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Rock petrophysical analysis of Upper Devonian Jean Marie gas reservoir rocks in the July Lake area of northeastern British Columbia and in the contiguous area in northwestern Alberta

A.P. Byrnes[1], J.C. Wendte[2], and D.G. Sargent[2]

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ABSTRACT

This paper provides a summary of the rock petrophysical analysis of the Upper Devonian Jean Marie Member (Redknife Formation) from the July Lake area of northeastern British Columbia and the contiguous area of northwestern Alberta. The database includes 198 one-inch (2.54 cm) diameter core plugs sampled from 18 cores in the July Lake area and 18 one-inch (2.54 cm) diameter core plugs sampled from 5 cores in northwestern Alberta. Overall, the analysis includes data obtained (number of samples shown in parentheses) for porosity (215), grain density (215), routine air permeability (216), *in situ* Klinkenberg permeability (216), pore volume compressibility (26), the Archie cementation exponent electrical property (71), effective gas permeability at critical water saturation (40), relative gas permeability at critical water saturation (40), critical brine saturation (67) and mercury intrusion drainage capillary pressure analysis (40). Key rock petrophysical data is also summarized for the two most significant reservoir facies at July Lake, the platy stromatoporoid-*Renalcis* reef facies and the detrital stromatoporoid-coral foreslope facies.

INTRODUCTION AND SCOPE OF REPORT

This report provides a summary of the rock petrophysical analysis of the Upper Devonian Jean Marie Member (Redknife Formation) from the July Lake area of northeastern British Columbia and the contiguous area of northwestern Alberta. The data base includes 198 one-inch (2.54-cm) diameter core plugs sampled from 18 cores in the July Lake area and 18 one-inch (2.54-cm) diameter core plugs sampled from 5 cores in northwestern Alberta. Overall, the analysis includes data obtained (number of samples shown in parentheses)) for porosity (215), grain density (215), routine air permeability (216), *in situ* Klinkenberg permeability (216), pore volume compressibility (26), the Archie cementation exponent electrical property (71), effective gas permeability at critical water saturation (40), relative gas permeability at critical water saturation (40), critical brine saturation (67) and mercury intrusion drainage capillary pressure analysis (40).

At July Lake, rock samples for petrophysical analysis were collected from a full spectrum of eight depositional facies, including both reservoir and non-reservoir lithologies. These facies include the basal open-marine limestone ramp, the oncolite-bearing ramp, the laminar stromatoporoid lower foreslope, the laminar stromatoporoid middle foreslope, the platy stromatoporoid-*Renalcis* reef, the *Amphipora*-coral bearing ramp, the detrital stromatoporoid-coral foreslope and the peloidal sand. Sampling was designed to represent the range of lithologies, porosity and permeability within each depositional facies.

Figure 1 is an interpretive cross-section showing the distribution of these facies or subdivisions of these facies, except for the peloidal sand facies, at July Lake. As discussed in an earlier report (Wendte et al., 2006), the Jean Marie Member in 16 of the 18 wells with examined cores at July Lake varies from 15.7 m to 21.2 m thick. In these wells, the intermediate and upper parts of the Jean Marie consist of coalescing patch reef facies that are interpreted to make up a shoal that extends for a distance of at least 30 km in a SSW-to-NNE direction. Of these 16 wells, 13 are active gas producers. The Jean Marie in the two other wells (c-32-E/94-P-16 and b-86-E/94-P-16), depicted at only the far NNE end of the interpretive cross-section in Figure 1, is thinner (11.7 m and 15.8 m, respectively) than the Jean Marie in all but one of the 16 shoal wells and contains reefal successions that are interpreted to not coalesce with those from other wells. Instead, the Jean Marie in these two wells is interpreted to be a proximal part of an off-shoal area. Both of these wells were abandoned.

At July Lake, peloidal sands either occur interstratified with foreslope facies or are associated with *Amphipora* dominated ramp or coral dominated ramp deposits, collectively termed the *Amphipora*-coral bearing ramp depositional facies of this report, of the uppermost growth cycle of the Jean Marie. These peloidal sand accumulations are designated as the foreslope sub-facies and upper ramp sub-facies, respectively, of the peloidal sand depositional facies.

In the contiguous area of northwestern Alberta, peloidal sands are the dominant facies in the upper two growth cycles of the Jean Marie. The deposits overlie tight brachiopod-bearing lime wackestones of the basal open-marine limestone ramp facies, which comprise the lower part of the Jean Marie Member. Because these peloidal sands are interpreted to have been deposited at moderate water depths on a widespread ramp, they are designated as comprising the regional ramp sub-facies, of the peloidal sand depositional facies, in this report.

SUMMARY OF ROCK PETROPHYSICAL DATA

Lithologies and key rock petrophysical data for the complete set of 216 samples are presented in Table 1. In this table, samples are grouped according to depositional facies. Sub-facies and/or variations in lithology are also noted for each of the depositional facies.

Table 2 shows a summary of pore volume compressibility data for 26 samples. Results of the drainage air-mercury capillary pressure analysis are presented in individual sample tables and figures in Appendix A (metric units) and Appendix B (imperial units).

Petrophysical terms at the headings for columns in Table 1 and Table 2 are defined as follows:

- *In situ* Klinkenberg permeability (k_{ik}, mD) – permeability to gas, corrected for Klinkenberg gas slippage effect, measured with core under a hydrostatic confining stress of 17.25 MPa.
- *In situ* Archie cementation exponent (m) – exponent in Archie electrical resistivity equation ($R_o/R_w = 1/\phi^m$; where R_o = rock resistivity ohm-m, R_w = brine resistivity ohm-m, ϕ = porosity, fraction; m = Archie cementation exponent) with rock resistivity measured with core under a hydrostatic confining stress of 17.25 MPa.
- Critical brine saturation (S_{wc}, fraction or %) – water saturation at which water effective permeability is “negligible” as defined by a gas-to-water flow ratio of $Q_g/Q_w > 99.99$.
- Effective gas permeability at S_{wc} ($k_{eg,Swc}$, mD) – gas permeability at critical water saturation. Measured as *in situ* Klinkenberg permeability with core partial water saturation at S_{wc}.
- Relative gas permeability at S_{wc} ($k_{rg,Swc}$, fraction or percent) – ratio of effective gas permeability at S_{wc} to *in situ* Klinkenberg permeability (Sw = 0); $k_{rg,Swc} = k_{eg,Swc} / k_{ik}$.
- Air-mercury threshold entry pressure (Pce, kPa) – minimum mercury (nonwetting phase) pressure necessary for mercury entry into rock pores.
- Threshold entry diameter (D_{te}, micron) – the maximum pore diameter associated with nonwetting-phase entry into the rock pore space.
- *In situ* pore volume compressibility (βi, 1/kPa) – pore volume compression measured as change in pore volume per unit pore volume per change in confining stress measured under *in situ* confining stress change from 20 MPa to 26 MPa.
- Threshold gas column height (Hte, m) – minimum gas column height above the free water level (level of zero capillary pressure) necessary for gas entry into water-saturated pore space. Hte is a function of gas and brine properties and reported Hte values assume “representative” Jean Marie values: temperatures range from 43-50ºC, gas pressures range from 5,920-6,000 kPa (average = 5,960 kpa) , methane-brine interfacial tension x cosine contact angle = 63-64 dyne/cm, brine density = 1.045 g/cc, gas density = 0.0375-0.045 g/cc (0.043 g/cc assumed), gas compressibility z = 0.92 at P,T, gas specific gravity = 0.58-0.64.

EXPERIMENTAL METHODS

Sample Preparation

Core plugs measuring approximately 2.54 cm in diameter and 2- to 9-cm long were cut from slabbed full-diameter core using a diamond core drill cooled with tap water. The ends were then cut off to obtain right cylinders using a diamond saw cooled by tap water. The cores were dried at 70°C and then vacuum/pressure saturated with methyl alcohol and soxhlet extracted with methyl alcohol to remove any remnant salts. The plugs were then dried in a vacuum oven at 70°C to a constant weight within ± 0.002 gm.

Porosity

Unconfined routine helium porosity was determined using a Boyle's Law technique. Dry sample weights were measured to ±0.001 gm and bulk volume was determined to an accuracy of ±0.01 cc by mercury immersion. For samples with large exterior pores, sample volume was determined by caliper measurement. Routine helium porosity was measured to an accuracy and precision of better than ± 0.1 porosity percent. For smaller samples (e.g. 2-cm long) with porosity less than 4% the accuracy of the porosity measurement was less than ±0.2 porosity percent. Porosity data are summarized in Table 1.

Routine Air and *In situ* Klinkenberg Permeability

To measure routine air and *in situ* (i.e. reservoir confining stress condition) Klinkenberg gas permeabilities, each core was placed in a Hassler-type confining-pressure cell and subjected to hydrostatic-confining stress of 4,150 kPa for routine conditions, and a pressure of 17,250 kPa to approximately simulate *in situ* reservoir stresses. A confining stress of 4,150 kPa simulates the confining pressures used by many routine laboratories. Klinkenberg permeabilities, which correspond to non-reactive liquid permeabilities or high-pressure gas permeabilities, were determined by pressure pulse decay. Measured routine air and *in situ* Klinkenberg permeability data are presented in Table 1.

Pore Volume Compressibility

To measure *in situ* porosity the cores were evacuated for a period of eight (8) hours and then saturated with a de aerated 200,000 parts per million by weight sodium chloride (ppmw NaCl) brine solution. After vacuum saturation, complete saturation was obtained by applying a pressure of 7,000 kPa for a period of 24 hours to the saturating brine and samples. Complete saturation was confirmed by agreement between helium-measured porosity and gravimetric-saturation porosity values within 0.1 porosity percent. After the cores had reached equilibrium with the brine, as described below, each was placed in a biaxial Hassler-type core holder and subjected to a series of increasing hydrostatic confining stresses from 140 kPa to 27,600 kPa approximating a range of reservoir stress conditions. Pore volume decrease was determined by measuring the brine displaced from the core by compression using a micropipette, correcting for system compressibility changes. Pore pressure was at atmospheric pressure. Porosity calculations were performed assuming that the grains of the rock were incompressible and hence the bulk volume decreased by the same amount as the pore volume. Equilibrium at pressure was assumed if pore volume change was less than 0.001 cc for a ten (10) minute period. Pore volume compressibility data are summarized in Table 2.

Critical Water Saturation

Absolute permeability is a highly useful property but the low-permeability Jean Marie is often at elevated water saturations and, therefore, gas permeability is diminished from absolute values due to relative permeability effects. In addition, though capillary pressure provides critical information concerning reservoir brine saturations it does not provide direct indication of water permeability. Critical water saturation is the water saturation at which water effective permeability is “negligible.” This can be operationally defined by several criteria. To measure critical water saturation each core was confined in a Hassler core holder under a hydrostatic confining stress of 17,250 kPa. Water-saturated air was flowed through the core, at an upstream pressure of approximately 7,000 kPa with the downstream at atmospheric pressure. Gas flow was maintained until effluent water flow, measured gravimetrically, was less than 0.0001 times the gas flow rate at the mean pore pressure in the core. When this condition had been reached the core was taken out of the core holder, reversed and placed back in the core holder and gas flow resumed. This redistributed any remaining mobile water in the core. Water saturation was calculated by weight change of the core by dividing remaining water in the core with initial water in the core as measured gravimetrically. This measurement records the critical water saturation as defined by the gas flow/water flow ratio, $Q_g/Q_w > 99.99$. This does not measure the saturation at which water flow is zero but is consistent with immobile water for “commercial” flow rates. Critical water (or brine) saturations are summarized in Table 1.

Effective Gas Permeability at Critical Water Saturation

With the core at critical water saturation, as described above, the *in situ* effective Klinkenberg gas permeability, $k_{iekg,Swc}$ was measured with the brine held stationary at the critical saturation. This methodology corresponds to steady-state relative permeability measurements with the brine phase held stationary. Klinkenberg permeabilities, which correspond to non-reactive liquid permeabilities or high pressure gas permeabilities, were determined by measurement of two gas permeabilities at two different pore pressures and extrapolation to infinite pore pressure to obtain the *in situ* effective gas Klinkenberg extrapolated permeability. Relative permeability values were calculated by dividing the measured effective gas permeability values by the previously measured *in situ* Klinkenberg gas permeability, k_{ik}, values obtained on the dry samples, $k_{rg} = k_{iekg,Swc}/k_{ik}$. Effective gas permeability data at critical water saturation are summarized in Table 1.

Electrical Resistivity

Subsequent to vacuum/pressure saturation with a simulated reservoir brine of 200,000 ppm NaCl brine (Rw = 0.049 ohm-mt @ 20°C), the cores were allowed to equilibrate with the brine for a period of seven (7) days. After this the formation resistivity factor (R_oR_w), representing the ratio of the brine-saturated core resistivity (R_o) and the brine resistivity (R_w) at 4,150 kPa confining stress was measured every day until values were constant within 2% over three measurements (i.e. 3 days). Once a plug had reached equilibration with the brine, the hydrostatic confining stress was increased to 17,250 kPa and the electrical resistivity was measured using a two electrode configuration with gold plated end electrodes. Brine-saturated core resistivity at 10 kHz (R_o) was recorded only after the core had achieved equilibrium with the confining stress as determined by no change in the pore volume over a period of ten (10) minutes as described above. Archie cementation exponents, m, representing the ratio of the logarithm of measured formation resistivity factor ($\log (R_oR_w)$) and the logarithm of porosity ($\log \phi$), are presented in Table 1. These cementation exponent values assume an Archie intercept, a = l, with $R_oR_w = 1$ at $\phi = 100\%$.

Drainage Air-Mercury Capillary Pressure

To obtain better resolution of the capillary pressure properties and a better understanding of the pore size distribution and pore entry throat sizes, forty samples were selected for air-mercury injection capillary pressure analysis (MICP). Samples selected for MICP analysis were primarily from the set of samples on which electrical properties were measured. Following electrical properties analysis, the cores were placed in a fresh water bath for two weeks. Following this the cores were dried at 70°C and vacuum/pressure saturated with methyl alcohol, placed in a soxhlet extractor, and soxhlet extracted with methyl alcohol to remove remaining salt. The cores were then dried at 70°C to a constant weight and the routine helium porosity measured again as described above. The samples were stored in a vacuum desiccator until ready for analysis. Each sample was transferred to the capillary pressure instrument and evacuated to a pressure of less than 0.01 torr for a period of 30 minutes. The sample was subjected to increasing mercury injection pressures ranging from 10 to 64,000 kPa. At each pressure, equilibrium was assumed to have been established when the volume of mercury injected was less than 0.2% of the pore volume, or 0.001 cc for low pore volume samples, for a three-minute period. Injected mercury volumes were corrected for system and mercury compressibility effects. Results for individual sample tables and figures are presented in Appendices A and B. Accuracy and precision vary with sample pore volume and outer pore sizes and surface roughness. Pump injection volumes are readable to 0.001 cc. Based on pore volumes from 0.1 cc to 3 cc, estimated precision for the saturation measurement is 1% - 0.1% for pore sizes less than 150 μm.

CHARACTERIZATION OF KEY ROCK PETROPHYSICAL DATA OF THE PLATY STROMATOPOROID-*RENALCIS* REEF FACIES AND THE DETRITAL STROMATOPOROID-CORAL FORESLOPE FACIES

Of the 13 gas producing wells with examined cores at July Lake, the platy stromatoporoid-*Renalcis* reef facies and the detrital stromatoporoid-coral foreslope facies are the most significant reservoir facies (Wendte et al., 2006). Platy stromatoporoid-*Renalcis* reef limestones are the dominant reservoir facies in 5 wells. Limestones and/or partially dolomitized limestones of the detrital stromatoporoid-coral foreslope facies are the dominant reservoir facies in 4 wells. For two wells, the dominant reservoir facies consists of a combination of limestones of the platy stromatoporoid-*Renalcis* reef facies and limestones and/or partially dolomitized limestones of the detrital stromatoporoid-coral foreslope facies. For another well, a combination of limestones and/or partially dolomitized limestones of the detrital stromatoporoid-coral foreslope and other facies make up the dominant reservoir facies. In still another well, the interval with the highest porosity and presumably the highest permeability was not cored.

The key rock petrophysical data, as well as significant lithological aspects, are summarized for both the platy-stromatoporoid reef facies and the detrital stromatoporoid-coral foreslope facies in Table 3. In this table, the platy stromatoporoid-*Renalcis* reef facies is divided into two key lithological components that together provide the pore network in the framestones that typify this facies. The first component is leached *Renalcis*, which occurs in a pendant manner beneath sub-horizontal plates of the frame building stromatoporoids. The second component is sediment, either infilling the shelter cavities beneath the platy stromatoporoids and the pendant *Renalcis*, or occurring as an intervening deposit between the framestones.

The detrital stromatoporoid-coral foreslope facies consists of mainly floatstones, with stomatoporoid and coral bioclasts, and packstones containing the before-mentioned bioclasts. These rocks are typified by low- to intermediate-mud peloid packstone matrices, and by a common but variable replacive dolomite content.

The summary, presented in Table 3, of the two depositional facies is based on both the rock petrophysical analysis and the petrographic examination of thin sections taken from the end of the core plugs. The analysis of the platy stromatoporoid-*Renalcis* reef facies is based on a total of 47 core plugs, 28 containing leached pendant *Renalcis* and the other 19 containing either shelter-cavity or intervening sediment. Of these core plugs, thin sections were examined for all 28 core plugs containing pendant *Renalcis* and for 13 core plugs containing either shelter-cavity or intervening sediment. The analysis of the detrital stromatoporoid-coral foreslope facies is based on a total of 28 core plugs (one broken during analysis), from which 18 thin sections were examined.

Overall, core-plug samples of both the platy stromatoporoid-*Renalcis* reef facies and the detrital stromatoporoid-coral foreslope facies exhibit a wide range of porosity and permeabilities. The dominant pore type in both facies is of leached origin, due to the dissolution of calcite. The dominant pores in the platy stromatoporoid-*Renalcis* reef facies are due to the dissolution of pendant *Renalcis*. These voids vary from micro-pores in partially leached *Renalcis* to molds where the *Renalcis* is completely dissolved. Micro-pores and coalesced micro-pores, of dissolution origin, in the peloidal matrix and (to a lesser extent) in the large bioclasts are the dominant voids in the detrital stromatoporoid-coral foreslope facies. In certain cases where the finer grained matrix has been virtually totally replaced by dolomite, the walls of the stromatoporoid and coral bioclasts are extensively to completely dissolved. This results in moldic, or near-moldic, pores separated by intervening equant calcite cements which previously infilled the primary chambers of these bioclasts (Figures 11B and 11C in Wendte et al., 2006).

The key differences between the two facies are controlled by variations in the texture of the matrix between the stromatoporoid frame builders or large bioclasts, the degree of replacement of the matrix by dolomite, and the degree of dissolution and fracturing. Samples of the detrital stromatoporoid-coral foreslope facies are characterized by a dominance of grain-support matrices and the common to abundant occurrence of matrix replacement dolomites. Conversely, samples of the platy stromatoporoid-*Renalcis* reef facies are characterized by a dominance of mud-support matrices with only very minor or rare occurrences of matrix replacement dolomites. As demonstrated in Wendte et al. (2006), the degree of calcite dissolution is generally greater in samples with a higher matrix replacement dolomite content. As a result, porosities and matrix-controlled permeabilities are, on average, higher for the detrital stromatoporoid-coral foreslope facies than for the platy stromatoporoid-*Renalcis* reef facies. The difference would be even more apparent if the one sample of coarse shelter-cavity sediment, from the platy stromatoporoid-*Renalcis* reef facies, with an anomalously high routine air permeability (2.06 md) and *in situ* Klinkenberg permeability (2.12 md) was removed from the sample set. The high permeabilities of this sample are due to the uncommon occurrence of a primary, macro-interparticle pore system. *In situ* Klinkenberg permeabilities for all other core-plug samples for the platy stromatoporoid-*Renalcis* reef facies, with no or no significant fracturing, are less than 1 md.

On the other hand, core-plug samples of either the shelter-cavity or intervening sediment component of the platy stromatoporoid-*Renalcis* facies are more commonly and intensely fractured than core-plug samples of the detrital stromatoporoid-coral foreslope facies. As a consequence, the overall range of permeabilities is higher for the shelter-cavity and intervening sediment samples of the platy stromatoporoid-*Renalcis* reef facies than for those samples of the detrital stromatoporoid-coral foreslope facies.

Centimetre-scale, gash-style fractures cutting shelter-cavity sediments provide the permeability necessary for economic flow rates from platy stromatoporoid-pendant *Renalcis* framestones. They interconnect molds of pendant *Renalcis* which otherwise have only limited connections between them (Figure 10 in Wendte et al., 2006). *In situ* Klinkenberg permeabilities measured from platy stromatoporoid-pendant *Renalcis* framestones, with either no or no significant fractures, are all less than 1 md.

ACKNOWLEDGEMENTS

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LIST OF APPENDICES

APPENDIX A. Tables and figures showing the results of the drainage air-mercury capillary pressure analysis for 40 individual samples, in metric units. (Note: Each table and figure listed below is also available as a Mircrosoft® Office Excel® 2003 file on this CD in the ".\append_a" dirctory).

15. Core I.D. 72, A-25-E/94-P-16, 1145.03m.
16. Core I.D. 73, A-25-E/94-P-16, 1142.38m.
17. Core I.D. 77, A-89-I/94-P-10, 1149.38m.
18. Core I.D. 88, C-54-I/94-P-10, 1133.49m.
19. Core I.D. 93, C-94-I/94-P-10, 1132.88m.
20. Core I.D. 97, A-21-A/94-P-15, 1120.7m.
21. Core I.D. 117, B-86-E/94-P-16, 1162.48m.
22. Core I.D. 123, C-92-J/94-P-10, 1167.33m.
23. Core I.D. 125, C-92-J/94-P-10, 1166.06m.
24. Core I.D. 126, C-34-A/94-P-15, 1134.49m.
25. Core I.D. 138, A-25-I/94-P-10, 1118.78m.
26. Core I.D. 143, B-50-I/94-P-10, 1139.89m.
27. Core I.D. 146, B-50-I/94-P-10, 1136.9m.
28. Core I.D. 149, C-32-G/94-P-10, 1143.84m.
29. Core I.D. 151, C-32-G/94-P-10, 1143.35m.
30. Core I.D. 159, C-34-A/94-P-15, 1139.38m.
31. Core I.D. 168, B-86-E/94-P-16, 1166.46m.
32. Core I.D. 169, A-89-I/94-P-10, 1153.21m.
33. Core I.D. 172, B-50-I/94-P-10, 1144.85m.
34. Core I.D. 180, C-34-A/94-P-15, 1139.96m.
35. Core I.D. 194, 8-10-117-12W6, 1008.55m.
36. Core I.D. 196, 13-14-118-12W6, 1056.05m.
37. Core I.D. 199, 13-14-118-12W6, 1051.5m.
38. Core I.D. 203, C-34-A/94-P-15, 1148.92m.
39. Core I.D. 209, C-92-J/94-P-10, 1179.96m.
40. Core I.D. 216, C-32-E/94-P-16, 1149.51m.

APPENDIX B. Tables and figures showing the results of the drainage air-mercury capillary pressure analysis for 40 individual samples, in imperial units. (Note: Each table and figure listed below is also available as a Mircrosoft® Office Excel® 2003 file on this CD in the ".\append_b" dirctory).

1. Core I.D. 3, A-89-I/94-P-10, 1158.37m.
2. Core I.D. 5, C-32-G/94-P-10, 1153.23m.
3. Core I.D. 10, C-74-A/94-P-15, 1175.11m.
4. Core I.D. 20, A-41-A/94-P-15, 1140.71m.
5. Core I.D. 24, A-89-I/94-P-10, 1156.33m.
6. Core I.D. 27, C-32-G/94-P-10, 1149.66m.
7. Core I.D. 29, C-54-I/94-P-10, 1141.38m.
8. Core I.D. 31, C-92-J/94-P-10, 1178.37m.
9. Core I.D. 35, D-37-I/94-P-10, 1133.21m.
10. Core I.D. 38, C-74-A/94-P-15, 1172.62m.
11. Core I.D. 41, A-25-I/94-P-10, 1121.63m.
12. Core I.D. 45, B-50-I/94-P-10, 1145.31m.
13. Core I.D. 48, C-94-I/94-P-10, 1139.03m.
14. Core I.D. 70, A-25-E/94-P-16, 1145.92m.
15. Core I.D. 72, A-25-E/94-P-16, 1145.03m.
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