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MINERAL RESOURCES DIVISION

GEOLOGICAL REPORT GR 82-6

GEOLOGY AND HYDROCARBON POTENTIAL OF THE LOWER AMARANTH FORMATION WASKADA - PIERSON AREA, SOUTHWESTERN MANITOBA

by
D. BARCHYN
PETROLEUM BRANCH

1982

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ABSTRACT

Commercial oil production from the Lower Amaranth Formation in southwestern Manitoba was first obtained in June of 1980 in the Waskada area (Twp 1, Rges 25, 26 WPM).Extensive development and exploration activity has followed and is currently still in progress.

The Lower Amaranth is a basal Mesozoic clastic red bed unit correlative with the Lower Watrous of Saskatchewan and the Spearfish of North Dakota. It is associated with a major Jurassic-Triassic transgressive event which affected the Williston Basin.

This report reviews available well data from a fifteen township area in the extreme southwestern corner of Manitoba. The lithology consists of dolomitic and anhydritic interbedded sands, silts and shales with stratigraphic zones of complex sandstone/siltstone lithology occurring in the lower part of the unit. Deposition appears to be related to intermittent, shallow, restricted marine conditions.

Pay zones are in dolomitic siltstones and sandstones, and trapping is stratigraphic in nature, related to a porosity-permeability pinchout governed by a lateral up-dip facies change.

Lower Amaranth oil migrated from imperfectly sealed traps in the underlying Mississippian strata. A close association between Mississippian and Lower Amaranth pools likely exists and can be used as an exploration tool.

ACKNOWLEDGEMENTS

The preparation of this report spanned a time period which saw rapid development of Lower Amaranth potential in southwestern Manitoba. The free exchange of ideas with geologists working the play was instrumental in making the compilation of this report possible.

I would especially like to thank Mr. John Henderson of Omega Hydrocarbons Ltd., and Mr. Roger Edmunds of The Lyleton Corporation for reviewing the draft and generously offering many interesting ideas and interpretations.

I would also like to thank Dr. H.R. McCabe of the Geological Services Branch, Manitoba Department of Energy and Mines for reviewing the draft and for many hours of interesting discussion of the geological problems at hand.

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CHAPTER I. INTRODUCTION

The Lower Amaranth Formation, defined as the Lower Amaranth unit of the Amaranth Formation of Stott (1955), occurs at the base of the Mesozoic section over a large area of the northeastern flank of the Williston Basin in southwestern Manitoba. It is representative of a basin wide episode of "red bed" sedimentation during Triassic and early Jurassic times and is correlative with the Lower Watrous Formation of Saskatchewan and, in part, with the Spearfish Formation of North Dakota.

The Lower Amaranth section has not previously been regarded as a primary target for oil and gas exploration in southwestern Manitoba. Most exploration effort has been directed towards regional truncation traps in Mississippian strata, with the overlying Amaranth red beds and evaporites forming the cap rock. Oil production from Spearfish strata in the Newburg and South Westhope fields of North Dakota, approximately twenty kilometres south of Waskada, was established in the fifties, but the lack of appreciable shows north of the border resulted in limited interest in the Lower Amaranth section in Manitoba.

In June of 1980, Omega Hydrocarbons Ltd. recompleted a former Mississippian producer in 11-30-1-25 WPM in the stratigraphically higher Lower Amaranth Formation. The well was put on stream and marked the first production of oil from a non-Mississippian formation in Manitoba. This success initiated a development and exploration effort in the Waskada area which is currently still in progress. By the end of 1982, it is expected that in excess of eighty Lower Amaranth producers will be completed in the Waskada area.

Concurrently, a second area of Lower Amaranth potential was identified in the South Pierson area by Cobra Oil and Gas Corporation (now The Lyleton Corporation). Only limited development has occurred in this area and the parameters of this pool are poorly defined at this time.

This study will focus on these two Lower Amaranth oil occurrences and the surrounding area. Most emphasis will be placed on the Waskada pool where there is better geological control. Specifically, the area under study includes the extreme southwestern corner of Manitoba comprising Townships 1-3; Ranges 25-29 WPM.

The study area and Lower Amaranth producing areas are illustrated in Figure 1.

The previous lack of success in the Lower Amaranth in Manitoba is reflected in the lack of research directed towards this Formation in the available literature. The purpose of this study is to attempt to start to fill this gap by investigating the known oil occurrences with the aim of determining the geological controls on these occurrences and identifying key exploration problems.

More specifically, this study will attempt to:

- place the Lower Amaranth Formation of the study area in the regional setting of the Williston Basin.
- describe the stratigraphy
- discuss the depositional environment
- describe the characteristics of the Waskada reservoir and relate them to the stratigraphy
- identify key exploration problems involved in the generation of Lower Amaranth prospects

At this stage of development of the Lower Amaranth play, such a study must be regarded as preliminary with strictly tentative conclusions. The proliferation of new data associated with the current development calls for continual reassessment of ideas. Nevertheless, enough information is now available to compile a useful "primer" for explorationists interested in the Lower Amaranth of Manitoba. This study is intended to serve that purpose as well as identify and discuss problems which require further research.

CHAPTER II. REGIONAL SETTING

The sedimentary strata present in southwestern Manitoba occur as a basinward thickening wedge-like segment of Paleozoic and Mesozoic strata on the northeastern flank of the Williston Basin. A major angular unconformity separates the Paleozoic and Mesozoic sections, with erosion having occurred at indeterminate times from late Mississippian through Early Jurassic. Basinward tilting of the Paleozoic strata also occurred during this erosional period, resulting in progressive erosional truncation of the Paleozoic strata at the unconformity surface. Deposition resumed in Mesozoic time with a sequence of Jurassic and Cretaceous strata deposited on the eroded Paleozoic surface. A schematic diagram of the present configuration is presented in Figure 2.

The Lower Amaranth Formation occurs at the base of the Mesozoic section and comprises the initial deposits on the eroded Paleozoic surface following the period of emergence. The stratigraphic position of the Lower Amaranth in the study area is shown in Figure 3.

Underlying Paleozoic strata within the study area comprise carbonates and evaporites of the Mississippian Mission Canyon and Charles Formations. These strata represent regressive carbonate-evaporite deposition which preceded the ultimate retreat of Mississippian seas from the area. As with all Paleozoic strata in the area, these beds are erosionally truncated and, in general, form northwest trending subcrop belts on the unconformity surface. However, structural anomalies within the Mississippian are responsible for pronounced irregularities in the configuration of subcrop belts although the unconformity surface in the study area is relatively flat.

The Lower Amaranth is overlain by evaporites of the Upper Amaranth Formation which are, in turn, overlain by carbonates of the Reston Formation, both of Middle Jurassic age. The nature of the Lower/Upper Amaranth contact has been the subject of controversy as some writers (Stott, 1955; McCabe, 1956) consider it to be conformable while others (Francis, 1956) envision a break in sedimentation. This controversy is also reflected in problems associated with dating of the Lower Amaranth. Due to the lack of faunal evidence, age assignment is dependent on the postulated relationships with surrounding strata. If a conformable relationship with the overlying evaporites and carbonates (Middle Jurassic) is favoured, a Jurassic age assignment would seem appropriate. However, if an unconformable relationship with overlying strata is assumed, and a correlation is made with Spearfish strata in the more central parts of the Basin, a Triassic age assignment is possible. This later view appears to be favoured by American authors, whereas most Canadian writers including the author favour a conformable upper contact and hence, a Jurassic age assignment.

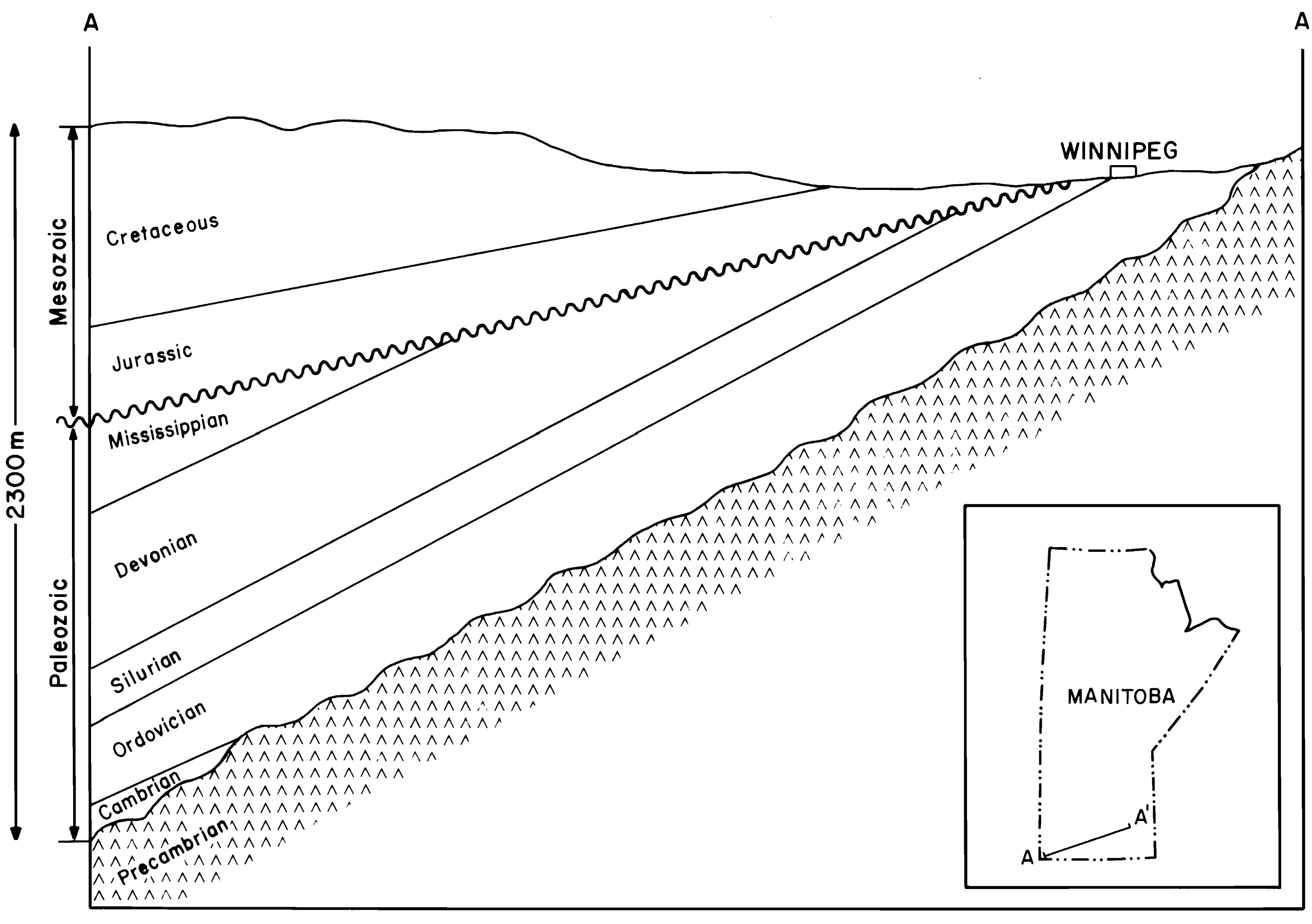


Figure 2: Schematic Section of Geological Structure in Southwestern Manitoba

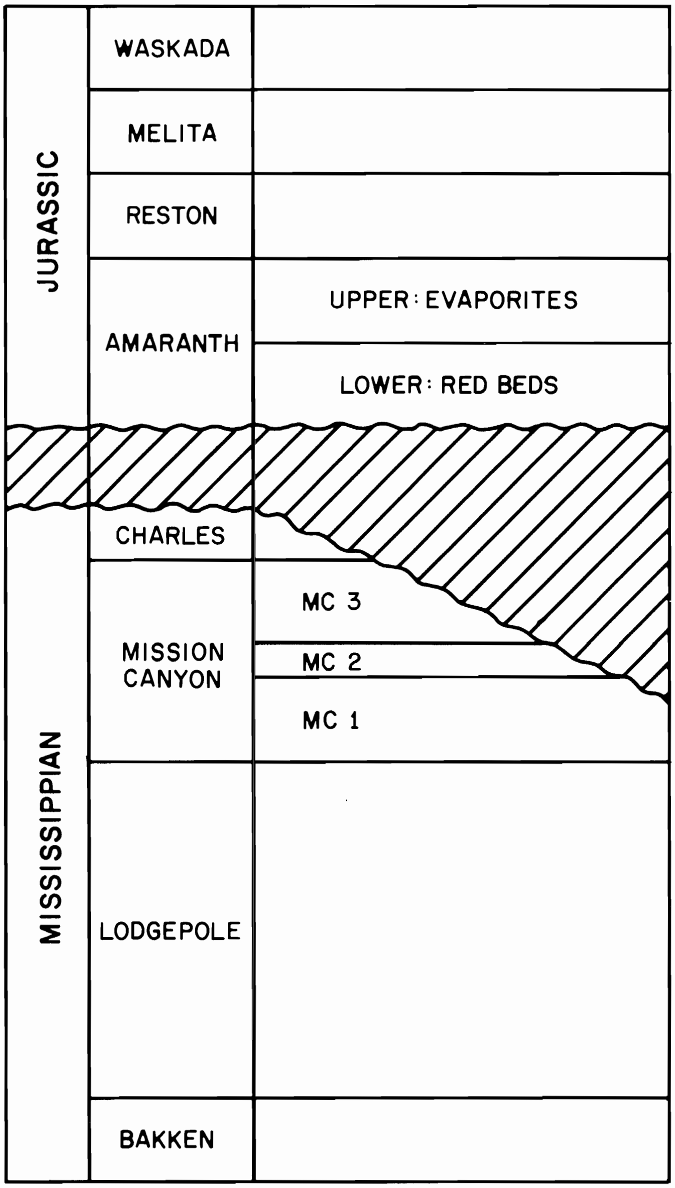


Figure 3: Stratigraphic Column

In general, the Lower Amaranth strata in Manitoba can be viewed as comprising the initial deposits of the major basin-wide transgression of Jurassic-Triassic seas. The distinctive red bed lithology is indicative of a transition from the continental environment associated with the widespread erosion of Paleozoic strata to the marine environment associated with the deposition of overlying evaporites and carbonates. The relationship to the Spearfish red beds in the central parts of the basin is likely time transgressive in nature, as the major transgression affected the central parts of the basin as early as Triassic time.

The upper contact of the Lower Amaranth is believed to be conformable in Manitoba on the basis of the observed lithological sequence and the consistent nature of the contact itself as seen in the study area. The lithological succession is one of interbedded shales, siltstones, and sandstones of the Lower Amaranth, overlain by evaporites of the Upper Amaranth which in turn are overlain by carbonates of the Reston. This sequence is indicative of an environmental change from transitional terrestrial/marine to restricted marine to open marine, which would be expected during a single major transgressive event.

In a stratigraphic cross-section from the Newburg producing area in North Dakota to the study area (Figure 4), the onlapping nature of the Lower Amaranth is evident. Lower Amaranth sedimentation effectively filled in relief on the Paleozoic erosional surface with resultant thickening of the basal members of the unit. The marker at the top of the Lower Amaranth is thought to approximate a time-stratigraphic marker representing termination of the supply of clastics to the basin and initiation of true restricted marine evaporatic conditions.

The basal sandstone which is productive in the Newburg area (Interval A, Figure 4) pinches out in a northward direction explaining the trapping mechanism at Newburg. The sandstones in Interval C which are water-saturated in the Newburg area are the reservoir beds up-dip at Waskada. The trap at Waskada, however, is related to a lateral facies change within Interval C rather than an onlapping configuration such as at Newburg.

Structure on the top of the Lower Amaranth in the study area is fairly regular, dipping to the southwest at about 4.2 m per km (Figure 5). This is an expression of post-depositional basinward tilting related to continued subsidence of the Williston Basin. Minor structural undulations may result from differential compaction and/or post-Lower Amaranth salt solution and collapse. No evidence of structural closure is seen in the study area, indicating that trapping is primarily stratigraphically controlled.

The Lower Amaranth isopach map (Figure 6) reflects the topography of the eroded Paleozoic surface and any differential subsidence component. Thickening of the basal part of the Lower Amaranth effectively "filled in" topographic lows accounting for most isopach variations. Again, differential compaction and salt solution and collapse contemporaneous with Lower Amaranth deposition may have affected the isopach pattern. Basin differentiation is not evident in the map area, indicating relatively uniform subsidence and uniform depositional environment.

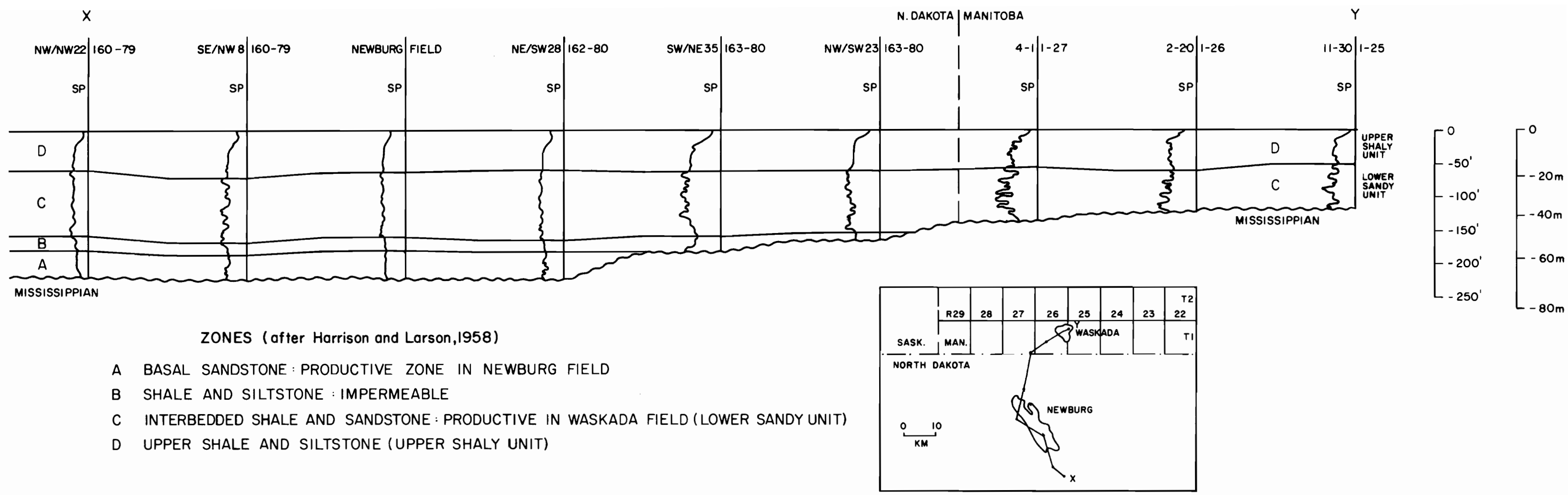


Figure 4: Stratigraphic Section: Newburg — Waskada

CHAPTER III. DESCRIPTIVE STRATIGRAPHY

The dominant lithology in the Lower Amaranth consists of a series of dolomitic siltstones and sandstones interbedded with argillaceous siltstones and shales exhibiting a mottled red to maroon color. The term "red beds" has commonly been applied to this unit as the basic character is similar to the typical red bed sequences discussed in the literature (Dunbar and Rodgers, 1957). A variety of lithofacies is present in a rather complex assemblage.

Two general observations concerning the unit as a whole are worthy of note. First of all, a twofold subdivision of the unit is possible, corresponding with the zonation of the Spearfish strata in North Dakota by Harrison and Larson (1958; Figure 4), and the recognition of a frosted grain unit and an overlying red silt-shale unit in the Lower Watrous strata of Saskatchewan by Cumming (1956). For the purposes of this study, the Lower Amaranth strata in the study area have been informally subdivided into a lower sandy unit and an overlying shaly unit as depicted in Figure 4. This subdivision is correlatable regionally and highlights the general fining-upward character of the section.

Secondly, dolomite and anhydrite are important constituents of the Lower Amaranth. Dolomite is associated primarily with the finer grained silty material, whereas anhydrite occurs as pore-filling cement in the coarser-grained sandy material and as massive nodules and lenses.

LITHOLOGY

For the purposes of this study, the Lower Amaranth has been classified into four general lithological types:

1. INTERBEDDED SHALE/SILTSTONE/SANDSTONE (SEE FIGURE 7)

This lithology exhibits many variations in grain size, color, and texture. Basically, it has a mottled appearance and is generally maroon to light brown. Shale interbeds are usually maroon to dark red in color reflecting the relatively abundant hematite. Coarser grained interbeds are lighter in color, generally grey to light brown.

The diagnostic feature of this facies is the conspicuous interbedding. Interbeds range in thickness from less than one cm. to about five cms. The interbeds are discontinuous and irregular with the coarser-grained components occurring in distinct lenses or pods, usually elongated in a horizontal or near-horizontal direction. Contacts between interbeds are sharp and irregular, giving a pseudo-brecciated appearance.

The ratios of clay, silt and sand sized material are highly variable with a general tendency for the clay ratio to increase upward in the unit.

2. SILTSTONE (SEE FIGURE 8)

This lithology occurs in distinct intervals up to two or three metres in thickness. It is generally light grey to light green in color and dolomitic. Most grains are in the silt to fine sand size range, but thin, discontinuous interbeds of coarser-grained material are common. Floating well rounded coarse quartz grains are abundant. In places, a faint lamination, often inclined and contorted is evident but in general, primary sedimentary structures are lacking. The distinction of this lithology from the interbedded lithology described above depends on the abundance of coarser clastic interbeds and the absence of appreciable shale content.

3. LAMINATED SANDSTONE (SEE FIGURE 9)

This lithology occurs in distinct sandy intervals up to four metres thick with a wide range of grain sizes and primary sedimentary structures. Color varies from light grey to greenish grey, and brown where oil stained. Grain size varies from medium to very fine. Sorting is variable with the medium-grained sandstones being moderately to well sorted and the finer sandstones showing a poorer degree of sorting. Roundness is also variable with a tendency for the medium sized grains to be rounded and the finer grains to be sub-angular. These sandstones fall into the compositional range of quartz sandstones to feldspathic sandstones. Quartz grains dominate with from 5-15% feldspar. Minor amounts of mafic grains commonly occur in thin laminae.

Matrix material is generally absent in the medium-grained sandstones, but a dolomitic mud matrix becomes an important constituent in the fine to very fine-grained sandstones. In places, this matrix has a granular appearance with individual dolomite rhombs visible, suggesting at least partial recrystallization of the mud matrix. Anhydrite cement is commonly associated with the medium-grained sandstones. Optical continuity of anhydrite crystals over several adjacent intergranular spaces is common suggesting a diagenetic origin of this material. The relationship between the size of the intergranular spaces and the composition of intergranular material is remarkably consistent, as the medium-grained sandstones are anhydrite cemented, whereas the fine and very fine-grained sandstones show a gradation to the dolomitic matrix. This relationship also holds true in the interbedded lithology where patches of anhydrite cement are associated with medium- grained interbeds in an otherwise dolomitic rock.

Primary sedimentary structures include horizonal lamination, cross-lamination with dips up to 20°, and small-scale current or ripple cross-lamination.

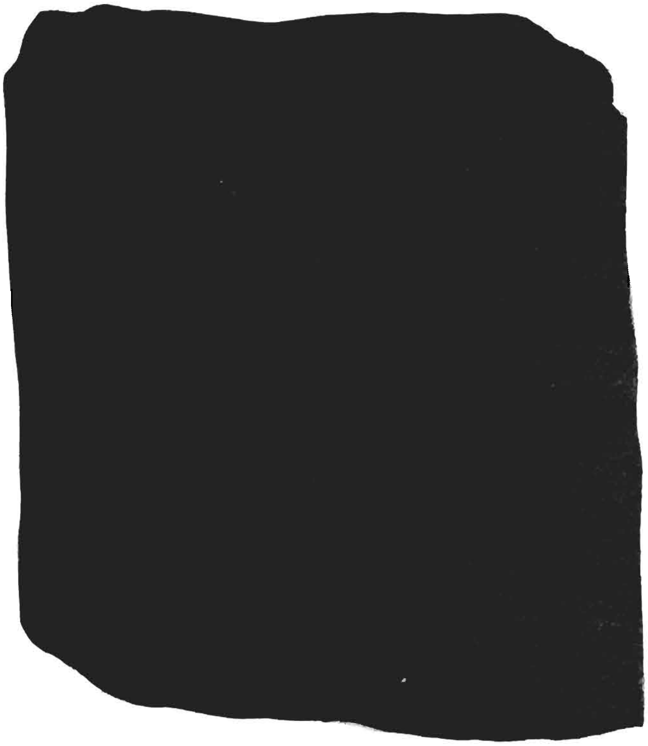
4. MASSIVE SANDSTONE (SEE FIGURE 10)

This lithology occurs in thin intervals of less than half a metre, usually associated with the laminated sandstones facies. Beds are usually light grey to reddish grey in color and coarse- to medium- grained. Grains are predominately quartz, subrounded to rounded and moderately sorted. Intraclasts of argillaceous material and anhydrite are common, often occurring in poorly defined, near-horizontal bands. The rock is well indurated due to anhydrite cementation. Matrix material is rare. Primary sedimentary structures generally are absent, but this facies often grades upwards to a cross-laminated sandstone. A pseudo-brecciated appearance is common with minor amounts of finer material occurring between patches of massive anhydrite-cemented sandstone.

ZONATION AND CORRELATION

An informal regional subdivision of the Lower Amaranth into a lower sandy unit and an upper shaly unit has been discussed previously. The lower sandy unit is of most interest as it includes the reservoir beds of the Waskada and South Pierson areas. A representative lithological section of the lower sandy unit from the Waskada pool including mechanical log plots is presented in Figure 11.

The sandstone and siltstone lithologies occur in intervals of up to 4 m in thickness, recognizable as "sandy" intervals on logs. These "sandy" intervals commonly contain a complex sequence of sandstone and siltstone lithologies. A common sequence consists of a massive, medium to coarse-grained sandstone occurring at the base of the "sandy" interval. The underlying bed, commonly a maroon shale, shows evidence of scour, and rip-up clasts of this material are present near the base of the sandstone. This massive sandstone, which can be up to about 30 cm thick, grades upward to a medium-grained, cross-laminated sandstone. The cross-laminations appear to be planar and exhibit dips of up to 20°. Small scale variation in grain size is responsible for the laminations.



a

Sample from 11-30-1-25 @ 2995′

a. Core Photograph

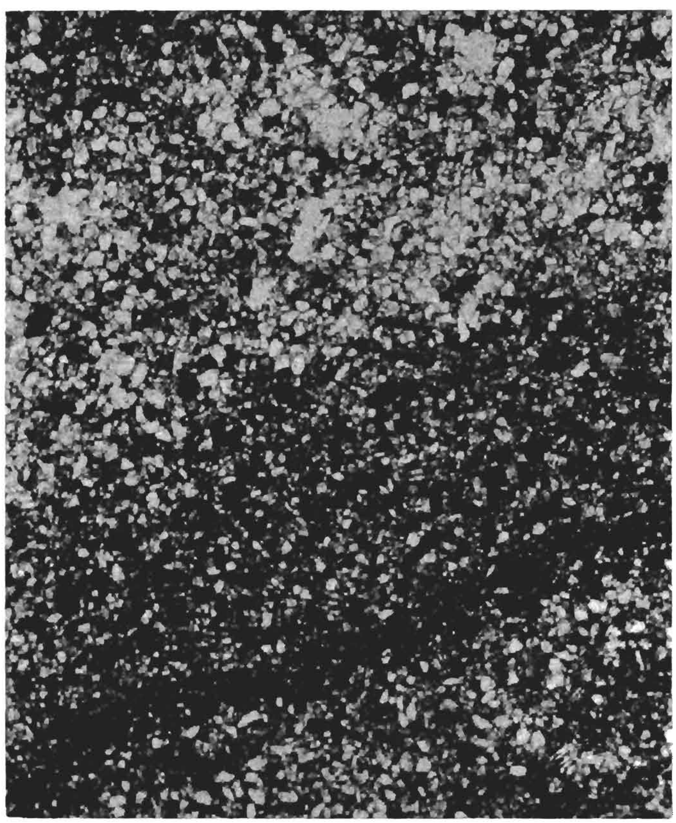
Note:

— irregular, discontinuous inter-beds
— pseudo-brecciated appearance

b. Photomicrograph

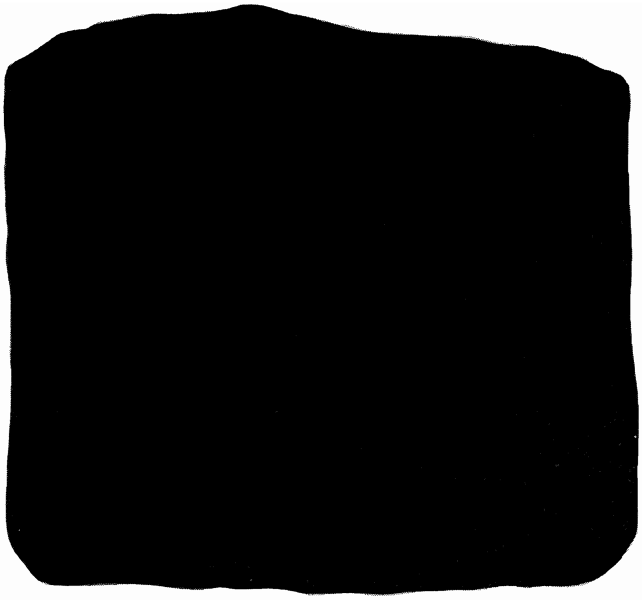
Note:

— silt to v. fine sand sized sub-angular grains
— bands of mafic grains
— dolomitic mud matrix
— anhydrite cement associated with coarser grains



b

Figure 7: Interbedded Shale/Siltstone/Sandstone



1cm

a

Sample from 11-30-1-25 @ 2981′

a. Core Photograph

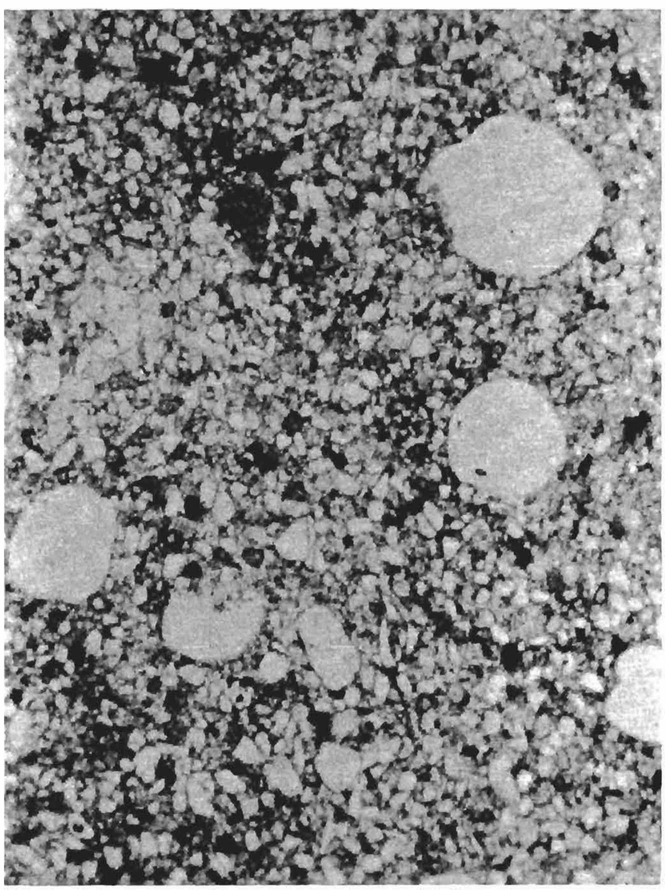
Note:

— faint suggestion of irregular lamination, swirled or brecciated appearance
— thin lenses of coarser-grained material

b. Photomicrograph

Note:

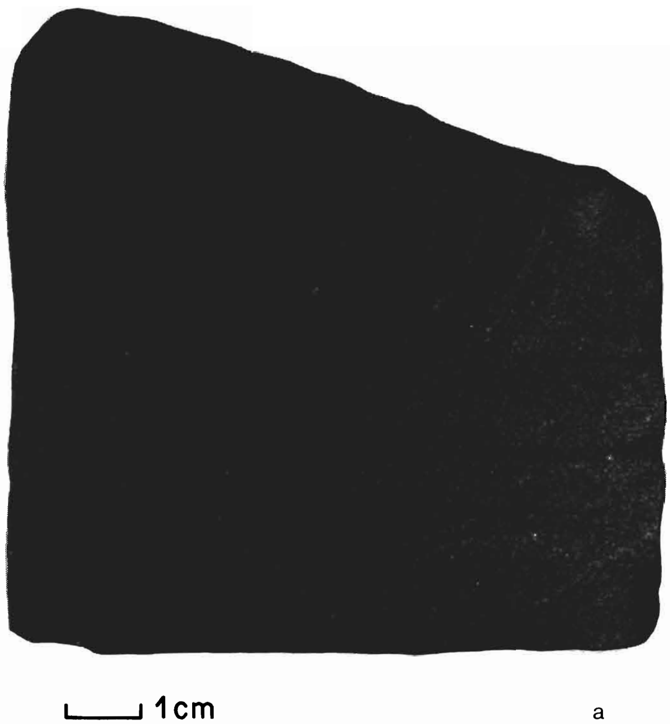
— silt to v. fine sand sized grains
— poor sorting
— "floating" well rounded coarse grains
— dolomitic matrix

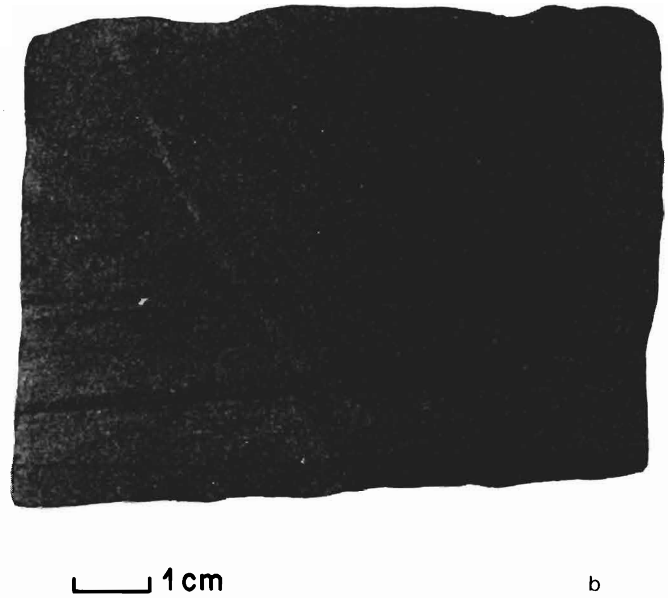


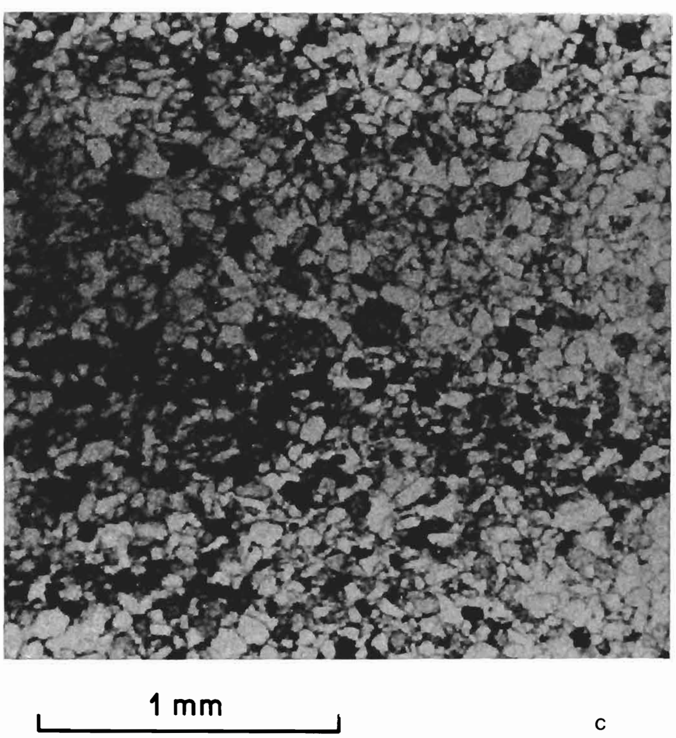
1mm

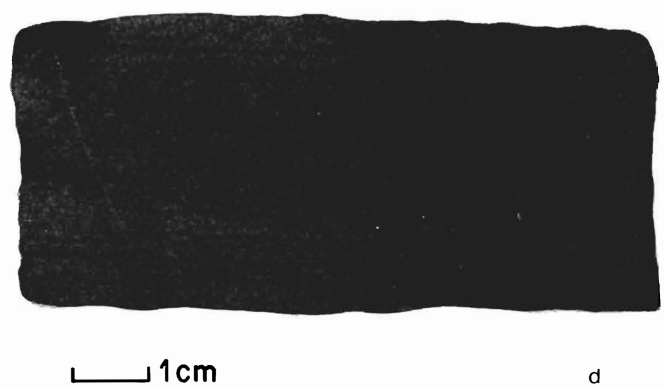
b

Figure 8: Siltstone









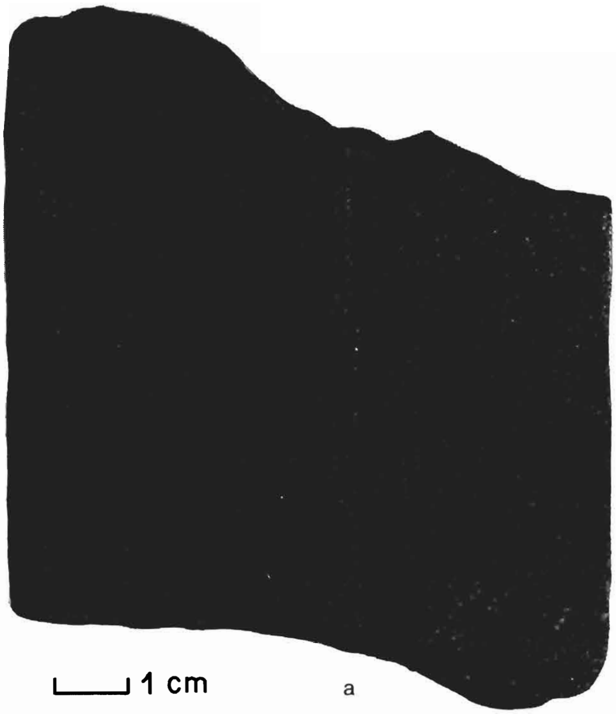
a. Core Photograph (5-22-1-26 @ 3005′)
Note:
— Small-scale current cross-lamination

b. Core Photograph (2-20-1-26 @ 3070′)
Note:
— High-angular planar cross-lamination

c. Core Photograph (6-21-1-26 @ 3031′)
Note:
— Horizontal lamination

d. Photomicrograph (6-21-1-26 @ 3031′)
Note:
— fine to v. fine, sub-angular grains
— dolomitic matrix
— laminae of mafic grains

Figure 9: Laminated Sandstone



a

Sample from 11-30-1-25 @ 2989′

a. Core Photograph

Note:

— massive texture
— clast of argillaceous material

b. Photomicrograph

Note:
— medium to coarse subrounded grains
— complete destruction of primary intergranular porosity by anhydrite cementation

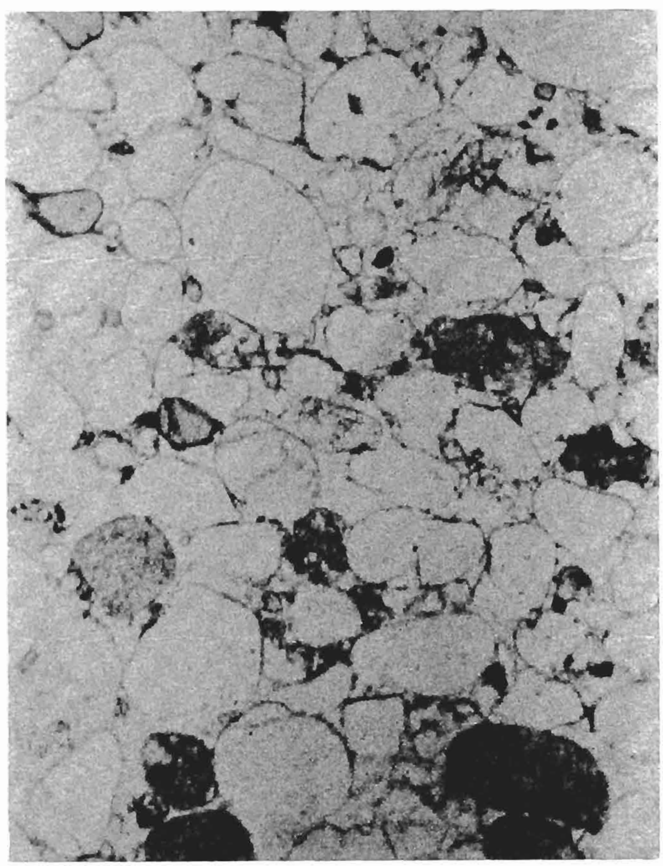


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Figure 10: Massive Sandstone

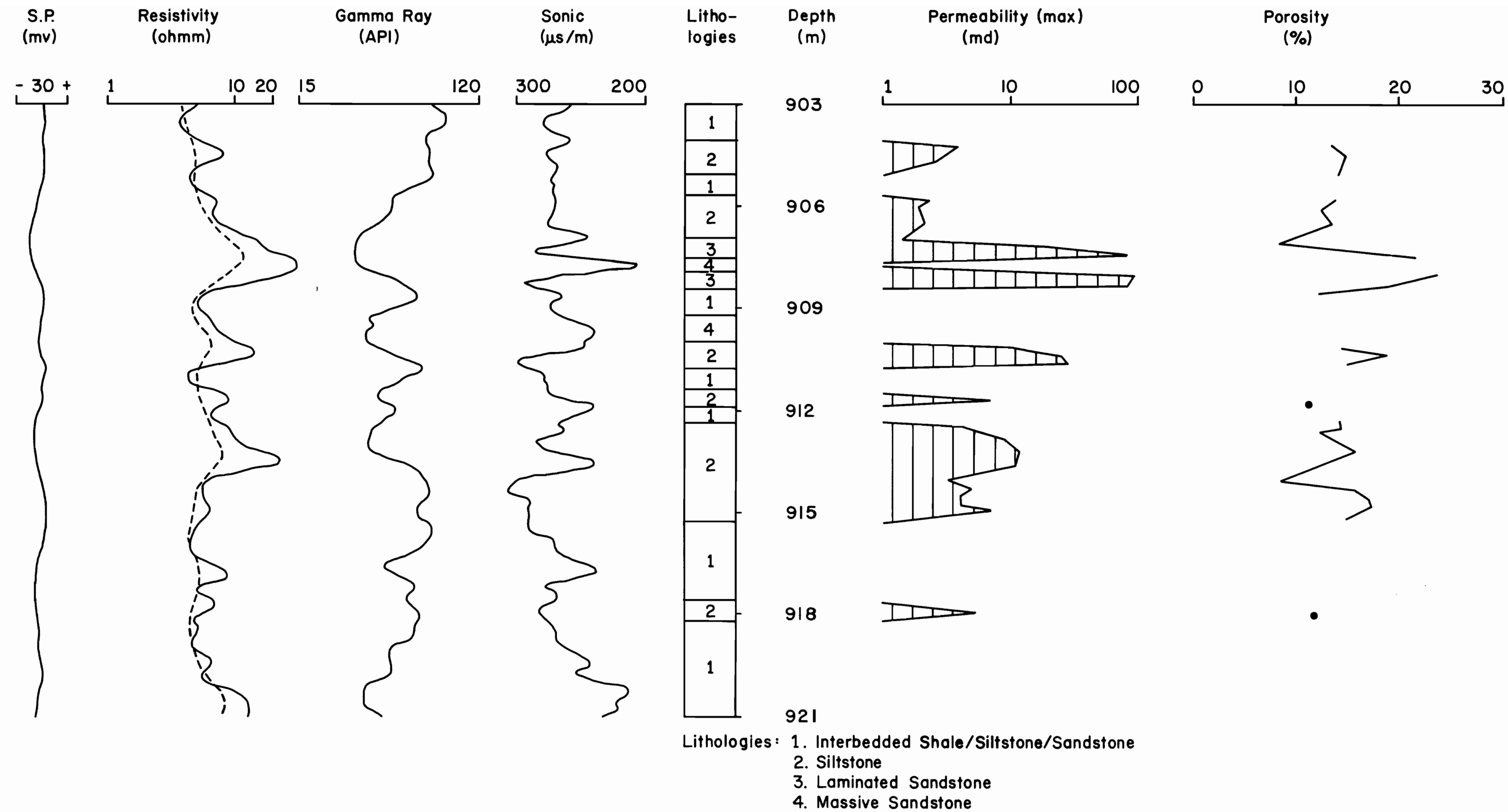

Figure 11: Lithology — Log — Reservoir Property Correlation: 8-26-1-26

Anhydrite cement commonly is associated with the coarser laminae. This sandstone, which may be up to about 20 cm thick grades upward to a fine-to very fine-grained laminated sandstone which exhibits a variety of sedimentary structures including horizontal lamination, low angle cross-lamination and small scale current or ripple cross-lamination. This unit may be up to 2 m in thickness and usually grades upward to a siltstone or interbedded shale and siltstone lithology.

This sequence appears to comprise a single depositional cycle. Many "sandy" intervals consist of a number of superimposed cycles where only small parts of individual cycles may be represented. The resulting interval can therefore be complex, but general fining-upward of the interval is usually observable.

Other "sandy" intervals are lacking in primary sedimentary structures and consist mainly of siltstone. Irregular interbedding with coarser material is also common, and contacts with interbedded shale and siltstone are often gradational. Extensive organic or mechanical re-working of this sediment appears to have been responsible for the destruction of most primary features.

Stratigraphic cross-section A-A′ (Figure 12) shows correlations across the study area. Two thin shaly markers (A and B markers), believed to be time-stratigraphic markers, have been correlated. The interval between the A marker and the unconformity is variable in thickness related to erosional topography on the uncomformity surface. A basal sand is common in the lows as are local discontinuous sandy intervals higher in the section such as in the 12-30-2-28 and 2-20-1-26 wells. Between the A and B markers is a regionally persistent "sandy" interval. The interval from above the B marker to the top of the lower sandy unit contains locally correlatable "sandy" intervals in the Waskada area and very little sand development elsewhere.

The correlation of sandy intervals discussed above is solely on the basis of log character. Core examination reveals that the log-defined correlatable intervals are essentially stratigraphic zones of very complex sandstone and siltstone lithology. The lateral continuity of the individual sandstone beds is highly questionable, but intervals of complex sandstone and siltstone lithology are correlatable locally and regionally.

The localized nature of distinct "sandy" intervals in parts of the section makes it difficult to designate a stratigraphically-defined sandstone member within the Lower Amaranth. The entire lower sandy unit can be regarded as a sandstone member with marked variations in the sand/shale ratio depending on the presence of localized "sandy" intervals.

To illustrate the distribution of these "sandy" intervals, a lithofacies map of the lower sandy unit of the Lower Amaranth is presented in Figure 13. The sandstone values presented here were inferred from wireline log responses, primarily resistivity readings. Departures from a shale "base line" were used as indicators of a "sandy" interval and the values calculated in this manner showed reasonable agreement with visual examination of cored sections.

CHAPTER IV. DEPOSITIONAL ENVIRONMENT

The Lower Amaranth is a complex lithological assemblage representing a complicated history of deposition and diagenesis. Much of the section consists of mixed clastic lithology lacking in fauna or primary sedimentary structures which are necessary for interpretation of depositional environments. The regional setting and features observed in the section offer some clues, but the evidence is by no means, conclusive. A simple depositional model would not be sufficient to explain the observed lithofacies distribution. However, depositional modelling, particularly as it applies to the sandstone reservoir facies, can be a useful exploration tool in attempting to predict the distribution of the sandstones.

The following discussion is not aimed at developing a comprehensive depositional model. Such an endeavour would require more detailed lithofacies examination on a regional scale and is beyond the scope of this study. Instead, the following can be viewed as a preliminary discussion of stratigraphic and lithological observations and how they relate to alternative environmental interpretations.

Regionally, deposition of the Lower Amaranth and its stratigraphic equivalents was associated with a major transgression of Jurassic seas over the northern part of the Williston Basin. The unit is widespread and has a basal onlapping character, essentially filling in erosional relief on the Paleozoic surface. Given such a setting, the overall environment can be described as transitional, representing the initial stages of a major transgressive event. Specific depositional environments in such situations can range from dominantly continental to marine.

The gross red bed lithology of the unit, although not necessarily a diagnostic environmental indicator, suggests some important characteristics of the depositional environment. Firstly, the red coloration of the sediment implies oxidizing depositional conditions, likely related to periodic wetting and drying of the sediment. Periodic sub-aerial exposure of the depositional surface is also supported by the occurrence of dessication cracks in some shaly interbeds. Secondly, the pronounced interbedding of fine and coarser clastics suggests that depositional energy was variable. These variations could be related to fluctuations in water depth or periodic storms.

The occurrence of well rounded frosted grains which "float" in a finer grained matrix can be interpreted to indicate eolian deposition. The abundance of this wind transported material is also suggestive of periodic emergence where eolian deflation and deposition were important agents. The anhydritic nature of the unit suggests that evaporative conditions were common, possibly associated with periodic emergence of the depositional surface.

The identification of a lower sandy member and an upper shaly member within the unit on a regional scale is indicative of a change in sedimentation patterns from early to late Lower Amaranth time. The lower sandy member, being a widespread zone of complex clastic lithology, suggests a period of highly variable depositional conditions. This is followed by a period of more stable depositional conditions as reflected by the more regular lithology of the upper shaly member with only minor and localized sandstone development. Within the lower sandy member, individual sandy intervals bounded by thin shaly marker beds can be correlated on logs over considerable distances (see Figure 12) suggestive of "blanket" type sedimentation. Detailed examination of these log-defined "blankets" reveals that they are really very complex zones of sand and silt lithology rather than homogeneous "blanket" sands. However, the consistency of the basic character of the section, as reflected by the correlatable log character on a regional scale, is suggestive of a marine-associated depositional environment.

In focussing on the sandstones, observations concerning mineralogy, primary sedimentary structures, distribution and morphology, and types of cement or matrix can provide insights to the depositional framework.

The sands are quartzose with minor feldspar and mafic minerals, suggestive of an original Precambrian source area to the north or east. The possibility that these sands are second-cycle, being erosional products of Paleozoic strata or eroded continental deposits on the basin flank cannot be overlooked. It is worth noting that most feldspar grains are remarkably fresh, suggestive of arid to semi-arid depositional conditions.

The primary sedimentary structures such as cyclical fining-upward sequences with scour surfaces, rip-up clasts, and large and small scale cross-lamination suggest cyclical variation of depositional energy common in, but not diagnostic of fluvial deposits. Significant channelling is not evident and it appears that these sands were deposited as thin, laterally- accreting sheets. The lateral continuity of individual fining-upward sequences is questionable but correlation of stratigraphic zones of this type of gross lithology is possible over considerable distances. These features suggest repeated periods of rapid high-energy deposition, perhaps related to storms and flash-floods during periods of emergence.

Mechanical re-working of sediment appears to have been widespread as evidenced by the abundance of sand and silt which is poorly sorted, commonly structureless or exhibiting only faint inclined, contorted and discontinuous laminations. This pseudo-brecciated appearance may be the result of dessication and re-deposition of a partially indurated laminated or massive sand. The lateral facies relationship between this structureless lithology and the laminated sandstone lithology may be explained in terms of localized preservation of primary structures versus widespread mechanical re-working of sediment.

Sand distribution, as illustrated by the Lithofacies Map, (Figure 13) shows a general decrease in sand content to the north and east and localized areas of increased sand occurrence in the Waskada and South Pierson areas. It should be remembered that lithological control is poor over much of the study area and the majority of data for this map was inferred from log responses. Given the relatively flat depositional surface, it is difficult to relate this sandstone distribution to any depositional facies control.

The mode of occurrence of the intergranular dolomite and anhydrite also has important environmental implications. If these minerals are penecontemporaneous, a shallow, restricted marine or lacustrine environment is suggested. The dolomite associated with the finer components may represent detrital carbonate mud. The anhydrite nodules showing growth by displacement suggest hypersaline conditions closely associated with deposition. On the other hand, these minerals may be secondary in origin, being products of a complex diagenetic history associated with the continued transgression, and subsequent deposition of Upper Amaranth evaporites. In this case, primary deposition need not have been associated with hypersaline conditions and a complex post-depositional diagenetic history may have introduced these components. The association of anhydrite with the coarser sands and dolomite with the finer sands would have to be accounted for by such a diagenetic model. Detailed petrographic study of the sands is required to better understand these mineralogical relationships and aid in environmental interpretation.

In assessing these observations, a complex and highly variable depositional environment is apparent. The regional continuity of the basic character of the section suggests a marine association. Periodic emergence is evident, indicating only intermittent inundation with terrestrial conditions during emergent periods. An extensive mud flat with playa lake development and eolian deflation and deposition is a possible environmental model for these emergent periods. Periodic flash-flooding of the flat with high-energy deposition of coarser clastics is suggested by the laminated and cross-laminated sands occurring as thin sheets. These sands may be representative of poorly developed fluvial systems associated with periodic terrestrial storms and floods. Alternatively, these sands may simply reflect winnowing of the sediment in shallows by wave action on a depositional surface below sea level during marine storms. Re-working of these laminated sands was widespread, with only localized preservation of the primary structures.

The local fluctuations in water depth may be attributed to local subsidence related to solution of the underlying Devonian Prairie Evaporite salts. Much of the pronounced structural disturbance in the underlying Mississippian strata has been attributed to early multiple stage salt solution and collapse, and it is quite possible that salt solution during Lower Amaranth time had a significant local effect on depositional patterns. It is interesting to note that the sandstone development in the Waskada area is coincident with pronounced Mississippian structural disturbance. Possibly, a combination of both eustatic and local salt solution effects resulted in a complex fluctuation of water depth and hence the depositional energy conditions which govern the distribution of the sandstones.

In summary, it appears that deposition was most likely related to intermittent shallow, restricted marine conditions. Sandy intervals may, in part, represent fluvial deposits on an intermittently emergent mud flat. Alternatively, winnowing of sediment by wave action in shallow marine conditions may be the primary depositional mechanism. Regardless, widespread reworking of the sands during the continued transgression is apparent, resulting in a more sheet-like morphology of sandy lithology.

CHAPTER V. RESERVOIR CHARACTERISTICS — WASKADA POOL

The first commercial production of Lower Amaranth oil was obtained upon recompletion of a former Mississippian producer located in Lsd. 11-30-1-25 during June of 1980. This success initiated the development of the Waskada Lower Amaranth Pool which is currently still in progress. Limited development of Lower Amaranth potential has also taken place in the South Pierson area, but the extent and quality of this pool is, as yet, poorly defined.

Given this state of development, reservoir parameters have not yet been clearly established. A full analysis of the reservoir characteristics of both Lower Amaranth pools will have to await further development drilling and production history. In this chapter, the available data on the Waskada pool will be used to present some characteristics of the reservoir through discussion of the relationship between lithology and reservoir quality, pool limits and their controls, in-place oil reserves and recovery factors, completion practices, and initial production rates.

Reservoir characteristics of Lower Amaranth lithologies are highly variable. Although the entire lower sandy unit can show an oil saturation, only the more porous, sandy beds have sufficient permeability to act as an effective reservoir. The reservoir therefore appears to consist of a system of horizontally connected permeable zones within the lower sandy unit.

A fairly consistent relationship exists between reservoir quality and lithology in the Lower Amaranth. The bulk of net pay is found in the siltstone/sandstone lithology. Porosity is both primary intergranular and secondary intercrystalline in the recrystallized dolomite matrix. Permeabilities are generally in the range of 1 to 10 md. even though, upon visual examination, this material appears to be tight. The laminated sandstone lithology has the best reservoir quality with permeabilities of over 100 md. in some cases. The massive sandstone lithology has consistently poor reservoir quality as virtually all of the primary intergranular porosity has been destroyed by anhydrite cementation. The interbedded shale/siltstone/sandstone lithology is generally tight.

To illustrate the relationship between lithology, reservoir properties and log responses, Figure 11 presents a representative section from the Waskada pool. The lithologies present in this section have been classified into the four general lithological types noted previously.

Using a permeability cut-off of 1 md. to define effective pay, a total of 8.2 m of net pay was identified in this section. The average porosity is 14.5% with an average permeability of 14.8 md. This section is typical of the Lower Amaranth pay zones found in sections 25 and 26 of Twp. 1, Rge. 26. To the south, there is a general decrease in occurrence of the laminated sandstone lithology and most of the pay is found in the siltstone/sandstone lithology.

An isopach of pore volume for the Waskada pool is presented in Figure 14. Again, a 1 md. permeability cut-off was used in defining effective pay. Note that the data are not sufficient to define the limits of the pool. A dip cross-section of the pool is presented in Figure 15. The up-dip limits of the pool are controlled by decreasing net pay associated with an, as yet undefined, permeability barrier. This decrease in net pay corresponds with a decrease in the sand-silt ratio (Figure 13) related to a facies change from the sandstone lithofacies to the interbedded lithofacies in the lower sandy unit. A diagenetic facies change may also be involved. Additional drilling and evaluation are necessary to define the extent of the pool in a northeasterly direction. The southern and western limits are defined by an edge water contact as indicated by the log response of Lower Amaranth sands in the dry holes in the west half of Twp. 1, Rge. 26 and recovery of salt water on drill stem tests. Given the complex stratification of the reservoir, the oil/water contact also is likely complex, involving significant transition zones in the low permeability strata.

As the limits of the pool have not yet been accurately defined, total in-place oil reserves cannot be calculated. However, in-place reserves attributable to a 16 ha. spacing unit based on estimated average reservoir parameters can be calculated as shown in Table 1. Note that these reservoir parameters, particularly net pays, are variable across the pool and more accurate reserve determination would require detailed mapping of pore volume.

TABLE 1: IN PLACE RESERVES CALCULATION

— for one 16 ha spacing unit using estimated average reservoir parameters.

A	=	Area (ha)	=	16
h	=	Net Pay (m)	=	8
P	=	Porosity	=	.15
Sw	=	Water Saturation	=	.40
Boi	=	Shrinkage	=	1.17

Oil in place (m^3) = 10 114 (A)(h)(P)(1-SW)(1/Boi)

99 584 m^3

(626 383 Bbls)

However, the above estimate can be used as a general indicator of in-place reserves for a typical spacing unit within the pool.

Source of reservoir energy, and ultimate recovery factors have not yet been established due to the short production history available at this time. Early indications from most wells suggest an initial production decline with little or no increase in water cut indicating a low energy, solution-gas drive reservoir. Given the relatively low permeabilities observed, primary recovery factors in such a situation are likely in the range of 10 to 15 percent. Using a 10% recovery factor, primary recoverable reserves per spacing unit based on the above in-place reserve estimate are 9958 m^3 or 62,638 Bbls.

Secondary recovery through waterflooding is being considered in this pool and could, perhaps, double the recoverable oil.

The most common completion practice for wells in the pool is to run and cement 114 mm production casing to total depth, usually in the Mississippian. Lower Amaranth pay is then perforated over a 5 to 10 m interval and then acidized. A polyemulsion fracturing job is then performed using 21 tonnes of 10-20 sand and 6 tonnes of 8-12 sand with a pressure of 16 MPa. Production tubing is then run and the well is placed on production, usually with pump and rods. A typical completion profile is presented in Figure 16.

Initial production rates for selected wells in the Waskada pool are presented in Table 2. These rates are average daily rates based on a five-day production test. The average initial production rate is in the range of 12 m^3D with a water/oil ratio of about .2. It is still too early in the production history of these wells to extrapolate a meaningful decline curve.

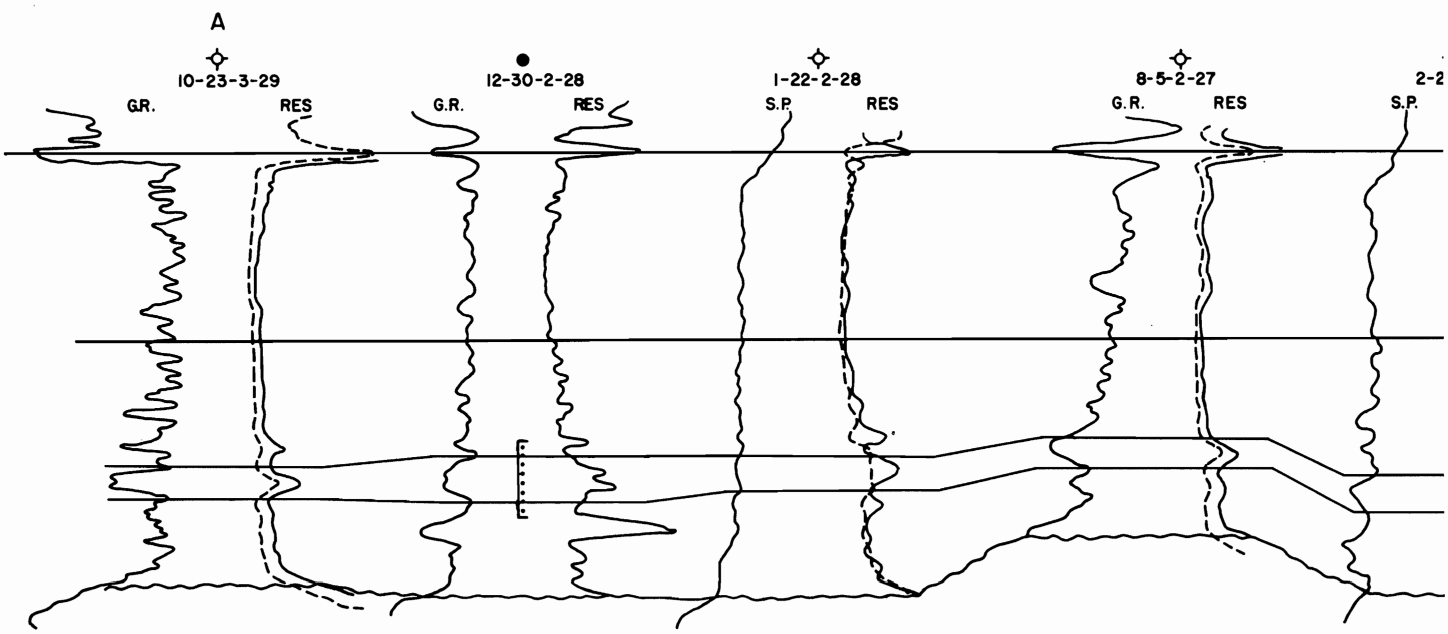

Figure 12: Stratigraphic Cross-Section A-A′

A complete version of this figure is included at the back of the file.

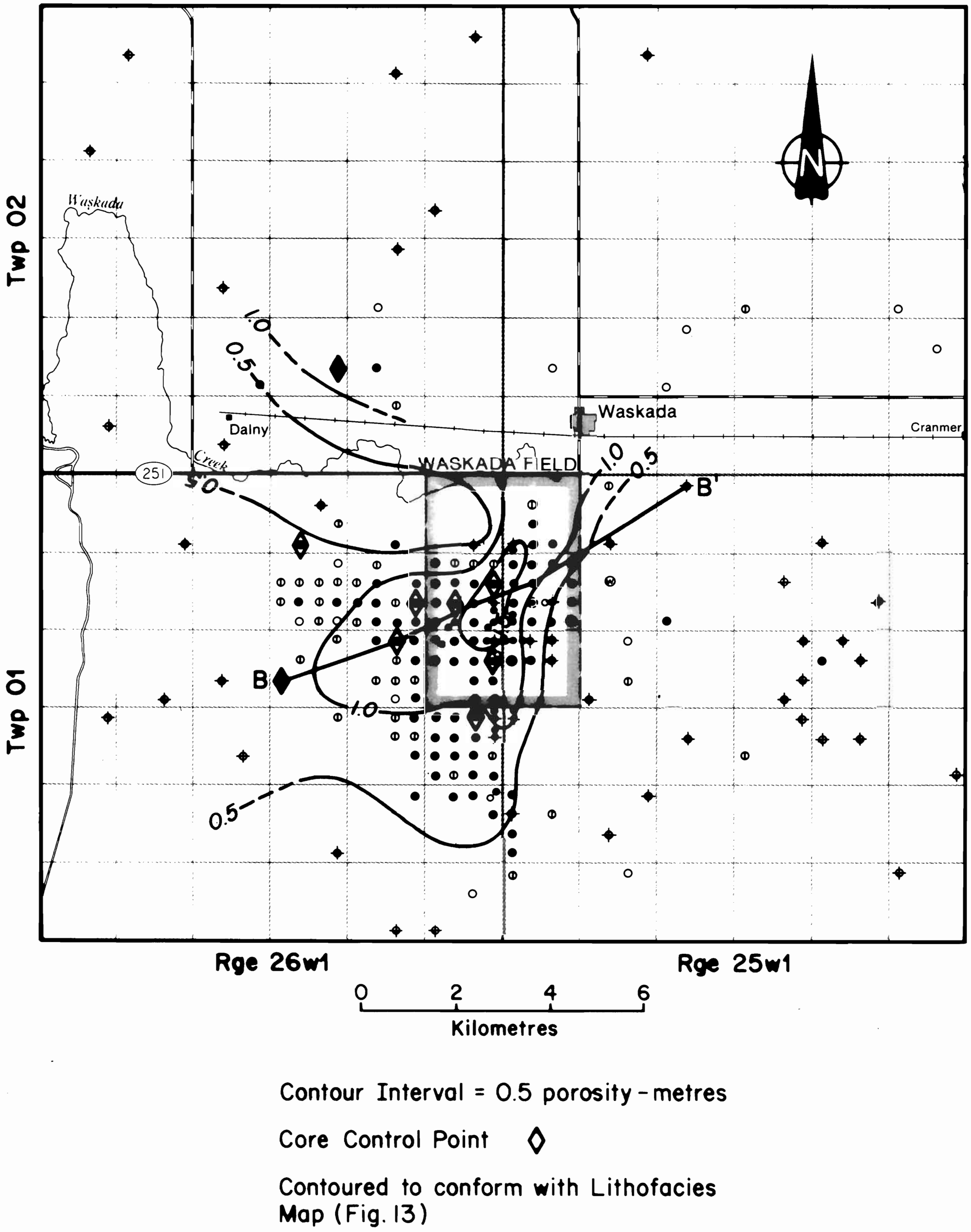

Figure 14: Pore-volume Isopach — Waskada Area

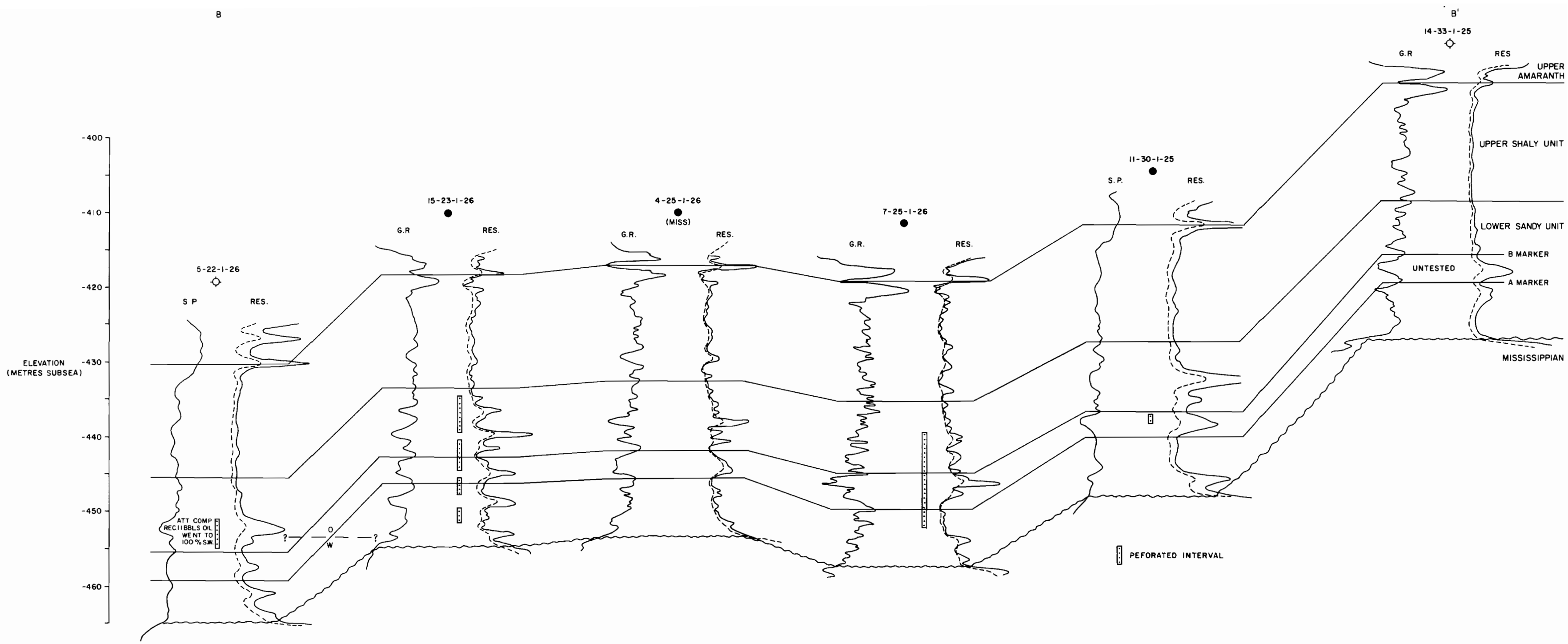

Figure 15: Structural Cross-Section B-B′

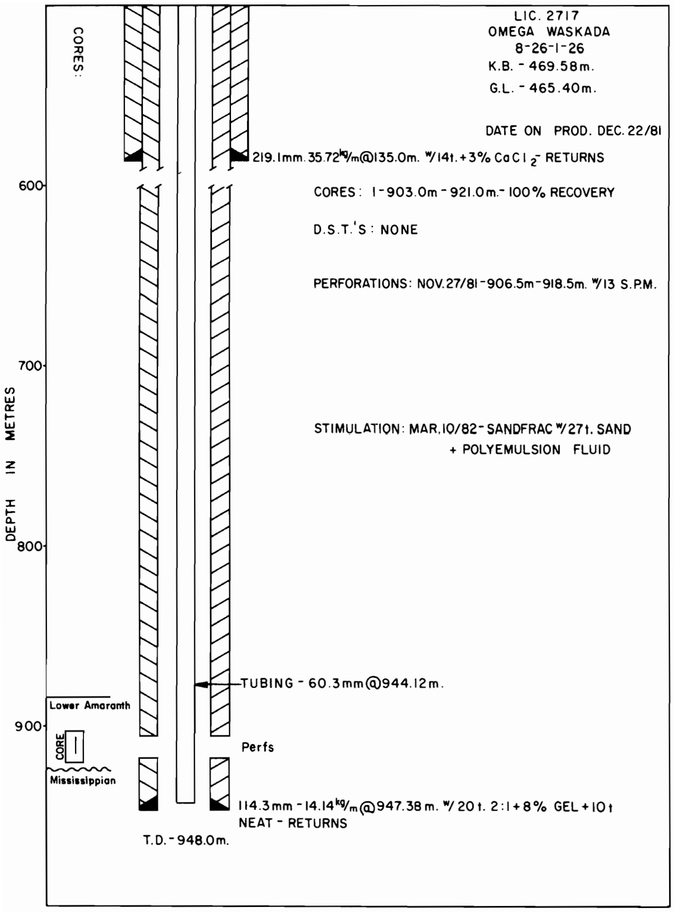

Figure 16: Completion Profile: 8-26-1-26

TABLE 2: INITIAL PRODUCTION RATES

Well	Oil Production (M^3/D)	Water/oil Ratio
15-13-1-26	16.3	.05
16-23-1-26	6.1	.14
7-24-1-26	14.1	.33
15-24-1-26	23.8	.21
5-25-1-26	7.7	.13
2-35-1-26	4.9	.25

CHAPTER VI. EXPLORATION PROBLEMS

Exploration for Lower Amaranth oil pools requires identification of favourable reservoir facies occurring in a trapping configuration, and identification of an oil source and migration route into such a reservoir.

The Waskada pool can be used as a model to identify such targets and apply the known concepts to exploration strategy.

Trapping is primarily stratigraphic in nature related to an up-dip porosity-permeability pinchout. The nature of this pinchout is not well understood but is likely related to a lateral up-dip facies change within the strata of the lower sandy unit. A depositional facies-related control on this pinch-out is not readily apparent with the available data. Further detailed environmental interpretation of the sandstones may lead to a depositional model capable of predicting sandstone distribution and trapping configurations.

Diagenetic facies should also be studied carefully, as the pinchout may be controlled to a large extent by a diagenetic overprint rather than primary depositional features. Secondary porosity in the dolomitic matrix material is of particular interest and regional diagenetic patterns would be useful in identifying favorable trends.

Mapping of these porosity-permeability pinchouts combined with structure on Lower Amaranth markers would be useful in identifying potential traps.

The second key problem in Lower Amaranth exploration is the identification of an oil source capable of charging the sandstone reservoirs. Although no geochemical evaluation is available, it would seem that source rock potential within the Lower Amaranth and its stratigraphic equivalents is very limited. The oxidized appearance and lack of appreciable organic content in these sediments suggests that the reducing environment necessary for preservation of organics did not occur in these strata. Also, the depth and time of burial were insufficient to create a favourable geochemical environment for petroleum generation.

A Mississippian oil source is supported by the similarities of physical characteristics of Lower Amaranth and Mississippian oils. Analysis of samples from the Waskada area indicate very similar oil density and sulphur content values. Both oils are believed to be Type II oils (Bakken-Madison Oil System) of Dow (1974) having been generated in organic-rich Bakken shales deeper in the basin.

Assuming a Mississippian source for the oil, a migration path into the Lower Amaranth reservoirs must also be identified. Dow (1974) identified the Charles salts as barriers to vertical migration of oil from the Madison system. Only beyond the subcrop edge of the Charles salt in North Dakota is there a possibility of vertical migration of oil into post- Mississippian reservoirs. Extensive lateral migration of oil has occurred through stratigraphically-defined permeable zones in the Mississippian and trapping is common where these zones are truncated at the unconformity. This is the case for most of Manitoba's Mississippian reservoirs. However, if the Amaranth section immediately above the unconformity is not totally impermeable, oil may migrate into the Lower Amaranth and have access to the sandstone reservoirs.

The Newburg and South Westhope Spearfish pools in North Dakota provide evidence of this sort of migration process. The reservoir in these cases actually straddles the unconformity, including both porous Charles strata and the overlying basal sandstone of the Spearfish. Although this situation is not directly analagous to Waskada, these pools demonstrate that post-Mississippian strata can be charged with Mississippian oil at the unconformity. This "leakage" effect from underlying Mississippian strata is believed to also apply to Lower Amaranth pools in the study area.

Given this migration path, it is possible to identify areas where the Lower Amaranth may have been charged with Mississippian oil on the basis of the geology of the Mississippian subcrop surface. Subcropping of the major zones of permeability will define potential gathering areas for Lower Amaranth oil. In the study area, the subcrop of the permeable MC3 member of the Mission Canyon Formation is of particular interest as the permeable zones are regionally extensive and are significant carrier beds as well as reservoir beds in the Pierson and Waskada Fields. A schematic diagram of such a migration path is presented in Figure 17. Again, the Charles subcrop edge is significant as extensive lateral oil migration likely occurred in the MC3 below the impermeable Charles, and the oil gained access to the Lower Amaranth mainly beyond the Charles subcrop edge. Other potential gathering areas are present down dip where stratigraphically higher permeable zones subcrop. These could represent additional migration routes if significant lateral migration within the Lower Amaranth sands is assumed.

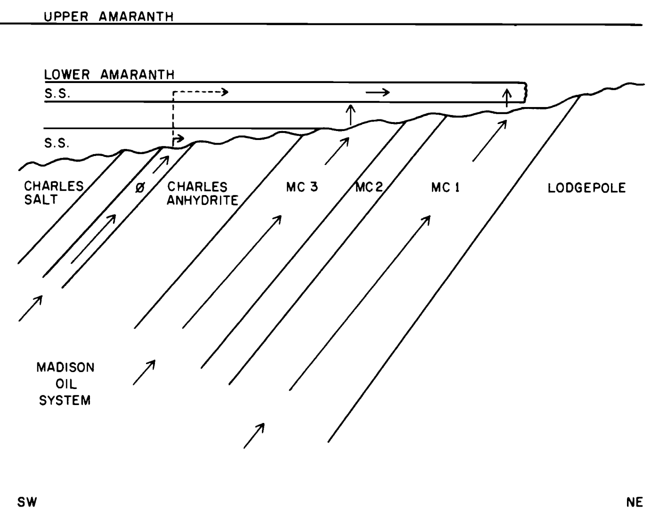

Figure 17: Schematic Migration Route of Lower Amaranth Oil

Given the generally low permeability of most basal sections in the Amaranth, the transfer of oil through the basal section and into the more permeable sandy reservoir presents a problem. The main MC3 subcrop belt rises structurally to the southeast and given the relative permeabilities of the MC3 and Lower Amaranth, the tendency would be for the oil to migrate in the direction of greatest permeability which would be along the subcrop belt below the unconformity. Trapping in the MC3 is achieved where either facies changes in the MC3, paleotopographic relief, or pre-erosional Mississippian structure halt the south-eastward migration of oil along the subcrop belt. The Mission Canyon oil pools at Pierson and Waskada are examples of such situations. However, the development of an oil column in the Mission Canyon at any point in time is likely instrumental in initiating transfer of oil into the Lower Amaranth. A certain minimum height of oil column may be required to generate a threshold buoyancy pressure required to force oil into the Lower Amaranth. Capillary pressure properties of the rocks involved would determine quantitatively how this process might have occurred. Such data are not presently available, but a possible schematic representation of the situation is presented in Figure 18. Here, the Lower Amaranth would act as a seal until the oil column reaches height h. At this point, buoyancy

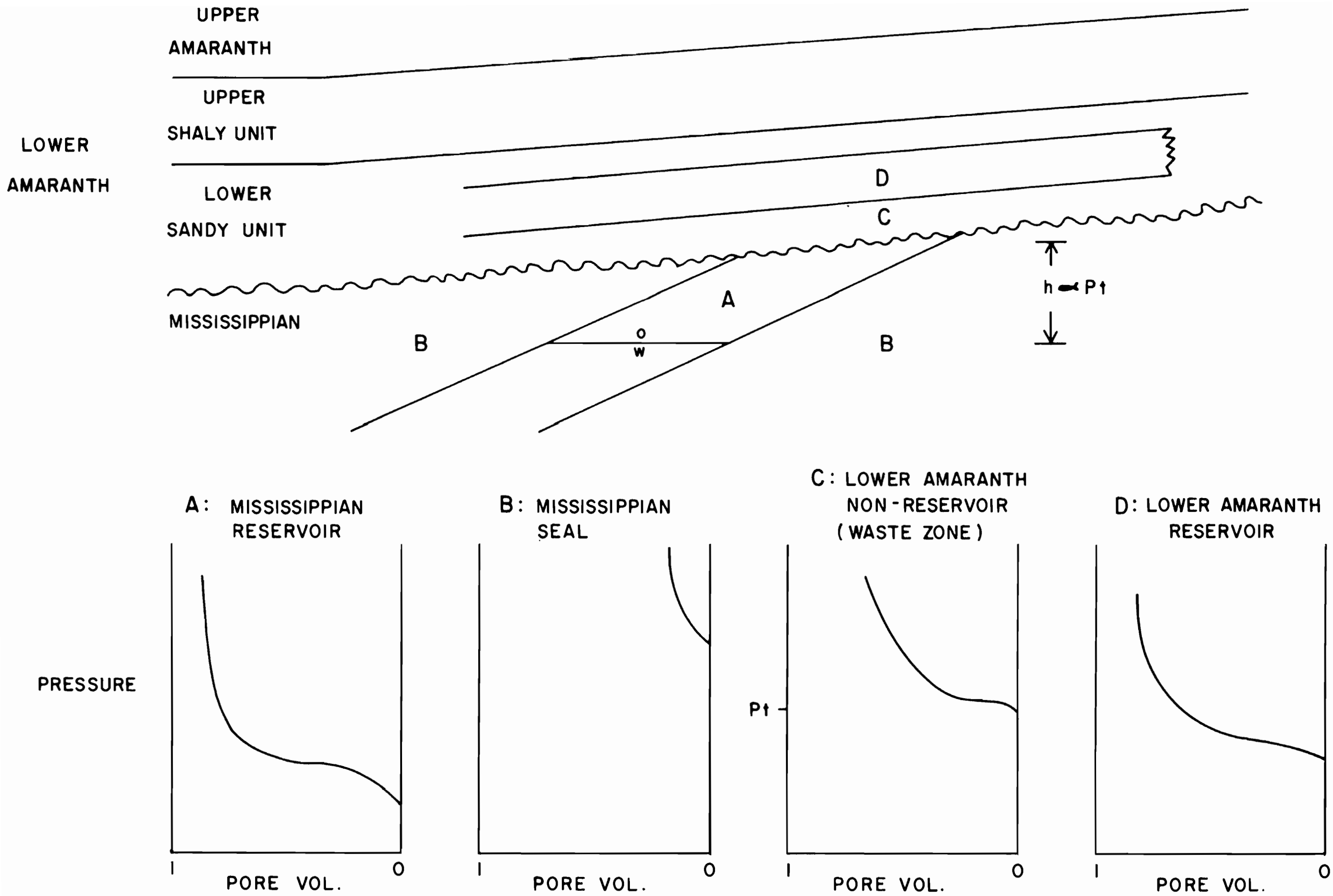

Figure 18: Hypothetical Capillary Pressure Curves

pressure of the oil column would be sufficient to force oil into the Lower Amaranth or cause the seal to "leak". This would provide the oil with access to the sandstone reservoirs.

Capillary pressure properties are a function of lithology and therefore are quite variable across the Mississippian-Lower Amaranth interface. Points of entry of Mississippian oil into the Lower Amaranth are likely sporadic across the study area depending on the presence or past presence of Mississippian oil columns and relative permeabilities of the lithologies involved. The occurrence of a tight dolomitized and anhydrite infilled zone of variable thickness at the Mississippian surface as well as vertically oriented fracture systems related to salt collapse further complicate the situation.

An oil migration route outlined in the preceding discussion is suggestive of an intimate association between Mississippian and Lower Amaranth pools. This association could provide a useful exploration tool as an integrated approach to Lower Amaranth and Mississippian exploration is required. A Mississippian pool occurring below favourable reservoir facies in the Lower Amaranth is suggestive of a Lower Amaranth prospect in the vicinity. The location would be dependent on the extent of up-dip lateral migration in the sands until a trapping configuration is reached. Even a show of oil in a wet Mississippian zone is significant in that it may be indicative of a trapping configuration where extensive leaking of oil into the Lower Amaranth has occurred. Conversely, Lower Amaranth oil pools and shows may be indicative of a Mississippian pool in the vicinity, most likely in a down-dip position.

The extent of lateral migration of oil within the Lower Amaranth is an important consideration in exploration strategy. If there is limited lateral continuity of the permeable zones within the sandstone intervals, lateral migration would be limited and trapping would occur in close proximity to the areas where oil gains access to the Lower Amaranth. If lateral continuity of the permeable zones is good, exploration should concentrate on the regional porosity-permeability pinchout trends in the Lower Amaranth.

Detailed environmental interpretation of the sandy intervals could lead a better idea of the extent of lateral continuity to be expected. Also, additional production and pressure data from the Waskada pool will aid in determining the drainage areas of individual wells and therefore provide an indication of the lateral continuity of the reservoir.

Capillary pressure data on the lithologies involved and static reservoir pressure data from the Mississippian and Lower Amaranth would be useful in further developing the ideas presented above.

The Waskada Lower Amaranth pool provides an excellent example of how the exploration concepts discussed above interact to produce a commercial reservoir. Figure 19 is a schematic cross-section of the Waskada area. The reservoir trap is provided by the porosity-permeability pinchout to the north and east. Porous Mississippian strata subcrop in the area and, more importantly, numerous Mississippian traps with associated oil columns are present. This provides several potential local migration routes into the Lower Amaranth accounting for the source of the oil.

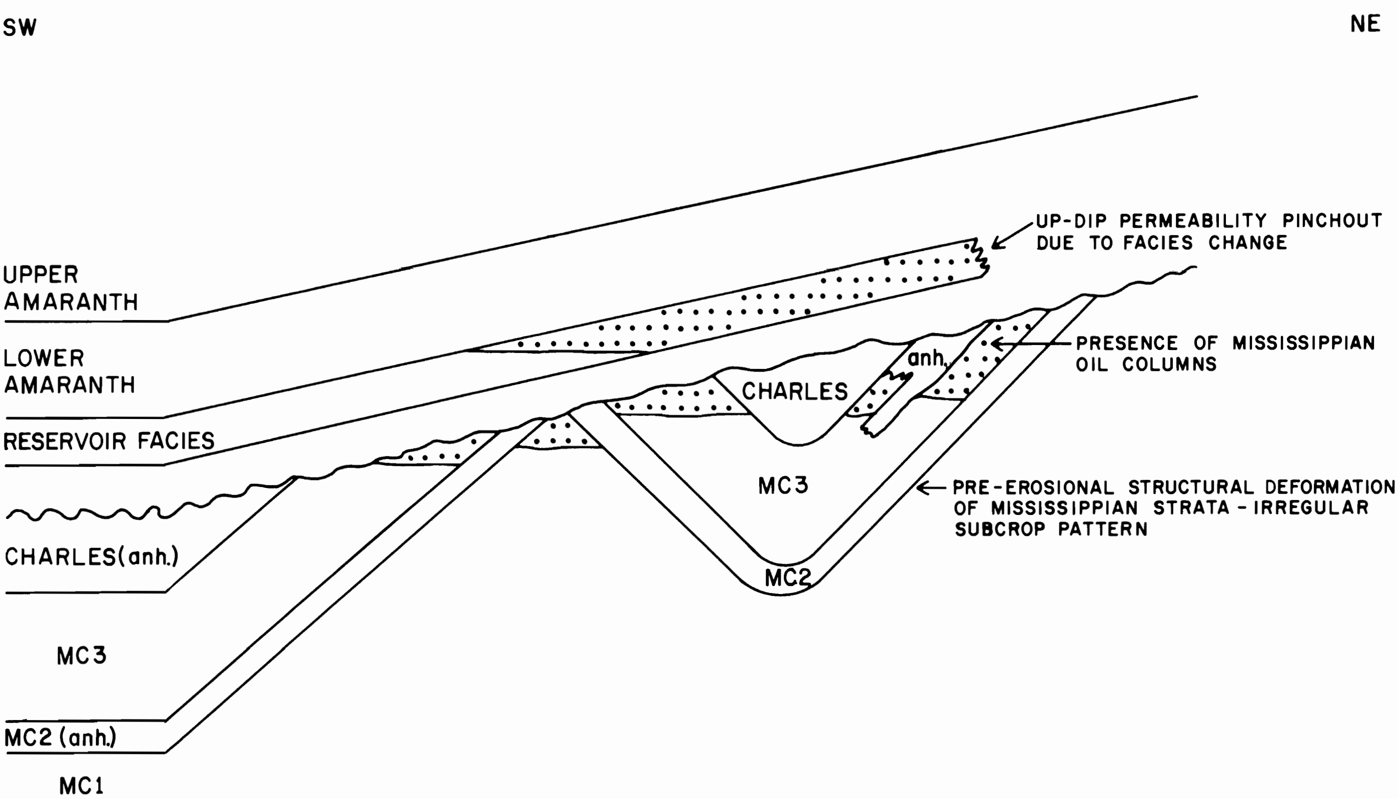

Figure 19: Schematic Section — Waskada Pool

CHAPTER VII. CONCLUSIONS

The Lower Amaranth Formation in the study area is an onlapping clastic unit representing the initial stages of a major transgressive event which affected the study area in Jurassic time. It is correlative with the Lower Watrous Formation of Saskatchewan and, at least in part, with the Spearfish Formation of North Dakota.

A two-fold informal subdivision of the Lower Amaranth into an upper shaly unit and a lower sandy unit is possible. Further stratigraphic subdivision of the lower sandy unit is possible by use of thin shaly beds which are correlative over the study area.

The lithology of the lower sandy unit consists of interbedded shale, siltstone and sandstone with dolomite and anhydrite being important constituents. The siltstones and sandstones occur in distinct beds of up to 4 m in thickness in the lower sandy unit. Sandstone intervals exhibit a fining upward character in places, with a variety of primary sedimentary features including large and small scale cross-lamination. Elsewhere, sandstone and siltstone beds appear to be re-worked sediment with little evidence of primary features.

A dolomite matrix is present in the finer sandstones and siltstones and appears to be partially recrystallized. Anhydrite cement is commonly associated with the medium and coarse-grained sands.

Deposition of the Lower Amaranth appears to be related to intermittent shallow, restricted marine conditions. Periodic emergence of the depositional surface with eolian and flood-related, high-energy fluvial deposition is suggested. Widespread re-working of the sediment accounts for the lack of primary sedimentary features in most of the sandstone and siltstone intervals. Depositional controls of sandstone distribution in the Lower Amaranth are not clearly understood.

A consistent relationship exists between lithology and reservoir quality in the Waskada Lower Amaranth Pool. The best permeabilities are observed in fine to very fine laminated dolomitic sandstones but the bulk of net pay is found in structureless fine sandstones and siltstones of low permeability. Porosity is both primary intergranular and secondary intercrystalline in the dolomite matrix. The trapping mechanism is stratigraphic with an, as yet undefined, porosity-permeability pinchout to the northeast and edge water to the southwest. Accurate determinations of total reserves and recovery factors will have to await further development drilling and production history.

Exploration for Lower Amaranth pools involves the identification of favourable reservoir facies in a trapping configuration, and determination of a migration route or oil source. Determining controls on sandstone distribution and diagenetic trends are therefore key exploration factors. The oil source is likely the underlying Mississippian with transfer of oil into the Lower Amaranth occurring at places where porous Mississippian beds subcrop at the unconformity. Due to the low permeability of the basal part of the Lower Amaranth, the development of a Mississippian oil column may be necessary to generate the buoyancy pressure required to force oil into the Lower Amaranth. The quantitative aspects of this process would be determined by the capillary pressure characteristics of the rocks involved.

An intimate association exists between Lower Amaranth and Mississippian oil pools. This association can be used as a powerful exploration tool and permits an integrated exploration approach. The extent of lateral migration of oil within the Lower Amaranth is an important consideration in this regard.

All phases of this study highlight the need for further research into many aspects of Lower Amaranth geology and reservoir potential. Detailed petrographic study of the lithologies involved and their relationships on a more regional scale is required to gain a better understanding of depositional and diagenetic environments. Since stratigraphic variation provides the prime trapping mechanism, prospect generation will require the use of depositional models capable of predicting occurrences of favourable reservoir facies. Capillary pressure data are required to gain an understanding of the complex relationship between Mississippian and Lower Amaranth pools and the significance of shows of oil in either. A better understanding of the migration route of oil into the Lower Amaranth is also important in prospect generation. The compilation of reservoir performance data is important in assessing the reservoir energy source, character, and therefore, ultimate oil recovery.

Perhaps the most significant aspect of this new discovery is the fact that this oil occurrence, in a sense, defied conventional wisdom. The Lower Amaranth has been regarded as an impermeable seal and most exploration attention has been focused on the underlying Mississippian. The discovery of Lower Amaranth oil provided the impetus for a complete re-assessment of the reservoir-seal relationships among the various rock types above and below the unconformity. Migration of Mississippian oil does not end at unconformity traps but can potentially continue into post-Mississippian strata.

The Waskada Lower Amaranth pool serves as a useful model for identifying the important geological controls on oil occurrences. Several of these have been discussed in this report and further development of this pool will undoubtedly clarify many of the unanswered questions. Detailed study of these problems is essential to maximize the potential of this pool and the knowledge obtained will prove invaluable when applied to future exploration strategies.

The knowledge obtained here can also be applied to similar geological settings in other regions and other strata. Exploration strategies based on trapping configurations below unconformities overlain by clastic units should take into consideration the reservoir-seal properties of the rocks involved and assess the possibility of oil migration through what is traditionally regarded as a "seal". The geological setting of the Lower Amaranth is not uncommon and many similar situations are available for examination.

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APPENDIX A

Table of Well Data

In the following table, the reported values were determined as follows: (See Figure A-1 for example).

1) *Structure (in metres)*
— structural elevation, using mean sea level as a datum, of the resistive marker at the top of the Lower Amaranth.

2) *Isopach (in metres)*
— thickness of Lower Amaranth from resistive marker to the Mississippian unconformity.

3) *Sandstone thickness (in metres)*
— net thickness of sandy intervals in the lower sandy unit of the Lower Amaranth as estimated from wireline log response.

4) *Sandstone Ratio*
— sandstone thickness (3) divided by thickness of the lower sandy unit (i.e. total isopach (2) minus 15 m.).

5), 6)
Indication of whether a significant cored section and analysis are available.

7), 8) *Net Pay (metres) (porosity — metres)*
— calculated from core analysis using a 1 md. cut-off to define effective pay.

NOTE: Only data from wells which were non-confidential and available as of September 5, 1982 were used in this study.

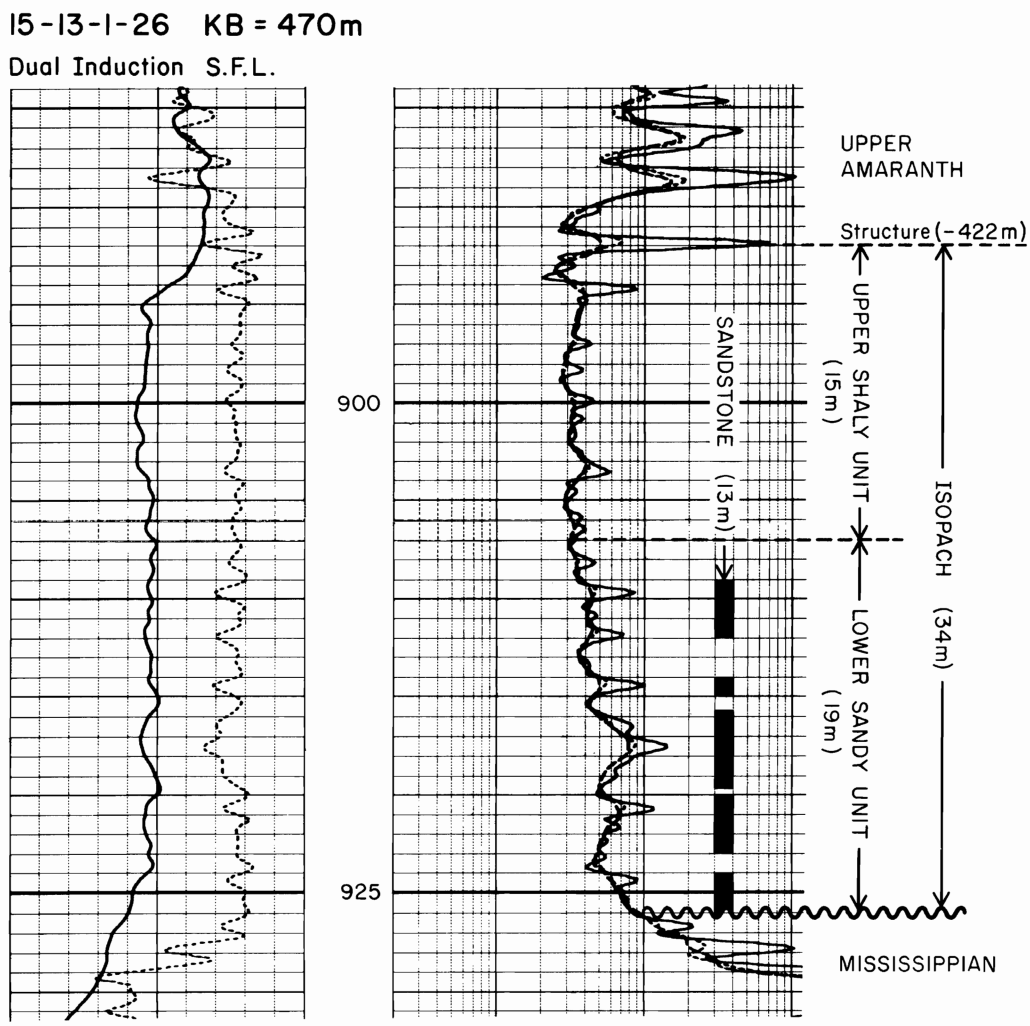

Figure A-1: Well Data Derivation Example

WELL	1 Structure (m)	1 Isopach (m)	3 Sandstone (m)	4 Sandst. ratio	5 Core available?	6 Analysis available?	7 Net pay(m)	8 P-M
13-1-1-25	-402	39	—	—				
16-8-1-25	-418	38	4	.17				
10-14-1-25	-391	35	5	.25				
12-14-1-25	-399	35	3	.15				
16-15-1-25	-399	35	5	.25				
11-16-1-25	-410	35	7	.35				
13-18-1-25	-417	33	7	.39				
10-19-1-25	-417	35	—	—				
11-19-1-25	-419	34	—	—				
12-19-1-25	-422	35	—	—				
13-19-1-25	-419	35	—	—				
14-19-1-25	-417	32	—	—				
15-19-1-25	-416	34	—	—				
2-22-1-25	-399	35	1	.05				
8-22-1-25	-398	34	3	.16				
16-22-1-25	-394	34	4	.21				
10-23-1-25	-391	36	5	.24				
12-23-1-25	-395	36	5	.24				
14-23-1-25	-393	34	6	.32				
10-27-1-25	-393	34	3	.16				
11-29-1-25	-408	35	4	.20				
1-30-1-25	-411	32	8	.47				
3-30-1-25	-415	35	5	.25				
4-30-1-25	-416	35	7	.35				
5-30-1-25	-414	36	8	.38				
6-30-1-25	-415	34	7	.37				
7-30-1-25	-410	34	7	.37				
11-30-1-25	-411	37	8	.36	X	X		
12-30-1-25	-412	37	9	.41				
4-31-1-25	-408	35	12	.60				
3-32-1-25	-405	36	6	.29				
14-33-1-25	-392	35	5	.25				
4-35-1-25	-389	37	6	.29				
4-1-1-26	-437	40	8	.32				
2-2-1-26	-444	40	6	.24				
1-10-1-26	-447	40	8	.32				
9-13-1-26	-419	34	11	.58				
14-13-1-26	-424	34	10	.53				
15-13-1-26	-422	34	13	.68	X	X	5.92	.81
16-13-1-26	-417	33	10	.59				
7-16-1-26	-447	35	9	.45				
16-18-1-26	-456	37	9	.41	X			
2-20-1-26	-447	37	11	.50	X			
6-21-1-26	-441	36	9	.43	X			
5-22-1-26	-430	35	9	.45	X	X	4.51	.81
15-23-1-26	-418	36	15	.71	X	X	8.94	1.23
16-23-1-26	-421	37	15	.68				
1-24-1-26	-420	36	12	.57				
8-24-1-26	-421	33	13	.72				
9-24-1-26	-420	34	12	.63	X	X	9.10	1.36
12-24-1-26	-421	33	12	.67				
13-24-1-26	-420	34	12	.63				
1-25-1-26	-415	33	10	.56				
2-25-1-26	-417	34	13	.68				
3-25-1-26	-418	36	12	.57				
4-25-1-26	-418	35	13	.65				
5-25-1-26	-420	36	13	.62				
6-25-1-26	-419	40	13	.52	X	X	7.72	1.26
7-25-1-26	-419	38	12	.52				
8-25-1-26	-415	36	14	.67				
9-25-1-26	-411	34	11	.58	X	X	13.43	1.94
10-25-1-26	-415	34	11	.58				

WELL	1 Structure (m)	1 Isopach (m)	3 Sandstone (m)	4 Sandst. ratio	5 Core available?	6 Analysis available?	7 Net pay(m)	8 P-M
11-25-1-26	-417	35	9	.45				
1-26-1-26	-419	36	15	.71				
2-26-1-26	-423	37	15	.68				
6-26-1-26	-420	35	9	.45				
8-26-1-26	-419	35	17	.85	X	X	8.20	1.19
1-32-1-26	-432	36	10	.48				
3-34-1-26	-424	39	8	.33	X	X	4.66	.70
10-34-1-26	-426	37	8	.36				
2-35-1-26	-419	38	7	.30				
2-36-1-26	-414	30	3	.20				
4-1-1-27	-475	41	13	.50				
3-2-1-27	-479	43	14	.50				
1-3-1-27	-492	46	14	.45				
10-9-1-27	-486	36	—	—				
12-9-1-27	-486	37	6	.29				
13-10-1-27	-486	38	—	—				
16-16-1-27	-479	43	12	.43				
5-20-1-27	-488	37	—	—				
1-21-1-27	-479	37	—	—				
7-21-1-27	-477	36	7	.33				
8-21-1-27	-477	37	11	.50				
12-22-1-27	-476	37	8	.38				
2-27-1-27	-468	—	—	—				
16-28-1-27	-470	37	—	—				
1-3-1-28	-518	43	15	.54				
3-4-1-28	-534	41	12	.46				
11-13-1-28	-497	37	10	.45				
14-15-1-28	-512	40	12	.48				
1-16-1-28	-515	38	11	.48				
5-17-1-28	-532	38	10	.43				
15-29-1-28	-513	38	9	.39				
3-33-1-28	-505	37	10	.45				
7-33-1-28	-502	38	10	.43				
15-5-1-29	-558	37	—	—				
8-15-1-29	-549	43	11	.39				
11-18-1-29	-563	48	13	.39				
5-34-1-29	-521	43	10	.36				
6-4-2-26	-428	36	8	.38				
9-6-2-26	-432	31	6	.38				
8-10-2-26	-418	36	10	.48	X	X	7.20	1.10
15-14-2-26	-408	38	9	.39				
6-16-2-26	-428	34	7	.37				
2-30-2-26	-424	35	5	.25				
5-32-2-26	-424	34	—	—				
10-36-2-26	-388	33	5	.28				
8-5-2-27	-467	34	5	.26				
10-6-2-27	-473	35	8	.40				
3-14-2-27	-449	35	—	—				
9-15-2-27	-450	30	—	—				
2-18-2-27	-470	35	8	.40				
1-19-2-27	-463	33	5	.28				
15-27-2-27	-440	32	4	.24				
13-30-2-27	-460	36	4	.19				
14-5-2-28	-500	42	9	.33	X	X	3.05	.41
15-5-2-28	-504	43	10	.36				
16-9-2-28	-490	38	12	.52				
1-11-2-28	-482	38	11	.48				
14-20-2-28	-485	37	11	.50				
1-22-2-28	-479	38	12	.52				
12-27-2-28	-473	36	10	.48	X	X	1.70	.19
15-27-2-28	-472	37	10	.45				
10-28-2-28	-475	35	9	.45				

WELL	1 Structure (m)	1 Isopach (m)	3 Sandstone (m)	4 Sandst. ratio	5 Core available?	6 Analysis available?	7 Net pay(m)	8 P-M
4-29-2-28	-485	37	—	—				
16-29-2-28	-479	37	6	.27				
12-30-2-28	-487	37	13	.59				
4-34-2-28	-469	37	8	.36				
11-8-2-29	-523	39	13	.54				
13-32-2-29	-502	37	7	.32				
15-32-2-29	-496	38	9	.39				
5-36-2-29	-485	37	12	.55				
1-15-3-25	-350	30	—	—				
15-20-3-25	-355	33	6	.33				
15-25-3-25	-330	27	3	.25				
4-32-3-26	-381	35	6	.30				
14-4-3-27	-442	34	—	—				
4-17-3-27	-436	36	5	.24				
4-1-3-28	-465	37	8	.36				
6-7-3-28	-477	35	5	.25				
8-7-3-28	-473	35	4	.20				
15-7-3-28	-472	33	4	.22				
12-10-3-28	-464	37	6	.27				
2-14-3-28	-454	37	7	.32				
4-16-3-28	-458	37	7	.32				
10-16-3-28	-459	38	—	—				
14-16-3-28	-461	38	5	.22				
5-17-3-28	-468	37	—	—				
13-17-3-28	-470	34	7	.37				
14-17-3-28	-469	34	8	.42				
1-18-3-28	-470	37	6	.27				
9-18-3-28	-467	32	6	.35				
12-18-3-28	-469	36	6	.29				
13-18-3-28	-468	36	4	.19				
15-18-3-28	-468	35	6	.30				
2-19-3-28	-467	37	5	.23				
4-19-3-28	-468	36	4	.19				
6-19-3-28	-467	34	4	.21				
10-19-3-28	-465	32	3	.18				
12-19-3-28	-466	38	3	.13				
3-20-3-28	-464	37	—	—				
4-20-3-28	-465	34	—	—				
2-21-3-28	-459	38	5	.22				
4-21-3-28	-461	37	4	.18				
10-21-3-28	-457	37	6	.27				
2-22-3-28	-453	38	5	.22				
4-22-3-28	-457	37	6	.27				
2-27-3-28	-450	35	5	.25				
4-29-3-28	-460	35	5	.25				
4-30-3-28	-462	36	4	.19				
12-2-3-29	-489	37	7	.32				
13-2-3-29	-489	35	7	.35				
6-3-3-29	-497	36	5	.24				
2-4-3-29	-501	38	5	.22				
1-8-3-29	-499	38	7	.30				
13-8-3-29	-494	32	2	.12				
8-10-3-29	-488	32	4	.24				
9-10-3-29	-488	32	4	.24				
2-11-3-29	-486	35	5	.25				
3-11-3-29	-487	—	5	—				
4-11-3-29	-489	33	5	.28				
5-11-3-29	-489	32	4	.24				
6-11-3-29	-485	31	3	.19				
7-11-3-29	-482	31	4	.25				
8-11-3-29	-482	32	—	—				
10-11-3-29	-483	34	3	.16				

WELL	1 Structure (m)	1 Isopach (m)	3 Sandstone (m)	4 Sandst. ratio	5 Core available?	6 Analysis available?	7 Net pay(m)	8 P-M
11-11-3-29	-486	33	3	.17				
4-12-3-29	-482	37	4	.18				
5-12-3-29	-480	36	—	—				
12-12-3-29	-481	37	4	.18				
2-13-3-29	-477	37	6	.27				
7-13-3-29	-475	37	6	.27				
10-13-3-29	-472	37	6	.27				
12-13-3-29	-480	37	6	.27				
14-13-3-29	-474	38	6	.26				
15-13-3-29	-472	38	7	.30				
16-13-3-29	-470	38	7	.30				
5-15-3-29	-488	36	6	.29				
3-16-3-29	-491	32	2	.12				
7-16-3-29	-489	32	3	.18				
8-16-3-29	-488	33	3	.17				
16-16-3-29	-487	32	4	.24				
7-20-3-29	-484	30	2	.13				
8-21-3-29	-485	30	3	.20				
10-23-3-29	-470	37	5	.23				
2-24-3-29	-472	37	5	.23				
4-24-3-29	-474	37	4	.20				
6-24-3-39	-471	38	6	.26				
8-24-3-29	-469	38	6	.26				
10-24-3-29	-469	34	4	.21				
8-26-3-29	-465	37	5	.23				
4-27-3-29	-481	34	5	.26				
12-29-3-29	-484	38	7	.30				
13-31-3-29	-480	35	7	.35				

APPENDIX B:
SELECTED CORE DESCRIPTIONS

Omega Waskada 11-30-1-25
2978-3024

Interval (ft.)	Thickness (ft.)	Lithology
2978 - 2980	2	Interbedded Siltstone and Shale — maroon to greenish grey, mottled appearance with irregular and contorted laminations. Psudo- brecciated appearance, anhydrite nodules.
2980 - 2982	2	*Siltstone* — greenish grey, highly dolomitic with faint irregular laminations. Minor lenses of medium grained anhydrite cemented sand and floating frosted quartz grains.
2982 - 2985	3	*Interbedded Siltstone and Shale* — sharp contact with above, similar to (2978-80).
2985 - 2988	3	*Interbedded Sandstone and Siltstone* — grey to maroon in color, mottled appearance with irregular interbeds. Sand is medium to coarse grained, anhydrite cemented, occurring in distinct pods or lenses, pseudo-brecciated appearance, abundant anhydrite nodules.
2988 - 89.5	1.5	*Sandstone* — light grey, medium to coarse grained, fining upward, anhydrite cemented, massive near base with argillaceous rip-up clasts, grading to cross-laminated (20°) near top, more dolomitic with patchy oil stain.
2989.5 - 92	2.5	*Siltstone* — sharp contact with above, similar to (2980-82).
2992 - 3012	20	*Interbedded Siltstone and Shale* — sharp contact with above, similar to (2978-80).
3012 - 16	4	*Sandstone* — light grey to greenish grey, fining upward with basal scour surface and breccia zone, anhydrite cemented and massive, grading to laminated dolomitic fine to very fine sand with light oil stain.
3016 - 24	8	*Interbedded Sandstone and Siltstone* — sharp contact with above, irregular and contorted laminations highly anhydritic, abundant well rounded, frosted quartz grains, unconformity at 3024′.

North American Arthur 2-20-1-26
3020-3081

Interval (ft.)	Thickness (ft.)	Lithology
3020 - 3030	10	*Interbedded Siltstone and Shale* — maroon to greenish grey, mottled appearance with irregular and contorted laminations. Anhydrite nodules common and abundant well rounded floating quartz grains, dolomitic matrix.
3030 - 3035	5	*Sandstone* — grey to greenish grey, coarse to very fine grained, dolomitic. Suggestion of several fining-upward cycles over scour surfaces. Coarse anhydrite-cemented massive sand grading upward to medium to fine grained dolomitic laminated and cross-laminated sand. Good porosity in fine to very fine sands with patchy oil stain. Mud crack on scour surface.
3035 - 3039	4	*Interbedded Siltstone and Shale* — sharp contact with above, similar to (3020-30).
3039 - 3042	3	*Interbedded Sandstone and Siltstone* — grey to greenish grey with medium-grained, anhydrite-cemented sandstone occurring in lenses and pods, pseudo-brecciated appearance. Patchy light oil stain, anhydrite nodules.
3042 - 3048	6	*Interbedded Siltstone and Shale* — sharp contact with above, similar to (3020-30).
3048 - 3056	8	*Sandstone* — light grey to greenish grey, fining upward, with massive coarse-grained anhydrite cemented sand at base with argillaceous rip- up clasts. Grades upward to laminated and cross-laminated medium to fine grained dolomitic sand with good porosity and patchy oil stain.

3056 - 3065	9	*Interbedded Siltstone and Shale* — sharp contact with above, similar to (3020-30).
3065 - 3075	10	*Sandstone* — light grey to greenish grey, medium to very fine grained, dolomitic well laminated with planar cross-lamination of up to 20°. Medium grained sands are anhydrite cemented, fine and very fine sands are dolomitic with fair to good intergranular porosity.
3075 - 3081	6	*Interbedded Siltstone and Shale* — similar to (3020-30) with increased anhydrite and floating frosted quartz grains towards base. Unconformity at 3081′.

Omega Dalny 3-34-1-26

909-925.3

Interval (m.)	Thickness (m.)	Lithology
909 - 910.5	1.5	*Interbedded Shale and Siltstone* — maroon to greenish grey, mottled appearance with irregular and contorted laminations. Anhydrite occurs in small blebs and nodules. Abundant well rounded, frosted quartz grains, dolomitic matrix.
910.5 - 911.5	1.0	*Interbedded Siltstone and Sandstone* — greenish grey, mottled appearance. Sandstone is medium to coarse grained and in irregular stringers and lenses giving a pseudo-brecciated appearance. Silt-stone is dolomitic and sandstone is anhydrite cemented.
911.5 - 913.5	2.0	*Interbedded Shale and Siltstone* — sharp contact with above, similar to (909-910.5) with higher silt content.
913.5 - 916.0	2.5	*Interbedded Siltstone and Sandstone* — grey to dark grey with patchy oil stain in thin bands of cross-laminated dolomitic sandstone. Scour surfaces overlain by medium- to coarse-grained, anhydrite-cemented sandstone. Horizontal fractures.
916.0 - 921.0	5.0	*Interbedded Shale and Siltstone* — similar to (909-910.5).
921.5 - 924.3	2.8	*Sandstone* — grey to reddish brown, with minor interbedded siltstone. Grain size varies from coarse to very fine with suggestion of numerous incomplete fining-upward cycles separated by scour surfaces. Coarse anhydrite-cemented sand with argillaceous rip-up clasts overlays scour surfaces. Grades up to laminated and cross-laminated medium to fine dolomitic sand with fair to good intergranular porosity and patchy oil stain. Very fine dolomitic sand to silt also present with faint suggestion of small scale ripple (?) cross-lamination.
924.3 - 925.3	1.0	*Interbedded Siltstone and Shale* — sharp contact. Abundant Mississippian fragments, brecciated appearance, detrital zone above the unconformity.

Cobra Shell Lyleton 14-5-2-28

989-1005

Interval (m.)	Thickness (m.)	Lithology
989 - 994	5.0	*Interbedded Siltstone and Shale* — maroon to greyish in color, mottled appearance with irregular inter-bedding, pseudo-brecciated appearance, dolomitic, anhydrite nodules, abundant floating frosted quartz grains, patchy fair porosity and light oil stain.
994 - 997.5	3.5	*Interbedded Sandstone and Siltstone* — grey to reddish brown, mottled, severely contorted interbedding, medium-grained anhydrite-cemented sand in irregular and swirling lenses or pods. Patchy porosity and oil stain, horizontal fractures.
997.5 - 1002.5	5.0	*Interbedded Siltstone and Shale* — maroon to reddish in color, similar to (989-994) but more shaly with only minor anhydrite.
1002.5 - 1005	2.5	*Interbedded Sandstone and Siltstone* — similar to (994-997.5) with increasing anhydrite towards base. Unconformity at 1005m.

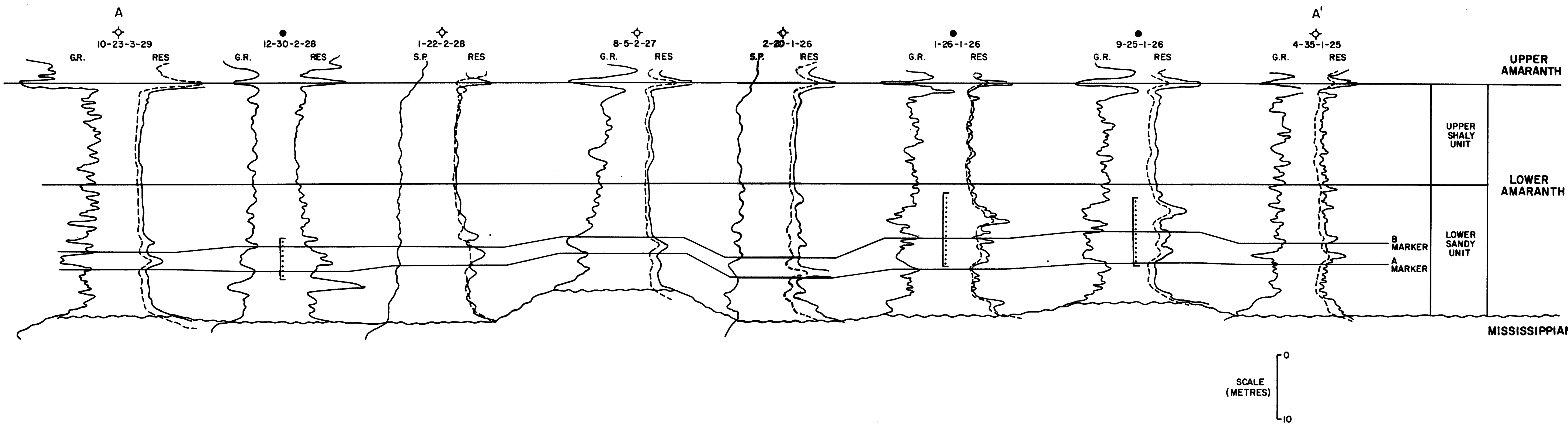

Figure 12: Stratigraphic Cross-Section A-A'