



GEOLOGICAL SURVEY OF CANADA

OPEN FILE 5661

Isotopic and fluid inclusion analysis of diagenetic mineral phases of the Upper Devonian Jean Marie Member (Redknife Formation) in the July Lake area of northeastern British Columbia

J.C. Wendte¹, I.S. Al-Aasm², G. Chi³, and D.G. Sargent¹

2007

¹ Geological Survey of Canada (Calgary), 3303-33rd Street, N.W., Calgary, Alberta, Canada T2L 2A7

² Earth Sciences, University of Windsor, 401 Sunset Avenue, Windsor, Ontario, Canada N9B 3P4

³ Department of Geology, University of Regina, 3737 Wascana Parkway, Regina, Saskatchewan S4S 0A2



GEOLOGICAL SURVEY OF CANADA

OPEN FILE 5661

Isotopic and fluid inclusion analysis of diagenetic mineral phases of the Upper Devonian Jean Marie Member (Redknife Formation) in the July Lake area of northeastern British Columbia

J.C. Wendte¹, I.S. Al-Aasm², G. Chi³, and D.G. Sargent¹

2007

©Her Majesty the Queen in Right of Canada 2007
Available from
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario K1A 0E8

¹ Geological Survey of Canada (Calgary), 3303-33rd Street, N.W., Calgary, Alberta, Canada T2L 2A7

² Earth Sciences, University of Windsor, 401 Sunset Avenue, Windsor, Ontario, Canada N9B 3P4

³ Department of Geology, University of Regina, 3737 Wascana Parkway, Regina, Saskatchewan S4S 0A2

Wendte, J.C., Al-Aasm, I.S., Chi, G, and Sargent, D.G.

2007: Isotopic and fluid inclusion analysis of diagenetic mineral phases of the Upper Devonian Jean Marie Member (Redknife Formation) in the July Lake area of northeastern British Columbia;
Geological Survey of Canada, Open File 5661, 7 p.

Open files are products that have not gone through the GSC formal publication process.

TABLE OF CONTENTS

TABLE OF CONTENTS	I
ABSTRACT.....	1
INTRODUCTION AND PURPOSE OF REPORT	1
OVERVIEW OF THE DIAGENETIC PARAGENETIC SUCCESSION	1
ISOTOPIC ANALYSIS.....	2
FLUID INCLUSION ANALYSIS	4
ACKNOWLEDGEMENTS	6
REFERENCES.....	6
LIST OF FIGURES	7
LIST OF TABLES	7

ABSTRACT

This report provides a summary of both the isotopic and fluid inclusion analyses of diagenetic mineral phases in the Upper Devonian Jean Marie Member (Redknife Formation) from the July Lake area of northeastern British Columbia. These mineral phases are part of two diagenetic realms. The first realm includes calcite cements that precipitated within pores in limestone of the Jean Marie Member. These limestones occur regionally throughout northeastern British Columbia, northwestern Alberta and the southern part of the Northwest Territories. These calcite cements include, in order of formation, radiaxial bladed calcite, non-ferroan equant calcite and ferroan equant calcite. The radiaxial bladed calcite cements occur selectively in patch reef limestones and are interpreted as having precipitated from marine fluids that flowed through an open reef framework. The regional distribution of the equant calcite cements suggests a passive, “closed system” origin, most likely as a by-product of pressure solution during burial. The succession from non-ferroan to ferroan equant calcite cements provides a template to which the position, within the paragenetic succession, of the diagenetic phases of the second realm can be related. The second diagenetic realm includes mineral phases that are interpreted to have formed from the upward flow of relatively hot fluids along faults or fault-associated fractures. The diagenetic phases in this realm include, in paragenetic order, matrix replacement dolomites and saddle dolomite cements, followed by low concentrations of sphalerite (or galena), barite, and dickite cements.

Seventy-two samples were selected from 18 cores for stable (carbon and oxygen) and radiogenic (strontium) isotopic analysis. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values are reported for 67 dolomite and calcite components, or combinations of these components. Strontium isotopic ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) are reported for 58 samples of dolomite, calcite, and barite.

Twenty-two doubly polished thin sections were examined for fluid inclusion microthermometry. Final melting temperatures and homogenization temperatures were measured for non-ferroan and ferroan equant calcite cements, saddle dolomite cement, sphalerite, and barite.

INTRODUCTION AND PURPOSE OF REPORT

Isotopic analyses of various mineral components and microthermometry of fluid inclusions from pore-filling cements were conducted as part of an investigation to better understand the diagenetic and porosity evolution of the Upper Devonian Jean Marie Member (Redknife Formation) in the July Lake area of northeastern British Columbia. This investigation is part of a broader study on the Jean Marie Member in the July Lake area, encompassing the depositional and petrophysical aspects as well. A previous report, Geological Survey of Canada Open File 5277 (Wendte et al., 2006), provides a summary of the stratigraphic evolution of the Jean Marie Member in the July Lake area and a brief characterization of its major reservoir facies. In addition, Open File 5277 includes a grid of six cross-sections, illustrating the distribution of the depositional facies of the Jean Marie Member, and presents a model illustrating the cyclic evolution of this unit. The purpose of this Open File is to make the results of both the isotopic and fluid analyses available to the oil and gas industry in a timely manner.

OVERVIEW OF THE DIAGENETIC PARAGENETIC SUCCESSION

[Figure 1](#) shows the succession of the main diagenetic phases in the Jean Marie Member at July Lake. These phases include radiaxial bladed and equant calcite cements, matrix replacement dolomite and saddle dolomite cement, as well as low concentrations of sphalerite (or galena), barite and dickite cements.

These phases are part of two diagenetic realms. The first realm consists of calcite cements that occur within dominantly primary pores in limestones. These calcite cements not only occur within limestones

in the July Lake area, but occur in virtually all limestones of the Jean Marie Member throughout northeastern British Columbia, northwestern Alberta and the southern part of the Northwest Territories. The initial cement is radialial bladed calcite. This cement occurs selectively, as well as ubiquitously, in shelter cavities of framestones and within pores in associated coarse shelter-cavity sediment of the platy stromatoporoid-*Renalcis* reef core-foreslope facies. Radialial bladed calcite is interpreted to have precipitated from marine fluids that flowed through an open reef framework.

Later calcite cements consist of equant calcite, ranging in composition from an earlier non-ferroan phase, through a transitional phase, to a later ferroan phase. The regional distribution of equant calcite cements, in virtually all limestones of the Jean Marie Member, suggests a passive, “closed-system” origin, most likely as a by-product of pressure solution during burial. These calcite cements are the dominant infiller of primary pores in limestones of the Jean Marie, resulting in almost a total destruction of primary porosity. The succession from non-ferroan to ferroan equant calcite cements provides a template to which the position, within the paragenetic succession, of the diagenetic phases of the second realm can be related.

The second diagenetic realm includes phases that are interpreted to have formed from the upward flow of relatively hot fluids along faults or fault-associated fractures. The diagenetic phases in this realm include, in paragenetic order, matrix replacement dolomites and saddle dolomite cements, followed by low concentrations of sphalerite (or galena), barite and dickite cements ([Figure 1](#)).

The matrix replacement dolomites occur in metre-thick dolostones near the top of the Jean Marie Member, but in only three of 18 wells, and in more areally widespread, partly dolomitized limestones (see position of dolostones and partially dolomitized limestones on cross-sections in Figures 3-8 of Wendte et al., 2006). The latter dolomites occur most commonly in grain-support limestones of the upper Jean Marie depositional cycle, especially in limestones of the detrital stromatoporoid-coral bearing floatstone facies. The replacive dolomites consist of ferroan planar crystals, most commonly finer than 200 μm in diameter. The occurrence of the metre-thick dolostones near the very top of the Jean Marie Member, in 3 of the 18 wells, suggests that overlying shales of the Redknife Formation provided an impermeable barrier to the upward flowing dolomitizing fluids along scattered fault conduits.

The occurrence of limestones with a high degree of dolomite corresponds to intervals with high concentrations of micro-pores. These micro-pores were formed by the dissolution of calcite, which is interpreted to be part of the dolomitization process (Wendte et al., 2006). Pores formed by the dissolution of calcite are the dominant pore types in the Jean Marie.

Saddle dolomite occurs as a common pore-lining cement in fractures, large primary pores in limestones and within vugs in dolostones. Saddle dolomite crystals are cloudy clear to white, ferroan and range up to 1.5 mm in crystal diameter. Sphalerite, or galena, and barite are present in low concentrations as cements in fractures, shelter cavities in limestones and within vugs in dolostones. Dickite, a mineral in the kaolin group, occurs most commonly as a pervasive cement in some fractures.

ISOTOPIC ANALYSIS

Seventy-two samples were selected from 18 cores for stable (carbon and oxygen) and radiogenic (strontium) isotopic analyses ([Table 1](#)). $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values were determined for 67 dolomite and calcite components, or combinations of these components. Strontium isotopic ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) were measured from 58 samples of dolomite, calcite and barite.

Isotopic samples were extracted by using a microscope mounted drill assembly and were then crushed to a power form. Dolomite and calcite samples chosen for oxygen and carbon isotopic determination were analyzed by using the selective acid extraction method of Al-Aasm et al. (1990). Powdered samples were reacted *in vacuo* with 100% pure phosphoric acid (H_3PO_4) for a minimum of four hours at 50°C for dolomite extraction and at 25°C for calcite extraction. CO_2 gas produced during this reaction was then analyzed for isotopic ratios on a Thermo Finnigan DeltaPlus isotope ratio mass spectrometer (IRMS) at

the University of Windsor, under the supervision of Dr. I.S. Al-Aasm. Carbon and oxygen isotope values are given per mill (‰) relative to the VPDB (Vienna PeeDee Belemnite) standard. The overall precision for this analysis is 0.03‰ for $\delta^{13}\text{C}$ and 0.04‰ for $\delta^{18}\text{O}$.

Samples of dolomite, calcite and barite were analyzed for strontium isotopic ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) at Uppsala University in Sweden, under the supervision of Professor S. Moard. Powdered samples were analyzed in a static multi-collector mode with Re filaments with standard references of NBS and ocean water. The strontium isotope values were normalized to a $^{87}\text{Sr}/^{86}\text{Sr} = 8.375209$, with a mean standard error for NBS-987 of 0.00003.

Figures 2, 3 and 4 show plots of $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$, $^{87}\text{Sr}/^{86}\text{Sr}$ versus $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ versus $\delta^{13}\text{C}$, respectively, for the calcite components. Two samples of marine radiaxial bladed calcite cements have $\delta^{13}\text{C}$ values of 3.87‰ (PDB) and 3.88‰ (PDB), $\delta^{18}\text{O}$ values of -6.44‰ (PDB) and -5.87‰ (PDB) and strontium isotopic ratios of 0.708386 and 0.709453, with mean values for $\delta^{13}\text{C}$ of 3.88‰ (PDB), for $\delta^{18}\text{O}$ of -6.16‰ (PDB) and for strontium isotopic ratios of 0.708920. Four samples of calcitic micrite matrix have a range of values for $\delta^{13}\text{C}$ of 1.27‰ (PDB) to 1.77‰ (PDB), for $\delta^{18}\text{O}$ of -7.20‰ (PDB) to -6.42‰ (PDB) and for strontium isotopic ratios of 0.708449 to 0.709977, with mean values for $\delta^{13}\text{C}$ of 1.56‰ (PDB), for $\delta^{18}\text{O}$ of -6.89‰ (PDB) and for strontium isotopic ratios of 0.708876. Excluding the isotopic values for a sample of non-ferroan equant calcite cement with an anomalously low $\delta^{13}\text{C}$ value of 1.45‰ (PDB), seven samples of non-ferroan equant calcite cements have a range of values for $\delta^{13}\text{C}$ of 3.10‰ (PDB) to 4.16‰ (PDB), for $\delta^{18}\text{O}$ of -9.14‰ (PDB) to -5.74‰ (PDB) and for strontium isotopic ratios of 0.707959 to 0.719048, with mean values for $\delta^{13}\text{C}$ of 3.63‰ (PDB), for $\delta^{18}\text{O}$ of -7.81‰ (PDB) and for strontium isotopic ratios of 0.710443. Four samples of ferroan equant calcite cements have a range of values for $\delta^{13}\text{C}$ of -0.16‰ (PDB) to 3.03‰ (PDB), for $\delta^{18}\text{O}$ of -15.16‰ (PDB) to 11.67‰ (PDB) and for strontium isotopic ratios of 0.708813 to 0.713007, with mean values for $\delta^{13}\text{C}$ of 1.26‰ (PDB), for $\delta^{18}\text{O}$ of -12.99‰ (PDB) and for strontium isotopic ratios of 0.711159.

All $\delta^{18}\text{O}$ values for these calcite components are more depleted than the estimated range of -4‰ (PDB) to -5‰ (PDB) for Late Devonian (Frasnian) marine calcites (Veizer et al., 1999). Strontium isotopic ratios for most of these calcite cements are slightly to moderately more radiogenic than the best estimate of Late Devonian seawater (0.70790 to 0.70805) by Denison et al. (1997). The upper range of $\delta^{13}\text{C}$ values measured for these calcite components, higher than approximately 3.80‰ (PDB), is interpreted to be the best estimate for Late Devonian marine calcite.

Figures 5, 6 and 7 show plots of $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$, $^{87}\text{Sr}/^{86}\text{Sr}$ versus $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ versus $\delta^{13}\text{C}$, respectively, for the dolomite components. Excluding the isotopic values of two samples of matrix replacement dolomites with anomalously depleted $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values, interpreted to be due to contamination with saddle dolomite cement, seventeen samples of matrix replacement dolomites have a range of values for $\delta^{13}\text{C}$ of 2.80‰ (PDB) to 4.44‰ (PDB) and for $\delta^{18}\text{O}$ of -9.16‰ (PDB) to -6.80‰ (PDB), with mean values for $\delta^{13}\text{C}$ of 3.59‰ (PDB) and for $\delta^{18}\text{O}$ of -8.19‰ (PDB). Twelve of these matrix replacement dolomites have strontium isotopic ratios that range from 0.708350 to 0.709269, with a mean value of 0.708652. Twenty samples of saddle dolomite cements have a range of values for $\delta^{13}\text{C}$ of 0.06‰ (PDB) to 2.70‰ (PDB) and for $\delta^{18}\text{O}$ of -12.83‰ (PDB) to -8.55‰ (PDB), with mean values for $\delta^{13}\text{C}$ of 1.30‰ (PDB) and for $\delta^{18}\text{O}$ of -11.23‰ (PDB). Eighteen of these samples of saddle dolomite cements have strontium isotopic ratios that range from 0.708585 to 0.712274, with a mean value of 0.709599.

Overall, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values for a combined set of matrix replacement dolomites and saddle dolomite cements fall along a covariant linear curve, with more depleted $\delta^{18}\text{O}$ values corresponding with more depleted $\delta^{13}\text{C}$ values. Excluding the two matrix replacement dolomite samples contaminated with saddle dolomite cement, the matrix replacement dolomites comprise a group with distinctly more enriched $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values than that for saddle dolomite cements. Using the fractionation between calcite and dolomite as 3 per mill (Land, 1980), the estimated range of $\delta^{18}\text{O}$ for Late Devonian (Frasnian) marine dolomites would be from -1‰ (PDB) to -2‰ (PDB). Thus, all the $\delta^{18}\text{O}$ values for matrix

replacement dolomites and saddle dolomite cements are significantly more depleted than the estimated range for Late Devonian (Frasnian) marine dolomites. The strontium isotopic ratios of both matrix replacement dolomites and saddle dolomite cements are slightly to moderately more radiogenic than the best estimate of Late Devonian seawater (0.70790 to 0.70805) by Denison et al. (1997). The upper range of $\delta^{13}\text{C}$ values measured for matrix replacement dolomites, from 3.88‰ (PDB) to 4.44‰ (PDB), is interpreted to be the best estimate for Late Devonian marine dolomite.

Five samples of barite have a range of strontium isotopic ratios from 0.708352 to 0.712099, with a mean value of 0.709589. All the measured strontium isotopic ratios are slightly to moderately more radiogenic than the best estimate of Late Devonian seawater (0.70790 to 0.70805) by Denison et al. (1997).

FLUID INCLUSION ANALYSIS

Twenty-two doubly polished thin sections were examined by Dr. Guoxiang Chi for fluid inclusion microthermometry. The primary objective of this analysis was to investigate the composition and thermal conditions of the fluids from which diagenetic cements precipitated, including non-ferroan equant calcite, ferroan equant calcite, saddle dolomite, sphalerite and barite (see [Figure 1](#)).

The doubly polished thin sections were first studied for fluid inclusion petrography and then selected fluid inclusions were analyzed for microthermometry. The “fluid inclusion assemblage” (FIA) method of Goldstein and Reynolds (1994) was used for fluid inclusion petrography. Thus, fluid inclusions entrapped at the same time and associated spatially are treated as an entity or FIA (e.g., a cluster, a healed fracture) and only one data point was counted in statistics for an FIA, no matter how many inclusions were studied in the FIA. This treatment avoids bias caused by large amounts of data from few highly populated fluid inclusion groups. For randomly and densely distributed fluid inclusions, several inclusions spatially close to each other were treated as an FIA. Isolated fluid inclusions were also treated like FIAs. Fluid inclusions occurring in clusters, in isolation, and randomly distributed in three dimensions were considered as primary or pseudosecondary inclusions, whereas those in long healed fractures were treated as secondary inclusions.

The microthermometric measurements were carried out with a Linkam heating-freezing stage, which has been calibrated with synthetic fluid inclusions. The precision of measurement is $\pm 1^\circ\text{C}$ at temperatures above 30°C , and $\pm 0.2^\circ\text{C}$ at lower temperatures. The fluid system is approximated by H_2O – NaCl – CaCl_2 , and the total salinity and the ratio of NaCl to total salinity are calculated using the melting temperatures of hydrohalite and ice, with a program by Chi and Ni (2007). In the cases where the hydrohalite melting temperature was not measured and the ice-melting temperature is higher than -21.2°C , the salinity is calculated with the equation of Bodnar (1993).

Four types of fluid inclusions were identified: 1) biphasic (liquid + vapour, with vapour generally $< 10\%$) aqueous inclusions, 2) monophasic (liquid-only) aqueous inclusions, 3) biphasic (liquid + vapour, with vapour generally $< 20\%$) oil inclusions, and 4) monophasic (vapour-only) hydrocarbon inclusions, likely dominated by methane.

Biphasic aqueous inclusions are present in all minerals studied (saddle dolomite, ferroan equant calcite, non-ferroan equant calcite, barite, and sphalerite). They occur both as primary and secondary inclusions, and only primary (and pseudosecondary) ones were studied. Monophasic aqueous inclusions occur mainly in barite, and are also found in sphalerite and ferroan equant calcite. Some of them appear to be secondary and were not studied. However, some of them cannot be distinguished from those of primary origin based on petrographic evidence, and these inclusions were studied for salinities. Oil inclusions occur both as primary and secondary inclusions, and both were studied. Monophasic hydrocarbon gas inclusions only occur as secondary inclusions, and these inclusions were studied.

The microthermometric results of primary (and pseudosecondary) aqueous inclusions are presented in [Table 2](#) and summarized in [Table 3](#), Figures [8](#), [9](#) and [10](#). These results are described and discussed below.

The first melting temperatures range from -67°C to -46°C, with a mean value of -56°C, -55°C, -53°C, -59°C and -54°C for saddle dolomite, ferroan equant calcite, non-ferroan equant calcite, sphalerite and barite, respectively ([Table 3](#)). This suggests a fluid system of H₂O–NaCl–CaCl₂ type for all the fluids involved in the different diagenetic events.

Homogenization temperatures ([Table 3](#) and [Figure 8](#)) range from 80°C to 163°C for saddle dolomite, 74°C to 136°C for ferroan equant calcite, 75°C to 119°C for non-ferroan equant calcite, 60°C to 118°C for sphalerite, and 55°C to 126°C for barite. The mean values of homogenization temperatures decrease from 117°C in saddle dolomite, through 110°C in ferroan equant calcite, 100°C in non-ferroan equant calcite, to 84°C in sphalerite and 88°C in barite. Note that the all-liquid inclusions, which likely have homogenization temperatures near the lower end of the spectrum, were not included in the calculation of the mean values.

Salinities ([Table 3](#) and [Figure 9](#)) range from 8.8 to 26.7 wt.% NaCl+CaCl₂ equivalent for saddle dolomite, 10.0 to 25.8 for ferroan equant calcite, 4.8 to 15.7 for non-ferroan equant calcite, 9.7 to 24.0 for sphalerite, and 9.4 to 23.2 for barite. The mean values of salinities decrease from 16.6 wt.% NaCl+CaCl₂ equivalent in saddle dolomite, through 13.7 in ferroan equant calcite to 10.5 in non-ferroan equant calcite, and then increase to 16.5 in sphalerite and 13.4 in barite.

There is no correlation between homogenization temperatures and salinities for fluid inclusions in saddle dolomite, ferroan equant calcite and barite, but a negative correlation appears to exist for those in non-ferroan calcite and sphalerite ([Figure 10](#)). Overall, the similarities do not correlate with homogenization temperatures.

Oil inclusions are present in saddle dolomite in four samples, in non-ferroan equant calcite in one sample, and in barite in two samples. Most oil inclusions in saddle dolomite are primary, with homogenization temperatures from 80°C to 132°C (mean = 98°C), and most in barite are secondary, having homogenization temperatures from 66°C to 105°C (mean = 77°C) ([Table 3](#) and [Figure 11](#)). Two secondary FIAs in saddle dolomite show T_h values from 74°C to 88°C (mean = 81°C), and three primary inclusions in barite have T_h values from 69°C to 89°C (mean = 78°C) ([Table 3](#)).

Although the overall range of homogenization temperatures is fairly large for a given mineral, the ranges within individual FIAs are very small. For example, one of the FIAs in barite in sample #21 shows T_h from 103°C to 108°C ($n = 11$), and another one has T_h from 70°C to 75°C ($n = 8$). The consistency of T_h values within individual FIAs indicates that the entrapment was homogeneous and that the fluid inclusions likely have not been stretched.

Hydrocarbon gas inclusions occur as secondary inclusions in ferroan equant calcite, non-ferroan equant calcite, and in barite, each in one sample. In all cases, the inclusions homogenize to the vapour phase. The T_h values range from -86.9°C to -86°C for ferroan equant calcite, -110°C to -104°C for non-ferroan calcite, and -89.1°C for barite. The narrow range of T_h values within individual minerals and FIAs ([Tables 2](#) and [3](#)) indicate that the fluid inclusions are well preserved.

The occurrence of primary oil inclusions in saddle dolomite indicates that oil migrated through during, or had charged the reservoir unit before, the precipitation of saddle dolomite. The fact that the T_h values of aqueous inclusions (mean = 117°C) are higher than those of oil inclusions (98°C), and the absence of gas inclusions in saddle dolomite indicate that the hydrocarbon was in the liquid field, undersaturated with gas, during the precipitation of saddle dolomite. This suggests a relatively high pressure system.

The occurrence of both secondary oil and gas inclusions in calcite and barite cements indicates that one or more oil and gas migration/charging events took place after these cements. The co-existence of oil and gas inclusions indicates that the oil was saturated with gas, suggesting a relatively low pressure condition. A quantitative estimation of the fluid pressures is possible only if the compositions of the oil

and gas inclusions are known, which require additional geochemical analysis beyond the scope of this study.

ACKNOWLEDGEMENTS

The study on the characterization of Jean Marie tight gas reservoirs is an activity within the Unconventional Gas Assessment project of the Geological Survey of Canada's Secure Canadian Energy Supply Program. Funding for this study is provided by the Geological Survey of Canada and a grant from the CCT11 Unconventional Gas Supply Program of Natural Resources Canada.

It is a pleasure to acknowledge the support and aid of our corporate and provincial government partners and geologists working for these companies and the [British Columbia Ministry of Energy, Mines and Petroleum Resources](#). Burlington Resources Canada Ltd. donated one-inch slabs of eighteen 18 m cores to the Geological Survey of Canada. Mr. Chris Adams ([B.C. Ministry of Energy, Mines and Petroleum Resources](#)), Dr. Alexis Anastas (formerly with Devon Canada Corporation), Mr. Tim Bird (Canadian Natural Resources Limited), Mr. Trevor Dufresne (Penn West Petroleum Ltd.), Mr. Mark Hayes (formerly with [B.C. Ministry of Energy, Mines and Petroleum Resources](#)), and Mr. Michael Sainas and Ms. Eileen Scott (Devon Canada Corporation) aided us through discussions and by providing key data. We have also benefited from discussions with Dr. Frank Stoakes ([Stoakes Consulting Group Ltd.](#)) and Dr. Graham Davies ([Graham Davies Geological Consultants Ltd.](#)).

REFERENCES

Al-Aasm, I.S., Taylor, B.E. and South, B.

1990: Stable isotope analysis of multiple carbonate samples using selective acid extraction; *Chemical Geology*, v. 80, p. 119-125.

Bodnar, R.J.

1993: Revised equation and table for determining the freezing point depression of H₂O–NaCl solutions; *Geochemica et Cosmochimica Acta*, v. 57, p. 683-684.

Chi, G. and Ni, P.

2007: Equations for calculation of NaCl/(NaCl + CaCl₂) ratios and salinities from hydrohalite-melting and ice-melting temperatures in the H₂O–NaCl–CaCl₂ system; *Acta Petrologica Sinica*, v. 23, p. 33-37.

Denison, R.E., Koepnick, R.B., Burke, W.H., Hetherington, E.A. and Fletcher, A.

1997: Construction of the Silurian and Devonian seawater ⁸⁷Sr/⁸⁶Sr curve; *Chemical Geology*, v. 140, p. 109-121.

Goldstein, R.H. and Reynolds, T.J.

1994: Systematics of fluid inclusions in diagenetic minerals; *SEPM Short Course 31*, 199 p.

Land, L.S.

1980: The isotopic and trace element geochemistry of dolomite: the state of the art, in, *Concepts and Models of Dolomitization*, Zenger, D.H., Dunham, J.B. and Ethington, R.L.; *Soc. Econ. Paleontologists and Mineralogists Spec. Publ.* 28, p. 87-110.

Veizer, J., Ala, D., Azmy, K., Bruckschen, P., Buhl, D., Bruhn, F., Carden, G.A.F., Diener, A., Ehneith, S., Gooderis, Y., Jasper, T., Korte, C., Pawellek, F., Podlaha, O.G. and Strauss, H.

1999: ⁸⁷Sr/⁸⁶Sr, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ evolution of Phanerozoic seawater; *Chemical Geology*, v. 161, p. 59-88.

Wendte, J.C., Sargent, D.G. and Al-Aasm, I.S.

2006: Interim report on the characterization of Jean Marie gas reservoir facies in the July Lake area of northeastern British Columbia; Geological Survey of Canada, Open File 5277, 5 p., 14 Figures, 1 Table.

LIST OF FIGURES

- [1.](#) Simplified paragenetic succession.
- [2.](#) Plot of $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$ for calcite components.
- [3.](#) Plot of $^{87}\text{Sr}/^{86}\text{Sr}$ versus $\delta^{18}\text{O}$ for calcite components.
- [4.](#) Plot of $^{87}\text{Sr}/^{86}\text{Sr}$ versus $\delta^{13}\text{C}$ for calcite components.
- [5.](#) Plot of $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$ for dolomite components, with least squares regression line.
- [6.](#) Plot of $^{87}\text{Sr}/^{86}\text{Sr}$ versus $\delta^{18}\text{O}$ for dolomite components.
- [7.](#) Plot of $^{87}\text{Sr}/^{86}\text{Sr}$ versus $\delta^{13}\text{C}$ for dolomite components.
- [8.](#) Histograms of homogenization temperatures for primary and pseudosecondary aqueous inclusions.
- [9.](#) Histograms of salinities for primary and pseudosecondary aqueous inclusions.
- [10.](#) Crossplot of homogenization temperature-salinity relationships for primary and pseudosecondary aqueous fluid inclusions.
- [11.](#) Histograms of homogenization temperatures for oil inclusions.

LIST OF TABLES

- [1.](#) Stable and radiogenic isotopic analyses of diagenetic minerals.
- [2.](#) Fluid-inclusion microthermometric results of diagenetic minerals.
- [3.](#) Summary of microthermometric results for fluid inclusions in different minerals.