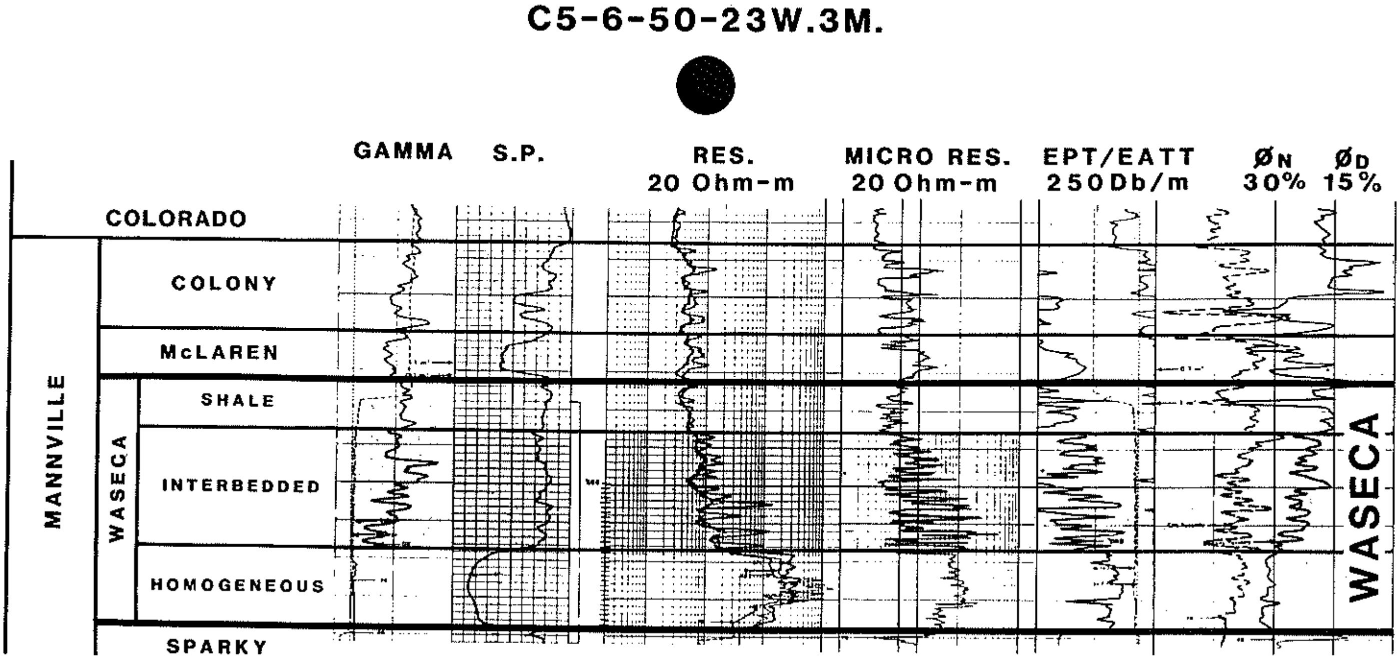

Fig. 12. Pikes Peak cyclic steam pilot — type log (See Fig. 11 for location). The different logs illustrate the various log responses in the interbedded unit. (For core analysis see Fig. 13). The EPT attenuation curve is less sensitive to thin beds than the microlaterolog, but is more sensitive than the conventional log suite.

Parallel laminations are the dominant sedimentary structure . Authigenic kaolinite is characteristic. No carbonate cement has been observed. The reservoir quality in the sands is similar to, or poorer than the underlying homogeneous sands with comparable, or lower oil saturation, porosity and permeability (Fig. 13).

The shales, which are intercalated with the sands of the interbedded unit, consist predominantly of kaolinite, illite and small amounts of smectite. Silt to clay sized quartz, feldspar and carbonates are present in varying amounts. The silt content, determined from thin sections and hand lens inspection, varies from almost zero to 30-50 percent. Structures in the unit are dominated by vague parallel or wavy laminations and flaser and lenticular bedding. Bioturbation is common, but decreases down section. Sideritic nodules, bands and layers are very common and are probably early diagenetic. Brine permeabilities generally are less than 1 md.

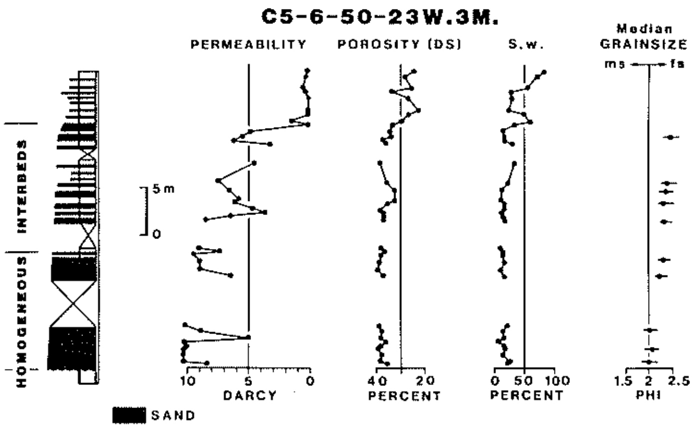

Fig. 13. C5-6-50-23W3M Pikes Peak. Core analysis and core description. The core analysis illustrates the decrease in reservoir quality to the top. Yet the grain size, permeability and porosity in the sands of the Interbedded unit is similar to the Homogeneous unit.

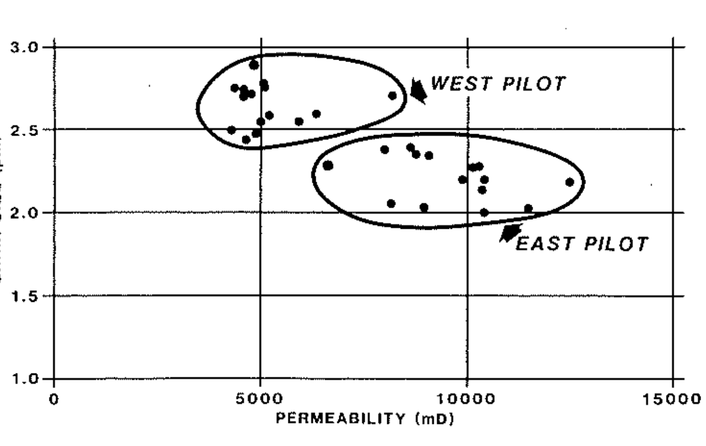

Fig. 14. Pikes Peak cyclic steam pilot. Comparison of median grain size and permeability from ten different wells indicating significant differences in reservoir quality between the east and west pilot reservoirs.

The lateral continuity of individual sand and shale beds in the Interbedded Unit is unknown. Thickness of the sand beds generally decreases upward with a corresponding increase in shale bed thickness. Thickness of sand beds in the lower section of the unit ranges from 80 to 120 cm and the shales are 10 to 20 cm thick. Shales in the upper part are up to 1 m thick. Basal contacts of the sands frequently are more bioturbated than the upper contacts and bioturbation increases upward within the unit.

C. The Sideritic Shale Unit

This unit consists of sideritic silty shale ranging in thickness from a few meters to over 20 m (Fig. 10).

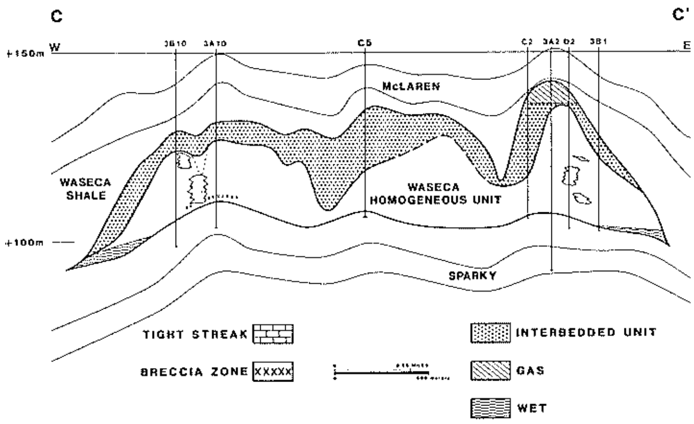

Fig. 15. East-West structural cross-section, Pikes Peak cyclic steam pilot. Location of the cross-section is indicated on Fig. 11. Between C5-6 and C2-6, there is an uncertain thick, only indicated on seismic (Fig. 17). The angle in the O/W structure illustrates the higher structure of the O/W contact close to the water free area. The curved O/W contact is characteristic of this reservoir.

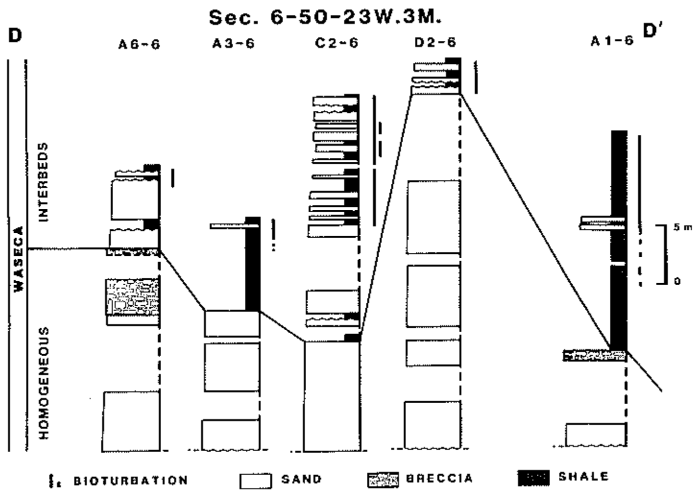

Fig. 16. Pikes Peak cyclic steam pilot — stratigraphical core cross section. The location of the section is indicated on Fig. 11. Dashed lines indicate missing core. The major sand body in D2-6 is interpreted as a point bar with the thalweg in the direction of A1-6. Relative grain size is indicated by the width of the sand column in the diagram.

The shales are similar in composition and structures to the shales in the underlying Interbedded Unit. Dominant structures in the shales are wavy to parallel laminations. Variation in bioturbation and other sedimentary structures are recognized in cores and can be used to differentiate several different shale types. Thin (mm-thick) coal laminae are rare. Sideritic concretions or banded layers and pyrite nodules are frequently present.

The Sideritic Shale Unit forms the upper reservoir seal for sands of the Homogeneous and Interbedded Units. The ironstone forming the boundary of the McLaren with the Waseca shale differs from the Sideritic Shale Unit only in the degree of cementation and the contact with underlying shales is gradual.

A difference in compaction is found between the shale and sand prone areas of the Waseca (Fig. 10). Coals at the top of the Sparky and the McLaren are assumed to have been parallel during deposition of the Mannville and present day structural configuration can be explained as a result of differential compaction of unconsolidated mudstones.

Paleontology

Shell fragments have not been noted in the pilot cores. Early diagenesis may have destroyed any shells that may have been present.

Foraminifera have been identified from the regional Waseca (Fuglem, 1970; Lorsong, 1982) but samples taken from the channel facies by Husky Oil Operations in the shales of the Interbedded Unit in the pilot area were silty and barren. Fuglem discussed the presence of agglutinated foraminifera in the Cummings, Lloydminster and Sparky Formations (determinations by T.P. Chamney). He found *Miliammina*, *Verneuilinoides*, *Ammobaculites*, *Hippocrepina*, *Bathysiphon* and *Saccamina*. In shale of the Waseca of the Northern Development C.S. #29 (5-10-50-26W3M) Fuglem reported *Hippocrepina* and *Reophax* (=Ammobaculites?).

Lorsong (1982) sampled cores in the Celtic, Tangleflags and Aberfeldy fields. In his samples of the Mannville 82 per cent contained marine fossils but 75 per cent also contained plant remains. In the Waseca, foraminifera were found throughout the section with two genera dominant in the assemblage: *Hippocrepina* and *Thuramminoides*. Rare *Saccamina* or *Bathysiphon* were found together with fishbone fragments and microseed *Microcarpolites* (determinations by P.F. Sherrington).

Log Response

The Homogeneous Unit Log signature is consistent with observations from core. Gamma and SP curves reflect the low clay content of the sand and the unit shows a blocky signature (Fig. 12). Resistivity and porosity log response are consistent with observed high oil saturations and excellent porosities.

The Interbedded Unit is characterized by a serrated, typically fining-up signature on Gamma and SP logs. Porosity and resistivity logs are serrated and reflect the upward decrease of reservoir quality. Porosity and resistivity logs display a bell-shaped profile of fining-up sequences. Log signatures are difficult to compare to the core in the Interbedded Unit because the logs are influenced by thin-bed effects. Sand quality may be very good in the core but the SP and Gamma are very suppressed by adjoining shale beds. Porosity readings can be too low, but also may be misleadingly high because of the coal content in the upper part of the interbeds. Resistivity is also suppressed by shale beds.

Husky Oil Operations ran EPT, Microlaterolog (Fig. 12) and Geodip/Dipmeter Logs to determine sand bed thickness and sand/shale ratios of the Interbedded Unit in uncored wells. Microlaterologs are now run on a routine basis to determine sand/shale ratios. High resolution logging has not permitted correlation of individual beds between wells.

Porosity logs of the regional Waseca are generally easily distinguished from logs from the channel facies. However, the SP log can show a bell-like character in the basal interbedded silt and shale portion of the regional Waseca which has a high irreducible water saturation and generally appears wet (Fig. 10). This SP log signature can easily be confused with a channel facies if it contains no oil and if no porosity log is present. A characteristic tight streak in the middle of the basal unit and the presence of the Upper and Lower Waseca regional sand may be the only indication that such a well was drilled in the regional facies.

Facies Distribution

Available log suites for most wells permit identification and correlation of the defined three rock units of the channel facies between the wells of the pilot area. The units generally are also traceable in the channel outside the pilot. An upward sequential transition from Homogeneous to Interbedded to Sideritic Shale Units has been observed in most well logs. Wells with only a shaled out section (Waseca Sideritic Shale Unit) are present locally throughout the area. The Homogeneous Sand Unit is distributed in elongate sand bodies (Fig. 9). This unit is well developed in two or more north-south aligned sand bodies in the pilot area. The Homogeneous and part of the Interbedded unit are also recognizable on high resolution seismic profiles and can be mapped (Fig. 17). The thickness of the sands varies from 0 to 30 m and the sand body is 500 to 700 m wide.

The Interbedded Unit flanks and/or overlies the Homogeneous Unit. The Sideritic Shale Unit overlies or flanks both other units and caps the reservoir (Fig. 10, 15). Completely shaled out sections are found on the west and east side of the pilot.

The relationship between the channel and the regional Waseca facies is not clear because of less well control in the transition area. Wells displaying characteristics of the regional Waseca facies can be found at a distance of only 50 m from wells that show channel facies. Erosional depth of the channel is variable and is estimated to be between 20 and 35 m. Only in a few wells is the Sparky Coal eroded, with channel depth exceeding 35 m.

In a few cases, the Upper Waseca sand overlies a shaled-out section (Sideritic Shale Unit) at the east side of the pilot, indicating that the Upper Waseca sand locally post-dates the channel (Fig. 10).

The Upper and Lower Waseca of the regional facies have excellent reservoir characteristics (grain size, porosity, etc.) in the vicinity of the channel, but a gradual reservoir deterioration is observed away from the channel. Thin coals start to develop on top of the Lower Waseca at a few kilometers from the channel. The Upper Waseca sands become shalier approximately 10 to 15 km west of the channel edge, which is reflected in the distribution of the Waseca regional oil fields. These oil fields are only present in vicinity of the channel. This relationship seems to be present to the east of the channel, but is more complicated because the presence of salt solution structures limits the density of well control (Fig. 9A).

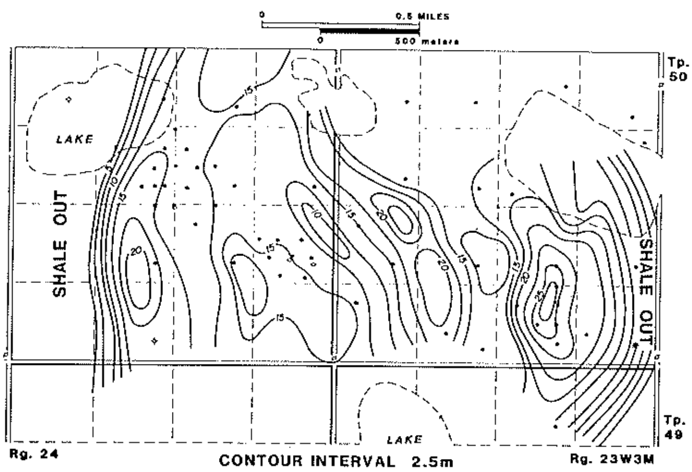

Fig. 17. Pikes Peak cyclic steam pilot — net sand map of the Homogeneous and and part of the Interbedded unit from seismic interpretation. Several lines used high resolution seismic with geophone spacing of 15 m.

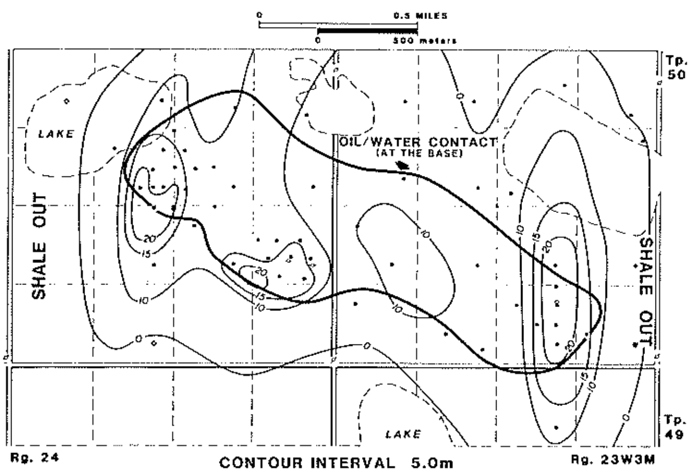

Fig. 18. Pikes Peak cyclic steam pilot — net oil pay isopach Waseca Homogeneous channel unit.

Between Twp. 51 and 48, tracing of the channel is relatively easy; to the north and the south it is more difficult. To the north, a study of wells influenced by salt removal indicates that the upper part of the Mannville section is commonly channelled. This, combined with the sparse well control, makes tracing of the channel to the northeast precarious. Discrete channel facies in the Waseca have been found in wells as far north as Twp. 57. South of the study area (south of the Golden Lake field, Fig. 9A), tracing of the channel is also more difficult because of lack of well control. Waseca channel facies are found in the Freemont field, 58 km south of the Pikes Peak field (Dunning et al., 1980).

Net Pay

Sandstones in the Waseca channel facies are mostly wet or contain significant bottom water where oil is present. The pilot is one of the few areas which has no water-leg. The oil viscosity is higher in the channel than in the regional Waseca sands.

Significant reservoir sands in the pilot area are limited to the Homogeneous Sand Unit (Fig. 18). Oil saturation in the Interbedded Unit has been excluded from net pay determinations because it is uncertain at this time whether oil will be produced economically from this part of the reservoir. In the area without bottom water, net pay thickness ranges from 5 to 20 m with an average around 10-15 m. Oil saturation exceeds 80 percent and the oil in place per unit volume of reservoir is estimated at 2805 m^3/ha-m.

Environmental Interpretation

General

Regionally traceable coal beds suggest a very flat paleosurface during deposition of the Mannville Group and a shallow water or sub-aereal depositional setting. Foraminifera identified from the Waseca indicate a marine influence during deposition of this formation.

Comparison of the assemblages found by Fuglem (1970) and the paleoenvironmental interpretations of foraminifera of the same age in McLean and Wall (1981), indicates estuarine, open marine and shelf like environments in several formations of the Mannville Group in the Lloydminster area. The agglutinated foraminifera in these formations are believed to have possessed a wide salinity tolerance. The assemblages that were described in the regional Waseca (Fuglem, 1970; Lorsong, 1982) with only *Hippocrepina* and *Thuramminoides*, suggest a brackish water - shallow marine environment (pers. comm., P.F. Sherrington). *Microcarpolites* is believed to be associated with coastal vegetation.

Despite excellent well control and general published studies, the paleogeographic setting of the Lloydminster area during Waseca deposition is still poorly known. Analysis of an isopach map of the Mannville Group published by Orr et al. (1977) and an isopach from the pre-Cretaceous unconformity to a radioactive Colorado shale marker (Base of Fish Scales) (Figure 3A), shows an isopach thick in the northeastern part of the area and relative thins to the south, southwest and north. The isopach thick has been related to subsidence caused by dissolution of salts within the Prairie Evaporite (Orr et al., op cit). MacCallum (1979) suggested that salt removal was initiated prior to Waseca deposition and is active today.

These conclusions suggest that areas with thick isopach values may have been topographic depressions during Waseca deposition. Thus, it is postulated that the region northeast of Pikes Peak was a relatively low area that may have been occupied by the sea from time to time. It is suggested that this depression influenced the orientation of drainage in the surrounding area.

Pikes Peak Channel

Lorsong (1982), McEachern (1982) and Putnam (1980, 1982) agree that the Pikes Peak Homogeneous and Interbedded Units represent channel deposits. Channel models known to the author that accommodate a marine influence and coal formation are restricted to deltaic distributaries, estuarine channels or tidal channels. The lack of paleogeographic framework for the upper part of the Mannville makes it difficult to select from these models.

Putnam (1980, 1982) proposed that the undifferentiated Waseca, McLaren and Colony in the study area were deposited within several fluvial channels, and drainage was into a boreal sea northwest of the Lloydminster area.

The present study found only one major Waseca channel in the area 20 km around the pilot (Fig. 9). Log correlations show that this channel is traceable from Golden Lake to the south of the pilot to Celtic-Westhazel to the north-northeast of the pilot (Fig. 9A). The overall north-northeast trend of the channel, dipmeter measurements which show a dominant northeast component in channel wells and the postulated depression to the northeast of the area all support the conclusion that flow direction in the channel was southwest to northeast.

Channel Evolution

The proposed depositional sequence in the pilot area consists of early erosion into the basal unit of the regional Waseca resulting in lag deposits, followed by deposition of the Homogeneous Sand Unit (Fig. 19). The structures in the lower parts of the Homogeneous Sand Unit and the associated shale breccias in the West Pilot probably represent sediments at the bottom of the channel deposited under relative high energy flow conditions. A process that could produce these breccias is erosional bank collapse. In the upper (5 to 10 m) part of the very thick Homogeneous Unit (15 to 25 m), structures suggest that the sediments were deposited under lower energy conditions. Variations in thickness of the combined Homogeneous and Interbedded units in the different areas represent relict channel morphology following abandonment.

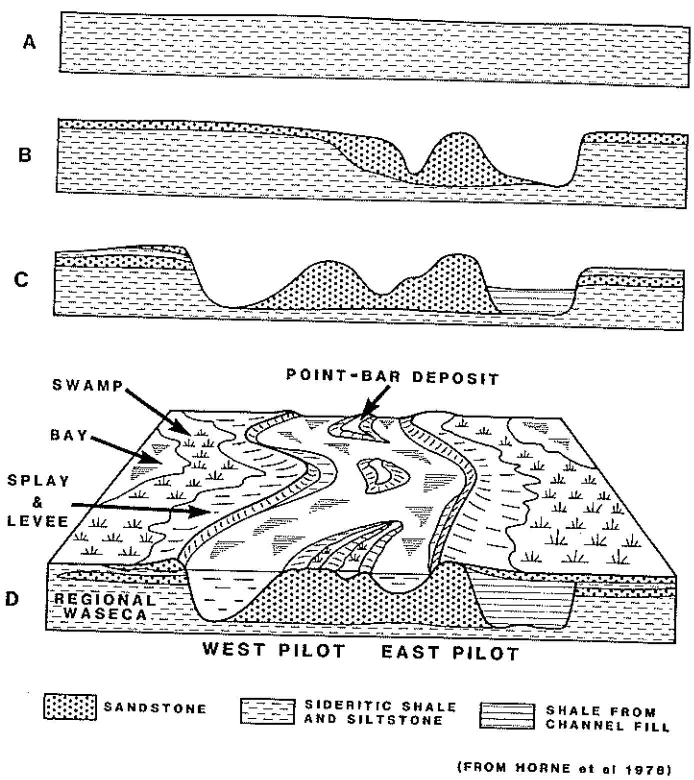

Fig. 19. Depositional model of the Waseca channel sands for the Pikes Peak area, illustrating the hypothetical stages of development of the reservoir sand and the upper regional Waseca sheet sands.

Comparison with well known tidal sediments in the North Sea and the U.S. Atlantic seaboard (Barwis, 1978) indicates several analogous characteristics between the sediments of the Waseca Formation of Pikes Peak and present day tidal point bars; these include, particularly, structures in the sedimentological sequence and grain size distribution. No exact modern tidal counterpart, known to the author, displays 20 to 30 m thick sand bodies in a channel system that is traceable over more than 50 km.

Examples of thick channel sands with very similar characteristics have been described from the ancient rock record. These channels also occur in a setting that displays sediments that show a transition from a sub-aerial exposure to a marine depositional environment. Examples include channels in the Lower Cretaceous Fall River Formation of Wyoming (Berg, 1968; Campbell and Oaks, 1973), the Lower Cretaceous McMurray (Dina) Formation, of Alberta (Mossop and Flach, 1983), or examples in the Carboniferous of Kentucky (Horne et al., 1978).

The thick sand bodies represented by the Homogeneous Sand Unit in the pilot area are interpreted to be point bars in a tidal, estuarine channel (Fig. 16, 19). The shaled-out sections are interpreted as the channel course prior to abandonment. The relict morphology and the stratigraphic relationships suggest that the channel course was abandoned at least once. The thalweg was positioned to the east in an early stage, as is suggested by the Upper Waseca regional sand that partly overlies the shale-filled channel in the East part of the field. The east part of the channel was abandoned and the channel migrated to the west side of the present field and deposited another point bar. Channel width from the top of the sand body to the cut bank exceeds 500 m to 1 km. The channel units have been mapped 20 km north and south of the pilot in detail and their distribution suggests a low sinuousity channel (Fig. 9). The Interbedded Sand and Shale Units may represent gradual abandonment of parts of the channel.

Heavy bioturbation in the upper part of the Interbedded Sand and Shale unit is limited to the upper 10 m of the channel facies. This may indicate that the mean water level was probably around the top or in the upper 10 m of the channel facies. The frequency and diversity of bioturbation as found in the Waseca channel facies is not typical for fluvial channels, and may be another indication that the channel is estuarine in nature.

Relationship of the Channel to Regional Waseca Facies

Sands of the McLaren Formation overlie both the regional Waseca facies and the channel facies. The regional facies of the Upper Waseca locally overlies the channel facies. This suggests that the channel facies was deposited before or contemporaneously with the upper regional Waseca sheet sands (Fig. 19) and before McLaren deposition.

Because the reservoir quality of the Upper and Lower Waseca decreases away from the channel and the channel has a coarser grain size than the regional sands, it is possible that the channel served as a source of the sediments of the Upper and Lower Waseca. The reservoir quality in the regional facies is generally better in the Lower than in the Upper Waseca. The channel sands of the Waseca in the east pilot of Pikes Peak are coarser and are of better reservoir quality than those of the west pilot (Fig. 14). This may suggest a genetic relationship between the east pilot point bar which was abandoned first, and the regional Lower Waseca. The west pilot may be related to the generally much thinner Upper Waseca. This relationship suggests that the Upper and Lower Waseca were partly formed as splay sands from the Pikes Peak channel and not deposited in a nearshore environment as suggested by Lorsong (1980). Yet because of the large areal extent of the formation a wave component in the deposition of the regional Waseca sands cannot be excluded.

Also, important regional Waseca oil fields, such as Golden Lake, Gully Lake, Lashburn-Low Lake and Celtic-Westhazel, produce from the Upper and Lower Waseca of the regional facies. These fields generally flank the Pikes Peak channel. The improved reservoir quality of regional Waseca sands in the vicinity of channels has been discussed and is compatible with a splay model. In some places, the relationship is obscured because the regional Waseca is wet, or oil may only be trapped on one side of the channel (Fig. 9A).

Relationship of the Waseca to Other Stratigraphic Units

The position of sea during the Upper Mannville was probably towards the northeast and possibly was related to a depression created, in part, by salt solution from the Devonian Prairie Evaporite (Fig. 3). The influence of minor relative sea-level variations dramatically changed the Lloydminster basin paleogeography because the area was very flat. The strongly correlative sand-shale cycles in the Mannville across this area, containing rather diverse marine foraminiferal faunas, are interpreted as minor transgressions and regressions of this sea (Fig. 20). In some of the cycles the marine influence may even extend beyond Wainwright, 100 km to the southwest (MacCallum, 1979). The very restricted brackish water-shallow marine Waseca foraminiferal faunas indicate a minor transgression cycle in this formation compared to transgressions related to the Cummings, Lloyd or Sparky Formations.

The Waseca was deposited during a general transgression following the regressional cycle of the Sparky (Fuglem, 1970). The minor regression probably ended after deposition of the Sparky coal or the deposition of the basal part of the regional facies of the Waseca Formation. The climax of the Waseca transgression is represented by the widespread shale that separates the Waseca from the McLaren. Faunas from this interval show a brackish water-marine influence. The interpretation of the Pikes Peak channel in a tidal/estuarine setting would be compatible with a transgressive setting.

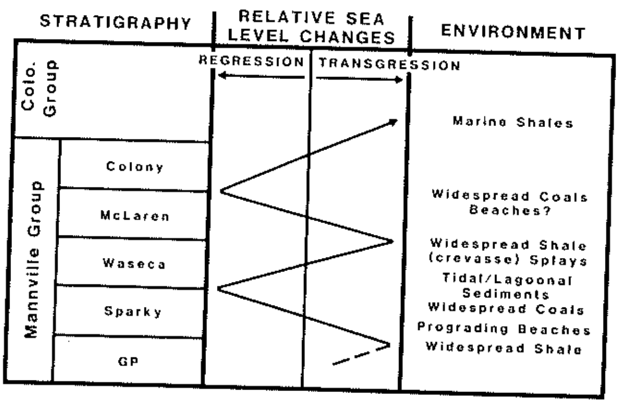

Fig. 20. The relationship between the Upper Mannville stratigraphical units in the Lloydminster area and major relative sea level changes explains the "sedimentary cycles". The Waseca was deposited during a general transgression, following the regressional cycle of the Sparky (after Fuglem, 1970). The climax of the Waseca transgression is represented by the wide-spread sideritic shale that separates the Waseca from the McLaren.

It is possible that the channel once extended a considerable distance to the southwest. A Waseca channel is present in the Freemont field (Dunning et al., 1980), and the basin setting suggests that this system might originate from the Macklin-Chauvin area (Twp. 43, Rge. 1W4M).

Conclusions

The Waseca Formation can be subdivided into a regional and channel facies. The regional facies includes an upper shale, two correlatable sand bodies separated by a thin shale, designated Upper and Lower Waseca, and a basal sequence of interbedded silt and shale. The channel facies can be subdivided into a Homogeneous Sand Unit, and Interbedded Sand and Shale Unit, and a Sideritic Silty Shale Unit.

Deposition in the Waseca took place during transgression of a sea located northeast of the Lloydminster area. The channel was formed in a tidal/estuarine setting and can be traced to the south-southwest of the study area.

Deposition of the Pikes Peak channel facies was contemporaneous with the regional Upper and Lower Waseca sands.

The Lower Waseca sands were formed at the same time as the Unit A sands in the East Pilot. The West Pilot Unit A sands were deposited during a later stage, together with the Upper Waseca.

Mannville structure in the area is dominated by a southeast-dipping trend and is complicated by salt solution to the northeast. A local structural high resulted in an area without bottom water in the Pikes Peak field.

Quartzose sands in the Waseca channel A and B units contain minor percentages of feldspar and clays. Authigenic kaolinite is the dominant clay mineral. Authigenic iron and calcium-magnesium carbonates locally form cemented sandstone beds.

Pay thickness in Unit A sands can exceed 20 m. Porosity averages 30 percent and maximum permeability ranges from 5 to 10 Darcys. Oil saturations are more than 80 percent.

The sands in the Homogeneous sand unit were formed by migrating point bars. Two stages of point bar formation are recognized, each having characteristic reservoir properties.

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