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Regional-scale variation of characteristics of hydrocarbon fluid inclusions and thermal conditions along the Paleozoic Laurentian continental margin in eastern Quebec, Canada*

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ABSTRACT

Fluid inclusions in diagenetic mineral phases and organic matter in host rocks were studied in Paleozoic strata along the Laurentian continental margin in eastern Quebec. The types of hydrocarbon fluid inclusions correspond broadly with the tectonic units: the St. Lawrence Platform contains oil inclusions; the Humber Zone contains mainly methane inclusions; and the successor basin (the Gaspé Belt) contains oil inclusions in the upper succession, oil and methane in the middle succession, and methane inclusions in the lower interval. The nature of hydrocarbon fluid inclusions also corresponds to the maturation level of organic matter in the host rocks: oil inclusions occur in host rocks that were heated to the oil window or the condensate zone, whereas methane inclusions occur in the condensate zone or dry gas zone, but mainly in the latter. The variation in the nature of hydrocarbon fluid inclusions is related to the thermal history of the successions studied: oil inclusions correspond to relatively low thermal conditions, and methane inclusions to relatively high conditions. These observations suggest that oil reservoirs, if they exist, are more likely to occur in host rocks that have not been buried beyond the condensate zone than in those that have gone through the dry gas zone. The occurrence of oil inclusions in condensate zone rocks suggests that oil was generated and migrated after maximum burial of the host rocks, from mature source rocks either overlying or overthrusted by the host rocks. However, the absence of oil inclusions in the dry gas zone rocks suggests that such a late oil generation-migration scenario may not be viable if the host rocks are heated far beyond the oil window. This is probably because these rocks are farther from, thus less likely connected to, a younger source rock. This study suggests that part of the St. Lawrence Platform and the Gaspé Belt have the thermal conditions for the formation of oil reservoirs, whereas the Humber Zone is prone to natural gas formation.

RÉSUMÉ

Les inclusions fluides dans des phases diagenetiques et la matière organique dans les roches hôtes de ces phases ont été étudiées dans des roches sédimentaires paléozoïques le long de la marge laurentieene de l'est du Québec. Une corrélation est observée entre le type des inclusions fluides d'hydrocarbures et les unités tectoniques : la plate-forme du Saint-Laurent contient des inclusions d'huile; la zone de Humber contient principalement des inclusions de méthane, et la succession du bassin successeur de la ceinture de Gaspé contient des inclusions d'huile dans la partie supérieure, d'huile et de méthane dans la partie médiane et de méthane dans la partie inférieure. La nature des inclusions fluides d'hydrocarbures est reliée au niveau de maturation thermique des roches hôtes : les inclusions d'huile s'observent dans les roches chauffées dans la fenêtre à huile ou dans la zone à condensat, alors que les inclusions de méthane sont trouvées dans les roches attribuées soit à la zone à condensat mais surtout à la zone à gaz sec. La variation de la nature des inclusions fluides d'hydrocarbures est largement reliée à l'histoire thermique des successions étudiées: les d'inclusions d'huile correspondent à des conditions de maturation thermiques relativement faibles (mature) alors que la présence de méthane correspond à des conditions plus élevées (supramature). Ces observations suggèrent que si des réservoirs à huile existent, ils se trouvent probablement plus dans les roches hôtes qui n'ont pas été enfouies au delà de la zone à condensat que dans celles qui ont traversé la zone à gaz sec. La présence d'inclusions d'huile dans des roches de la zone à condensat suggère que l'huile a été généré et a migré après l'enfouissement maximum des roches hôtes, à partir de roches mères matures sus-jacentes ou chevauchées par les roches hôtes. Cependant, l'absence d'inclusions à huile dans

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les roches de la zone à gaz sec suggère que ce scénario de génération et de migration tardive d'huile n'est pas probable si les roches hôtes ont été chauffées bien au delà de la fenêtre à huile, probablement parce que ces roches sont plus loins, et probablement non-connectées à une roche mère plus jeune. Cette étude suggère que une partie de la plate-forme du Saint-Laurent et la ceinture de Gaspé ont les conditions thermiques pour la formation des réservoirs d'huile, alors que la zone de Humber est encline à la formation de gaz naturel.

Traduit par Lynn Gagnon

Introduction

Paleozoic sediments deposited along the Laurentian continental margin in eastern Quebec, now preserved in the St. Lawrence Platform and the adjacent Appalachian Orogen (Fig. 1), have been the targets of hydrocarbon exploration for a long time. However, despite intensive exploration activities in the 1960's and 70's, no important oil fields have been found. The recent discovery of oil reservoirs in lower Paleozoic rocks in western Newfoundland (Cooper *et al.*, 1997) has renewed the interest for hydrocarbon potential in eastern Quebec. Potential source rocks have been shown to exist in the Upper Ordovician of the St. Lawrence Platform (Macauley *et al.*, 1990; Bertrand, 1991), certain Silurian-Devonian intervals in the Gaspé Belt (Bertrand, 1987), and some Cambrian-Ordovician intervals in the Humber Zone. Given the availability of potential source rocks, the formation of economic petroleum accumulation appears to depend largely on thermal conditions and the availability of reservoirs and traps, which in turn are related to the timing of hydrocarbon migration. This paper addresses the regional thermal condition from two different approaches: fluid-inclusion microthermometry in diagenetic phases, and organic matter maturation in sediments. The maturation level of organic matter in sedimentary rocks reflects the accumulated effect of burial and other thermal events, whereas the temperatures and pressures estimated from fluid inclusions indicate the T-P conditions at a specific moment of basin evolution. In addition, hydrocarbon-bearing fluid inclusions can be used as indicators of hydrocarbon migration events. The combination of the fluid-inclusion and organic matter maturation data can provide useful information about the thermal evolution of the basin and the relative timing of hydrocarbon migration events.

A large amount of data has been reported on the maturation of organic matter in Paleozoic rocks in southern and eastern Quebec (Sikander and Pittion, 1978; Ogunyomi *et al.*, 1980; Legall *et al.*, 1981; Islam *et al.*, 1982; Bertrand, 1987, 1990b; Héroux and Tassé, 1990; Héroux and Bertrand, 1991; Yang and Hesse, 1993; Bertrand *et al.*, 1992; Bertrand and Dykstra, 1993). Relatively few fluid-inclusion data have been published for the same region (Islam and Hesse, 1983; Levine *et al.*, 1991; Chi and Lavoie, 1998a; Chi *et al.*, 2000). This paper reports on new organic matter maturation and fluid-inclusion data in several areas of the St. Lawrence Platform and the Humber Zone, and summarizes the published data for other areas. The purpose of the paper is to characterize the regional-scale variation of fluid inclusion and organic matter characteristics, and to discuss the significance of these characteristics for hydrocarbon exploration strategies. However, the development of exploration models in specific target areas requires more detailed stratigraphic, structural, diagenetic and organic geochemical studies as well as better constraints on the timing of hydrocarbon migration events.

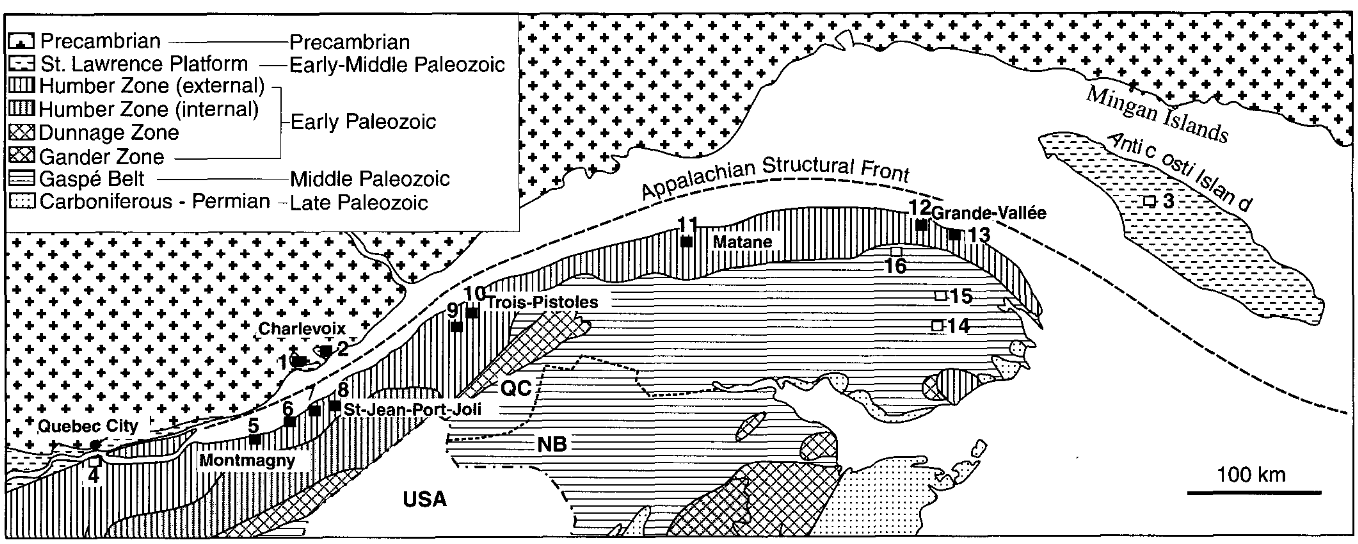

Fig. 1. Regional geological map of eastern Quebec (simplified from Williams, 1995). The areas covered in this study are shown in black squares, and those studied previously and compiled in this paper are shown in white squares. 1. Baie St-Paul, 2. La Malbaie; 3. NACP-44 Well (Anticosti Island); 4. South shore of the Quebec City area; 5. Montmagny; 6. Cap St-Ignace; 7. Les Ilets; 8. St-Jean-Port-Joli; 9. Ile-Verte; 10. Trois-Pistoles; 11. Matane; 12. Rivière Madeleine (Grande-Vallée); 13 Petite-Vallée; 14. St-Jean Anticline; 15. Rivière Mississippi; 16. Rivière Madeleine.

Geological Setting

The study area ranges from Quebec City to the Gaspé Peninsula, over a distance of more than 700 km along the St. Lawrence River. It covers three major tectonic units: from northwest to southeast, the St. Lawrence Platform, the Humber Zone and the Gaspé Belt (Fig. 1). The stratigraphy of the three tectonic zones is summarized in Figure 2.

The strata of the St. Lawrence Platform consist of Cambrian to lower Middle Ordovician passive margin platform sedimentary rocks and upper Middle Ordovician to Lower Silurian foreland basin sedimentary rocks. The foreland basin sedimentary rocks are exposed in the Quebec City and Charlevoix areas and on Anticosti Island. The passive margin platform sedimentary rocks, which are well exposed to the southwest of the study area, are rarely exposed in eastern Quebec (*e.g.* the Mingan Islands). Here, they are either hidden beneath nappes of the Humber Zone (*e.g.* the Quebec City area, St-Julien *et al.*, 1983), or are overlain by younger foreland platform sediments (*e.g.* on Anticosti Island). The possible existence of passive-margin platform strata in eastern Quebec is indicated by the presence of platform facies fragments in slope conglomerates in the Humber Zone (Lavoie, 1997). A major portion of the platform is now buried under the St. Lawrence River and the Gulf of St. Lawrence (north of the 'Appalachian Structural Front' shown in Figure 1).

The Humber Zone comprises Cambrian to basal Middle Ordovician passive margin slope, rise and foredeep sediments that were thrust over the autochthonous Cambrian to Upper Ordovician rocks of the St. Lawrence Platform during the Taconian Orogeny (Middle–Late Ordovician). The Humber Zone is divided into a more deformed and metamorphosed internal zone and a less deformed and metamorphosed external zone (see Williams, 1995, and Figure 1). The external Humber Zone structure is a foreland fold and thrust belt, and is composed of a number of nappes.

The Gaspé Belt is composed of Upper Ordovician to Middle Devonian marine to continental sediments in successor basins that were built upon basements belonging to the Humber, Dunnage and Gander zones (see Williams, 1995, and Figure 1). The sediments of the Gaspé Belt experienced a Late Silurian to Early Devonian salinic disturbance, and were deformed mainly during the Middle Devonian Acadian Orogeny (Malo and Kirkwood, 1995).

Sampling and Study Methods

The localities of samples for fluid-inclusion studies are shown in Figure 1, and their UTM coordinates are given in the Appendix. Samples of the St. Lawrence Platform were collected from outcrops of the Charlevoix area (Baie St-Paul and La Malbaie). Samples of the Humber Zone (external) were collected from outcrops along the south shore of the St. Lawrence River in the following localities: Montmagny, Cap St-Ignace, Les Ilets, St-Jean-Port-Joli, Ile-Verte, Trois-Pistoles, Matane, Rivière Madeleine (Grande-Vallée) and Petite-Vallée (labelled 5 –13 in Figure 1). Also shown in Figure 1 are localities from previous studies. Results from these localities were compiled for this study. They include the NACP-44 well on Anticosti Island, the south shore of the Quebec City area and eastern Gaspésie (St-Jean Anticline, Rivière Mississippi and Rivière Madeleine). Much more samples were analyzed for reflectance of organic matter than for fluid inclusions, and only those closest to the fluid-inclusion samples are reported in this study. In

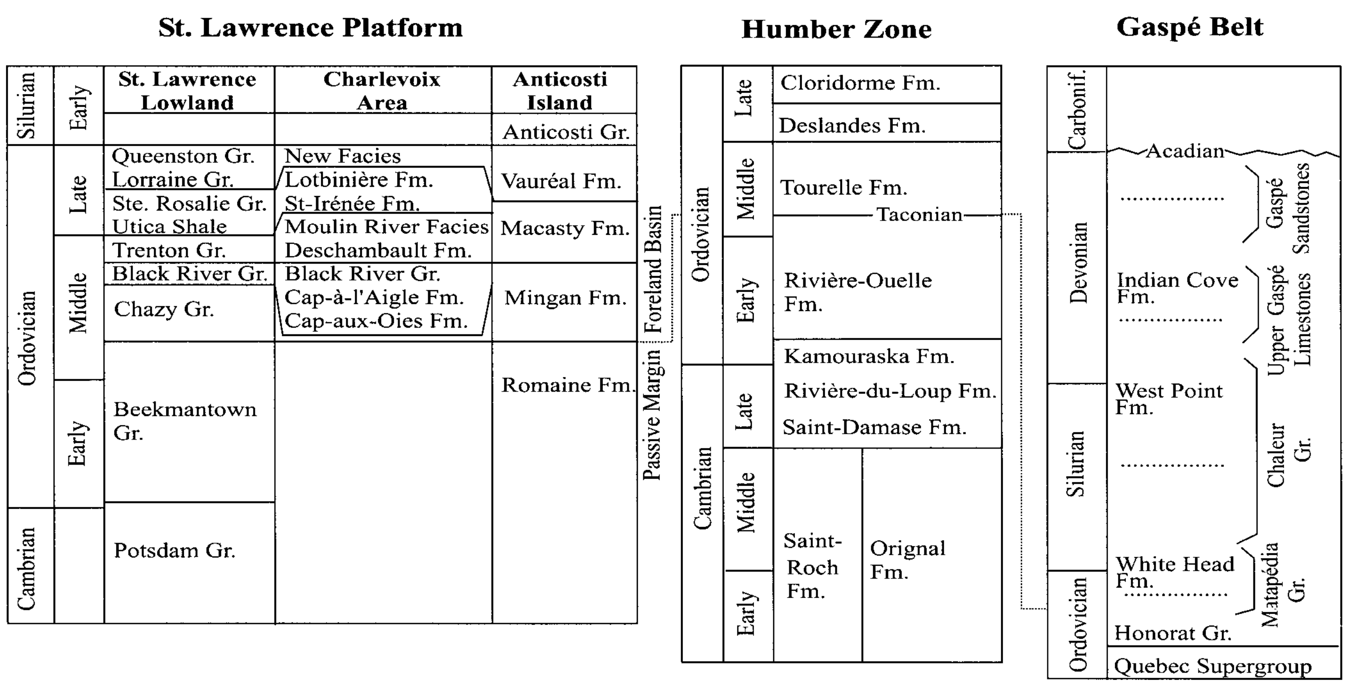

Fig. 2. Generalized stratigraphic columns of the three major tectonic units: the St. Lawrence Platform, the Humber Zone, and the Gaspé Belt.

a few cases, organic matter reflectance data from the same stratigraphic unit are unavailable near the fluid-inclusion samples, and data from the overlying or underlying stratigraphic units are listed for comparison.

Fluid-Inclusion Microthermometry

Conventional petrography was carried out on each sample before fluid-inclusion microthermometry. Routine microscopy and cathodoluminoscopy were used to distinguish various diagenetic mineral phases and establish their paragenetic sequence. Fluid inclusions in diagenetic minerals were then examined in order to determine their timing relative to the host mineral (*i.e.* primary versus secondary) and suitability for microthermometric study. Because fluid inclusions showing clear relationships with growth zones of crystals were rare, we consider the following modes of occurrence of fluid inclusions as a possible indication of primary or pseudosecondary origin: isolated, clustered, scattered and randomly distributed in three dimensions. Fluid inclusions showing obvious post-trapping alterations (*e.g.* necking) were avoided.

Microthermometric measurements were carried out with a U.S.G.S heating/freezing stage made by Fluid Inc. The homogenization temperature (T_h) and final ice-melting temperatures ($T_{m\text{-}ice}$) of aqueous fluid inclusions were measured with a precision of $\pm$ 1°C and $\pm$ 0.2°C, respectively. The T_h and $T_{m\text{-}ice}$ data were reported for fluid-inclusion assemblages (Appendix), not for individual fluid inclusions. Thus, in the case of an isolated fluid inclusion, its T_h and $T_{m\text{-}ice}$ values were reported as they were measured, whereas in the case of 10 fluid inclusions from a cluster being measured for T_h and $T_{m\text{-}ice}$, only the range and mean of T_h and $T_{m\text{-}ice}$ were listed. The mean values thus obtained were subsequently used to calculate the range and mean of fluid inclusions from a specific diagenetic mineral phase. The same procedure was used in constructing all the histograms in this paper, unless indicated otherwise. Such a treatment of data aims to give equal weight to each fluid-inclusion assemblage, and to avoid over-weighting certain fluid-inclusion assemblages where numerous measurements were made. It should be pointed out that scattered or randomly distributed fluid inclusions within a crystal were treated as a fluid-inclusion assemblage, although they may not be strictly contemporaneous.

Oil inclusions were studied with a Zeiss II photomicroscope equipped with an HBO W/2 100 high-pressure mercury lamp, a 1UG1 excitation filter (368 nm), a Zeiss FL prism, an oil immersion NEOFLUAR 100X objective and an optovar set at 1.25X. The fluorescence spectra of the oil inclusions were calibrated against a uranyl glass GG17 standard at each 10 nm interval in wavelengths ranging from 400 to 700 nm.

When aqueous fluid inclusions coexist with hydrocarbon inclusions, it is assumed that the aqueous phase was saturated with hydrocarbon components at entrapment, and the homogenization temperatures of aqueous fluid inclusions were equal to the trapping temperatures (Burrus, 1992). Fluid pressures were estimated from the intersection of the isochores of the hydrocarbon inclusions and the inferred trapping temperatures. Isochores of methane inclusions were calculated using the Flincor program of Brown (1989), and those of oil inclusions were constructed with the VTFLINC program of Calsep A/S. Because the composition of the oil inclusions was unknown, it was modeled by mixing a generic black oil and volatile oil that had API values of 34.3 and 50.1, respectively (Burrus, 1992). The proportions of the end members were calculated from the API values of the oil inclusions, which were estimated from their fluorescence spectra (Stasiuk and Snowdon, 1997). Two different API values were obtained from an oil inclusion using the L_{max} and Q values of the fluorescence spectra, respectively, and their average was used in the mixing model.

Organic Matter Petrography

The reflectance of dispersed organic matter was used as an indicator of the thermal maturation of the host rocks. Organic matter (OM) concentrates (kerogen) were obtained following the method described by Bertrand and Héroux (1987). Transparent strewn mounts were prepared and polished, according to the method of Bertrand *et al.* (1985). A Zeiss II photo-reflectometer microscope with transmitted and reflected light capability was used to measure reflectance at 546 nm with a 40X oil immersion objective from a 3 mm illuminated spot on a polished surface of kerogen (1.515 refractive index oil). Reflectance was measured on randomly oriented organic particles under nonpolarized reflected light. In order to check drift, the reflectance in oil (R_O) of a standard glass (R_O = 1.025%) was measured every 60 readings, or less if the sample did not contain enough organic particles for more measurements.

Microscopic identification of kerogen was based on morphology and optical properties according to the methods described by the International Commission of Coal Petrology (1971, 1995), Alpern (1970) and Stach *et al.* (1982). The nomenclature of solid bitumen is from Bertrand (1993). A microcomputer was used to record data, build histograms and calculate statistical parameters. The R_O of zooclasts (chitinozoans, graptolites and scolecodonts) and pyrobitumen was converted into R_O vitrinite-equivalents ($R_{O\ vi\text{-}eq}$) according to the method of Bertrand (1990a, 1993).

Results

The paragenetic sequences of diagenetic minerals in samples studied are summarized in Table 1. The results of fluid-inclusion microthermometry and organic matter reflectance obtained from this study, and those compiled from previous studies, are listed in Table 2. More detailed microthermometric data for individual fluid-inclusion assemblages can be found in the Appendix. The analytical results are described separately for the three different tectonic units (*i.e.* the St. Lawrence Platform, the Humber Zone and the Gaspé Belt).

The St. Lawrence Platform – Charlevoix Area

Four samples from the Charlevoix area were studied for fluid inclusions, one each from the Deschambault Formation, Black River Group, the Moulin River Facies and the St-Irénée Formation. These strata are of late Middle to Late Ordovician age (Fig. 2), and were formed during the foreland basin stage of the St. Lawrence Platform.

Sample 98BSP2-1 consists of limestone from the Moulin River facies. It contains a post-stylolite fracture filled by calcite (Cf1), which in turn was fractured and filled by a second generation of calcite (Cf2) (Table 1). Sample 98BSP1-5b is a sandstone from the St-Irénée Formation, which was first cemented by quartz overgrowth and then by calcite (Cp). The sample contains a fracture that is filled by calcite (Cf) and barite (Bf) (Table 1). Sample 98MAL1-6 consists of limestone from the Black River Group. It contains abundant millimetre-size pores (Fig. 3A), which were first filled by a thin layer of calcite cement showing weak orange cathodoluminescence (Cp1), and then by a dominant calcite cement, which is dull to non-luminescent under CL (Cp2) (Table 1). Sample 98MAL1-7 is a calcarenite cemented by an early phase of calcite characterized by well-zoned cathodoluminescence (Cp1) and a late phase of calcite, which is dull to nonluminescent under CL (Cp2) (Table 1).

Fluid inclusions in quartz overgrowth are commonly aqueous and contain only liquid at room temperature. The fluid-inclusion microthermometric data of the calcite cements are shown in Table 2 and Figure 4. The microthermometric attributes of aqueous fluid inclusions vary among the different mineral phases. Figure 4 shows that Th values are lower in early pore-filling calcite (*i.e.* < 80°C in Cp1 in 98MAL1-6 and 98MAL1-7) than in late, pore-filling or fracture-filling calcites (mainly between 80 and 160°C). Salinities vary from as low as 0.4 in Cf2 of 98BSP2-1 to as high as 26.5 wt% NaCl equivalent in Cp2 of 98MAL1-6 (Table 2). Note that aqueous fluid inclusions from the calcite phases that contain oil inclusions are characterized by relatively high salinities, *i.e.* 14.9 to 15.1 wt% NaCl equivalent in Cf1 of 98BSP2-1, and 7.0 to 26.5 wt% NaCl equivalent in Cp2 of 98MAL1-6 (Table 2).

One gaseous inclusion was observed in Cp1 of 98MAL1-7 and showed a T_h value of –74.2°C (homogenized into vapour phase). This inclusion probably contains CH_4 and other light hydrocarbons. A few oil inclusions were observed in Cf1 of 98BSP2-1. They are colourless under transmitted light and yellowish white under fluoroscope, and show T_h values between 67.1 and 76.2°C. No fluorescence spectra were obtained from these oil inclusions. A number of colourless oil inclusions were observed in Cp2 of 98MAL1-6, which show T_h values between 39.6 and 42.0°C, and coexist with aqueous inclusions in the same calcite crystal (Fig. 3B). The oil inclusions show greenish white fluorescence, and a fluorescence spectrum characterized by a L_{max} value of 510 nm and a Q value of 0.082 (nine measurements). The API value estimated from the L_{max} and Q values, according to linear equations regressed from the data of Stasiuk and Snowdon (1997), are 44.9 and 36.2, respectively. The average of these API values is 40.6. Note the T_h values of oil inclusions are consistently lower than those of coexisting aqueous inclusions.

Using the average API value of 40.6, the composition of the oil inclusions in Cp2 of 98MAL1-6 is modeled by mixing 60% black oil (API= 34.3) and 40% volatile oil (API=50.1). The isochore of the oil inclusion was constructed using the VTFLINC program of Calsep A/S (Fig. 5). The trapping temperature is assumed to be equal to the Th of coexisting aqueous fluid inclusions, which is 96.3°C (Table 2), and the fluid pressure corresponding to this temperature is calculated to be 565.1 bars (Fig. 5 and Table 3).

The $R_{O\ vi\text{-}eq}$ (%) values of organic matter in the host rocks corresponding to samples 98BSP2-1, 98BSP1-5b and 98BSP1-7 are 1.25, 2.45 and 1.11, respectively (Table 2). No sample from the Black River Group was analyzed for R_O at the locality of 98MAL1-6, but 98BSP1-7 is from the immediately

Table 1. Paragenetic sequences of samples studied.

Sample No.	Lithology	Paragenetic sequence
98BSP2-1	Limestone	Stylolite -> fracture-filling calcite 1 (Cf1) -> deformation -> fracture-filling calcite 2 (Cf2).
98BSP1-5b	Sandstone	Quartz overgrowth -> pore-filling calcite (Cp) -> pore-filling calcite (CP) + facture-filling calcite (Cf) and barite (Bf).
98MAL1-6	Limestone	Early pore-filling calcite (Cp1) -> late pore-filling calcite (Cp2).
98MAL1-7	Calcarenite	Early pore-filling calcite (Cp1) -> late pore-filling calcite (Cp2).
97LKA-MY-320	Sandstone	Quartz overgrowth (Qp) -> fracture-filling quartz (Qf) -> deformation.
97LKA-MY-17C	Sandstone	Quartz overgrowth (Qp) -> fracture-filling quartz (Qf1) -> deformation -> Qf2 + Cf2.
98CSI6-1	Sandstone	Fracture-filling calcite (Cf1) and quartz (Qf1) -> deformation.
98LI14-1	Sandstone	Quartz overgrowth (Qp) -> fracture-filling quartz (Qf1) and calcite (Cf1) -> weak deformation.
98SJPJ1-2	Sandstone	Quartz overgrowth (Qp) -> pore-filling calcite (Cp) -> deformation -> fracture-filling quartz (Qf) and calcite (Cf).
98SJPJ13-1	Conglomerate	Quartz overgrowth (Qp) -> Qp + pore-filling calcite (Cp) -> deformation.
98SJPJ17-1	Sandstone	Quartz overgrowth (Qp) -> Qp + fracture-filling quartz (Qf) -> deformation.
983P6-1	Sandstone	Quartz overgrowth (Qp) -> Qp + fracture-filling quartz (Qf1) and calcite (Cf1) -> weak deformation -> Qf2.
983P24-1	Sandstone	Quartz overgrowth (Qp) -> Qp + Cp -> fracture-filling calcite (Cf1) and quartz (Qf1) -> deformation -> Cf2 + Qf2.
983P25-1	Limestone	Fracture-filling calcite (Cf1) -> stylolite -> Cf2 -> Cf3 -> deformation -> Cf4.
98IV1-1	Grainstone	Pore-filling calcite (Cp1) -> stylolite -> Cp2.
98IV11-1	Sandstone	Quartz overgrowth (Op) -> fracture-filling quartz (Qf1) -> Qf2 + calcite (Cf2) -> deformation -> Qf3.
97LKA-MT-223	Sandstone	Quartz overgrowth (Qp) -> Qp + fracture-filling quartz (Qf) -> deformation.
97LKA-MT-224	Sandstone	Quartz overgrowth (Qp) -> stylolite -> Qp + fracture-filling quartz (Qf) -> deformation.
97LKA-MT-e	Sandstone	Quartz overgrowth (Qp) -> Qp + fracture-filling quartz (Qf) -> deformation.
97LKA-MT-2C	Limestone	Pore-filling calcite (Cp1) -> stylolite -> Cp2 -> fracture-filling calcite (Cf) -> weak deformation.
97LKA-RM-24A	Sandstone	Quartz overgrowth (Qp) -> deformation -> fracture-filling quartz (Qf).
97LKA-RM-25A	Sandstone	Quartz overgrowth (Qp) -> deformation -> fracture-filling quartz (Qf).
97LKA-RM-26A	Sandstone	Quartz overgrowth (Qp) -> deformation -> fracture-filling quartz (Qf).
97LKA-RM-26B	Sandstone	Quartz overgrowth (Qp) -> deformation -> fracture-filling quartz (Qf).
97LKA-PV-4B	Limestone	Fracture-filling calcite -> deformation.

Table 2. Results of fluid-inclusion microthermometry and organic matter reflectance

Sample		Fluid-inclusion microthermometry							Organic matter reflectance		
		Host mineral*	Type	Salinity (wt.% NaCl equiv.) Range	Mean (n)**	T_h (°C) Range	Mean (n)**	Ref. ***	Formation/ rock	$R_{O\ vi\text{-}eq}$(%) Mean (n)	Ref. ***
No.: 98BSP2-1	Area: Baie St-Paul	Cf1	Aq	14.9 ~ 15.1	15.0 (2)	142.3 ~ 157.8	150.9 (3)	(1)	Same fm.	1.25 (84)	(1)
Fm.: Moulin River	Litho.: Limestone		Oil			67.1 ~ 76.2	71.7 (2)		shaly		
		Cf2	Aq	0.4	0.4 (1)	126.0 ~ 129.3	127.7 (2)		limestone		
No.: 98BSP1-5b	Area: Baie St-Paul	Cp	Aq	0.9 ~ 2.4	1.7 (3)	110.6 ~ 137.6	123.1 (3)	(1)	Same fm.	2.45 (61)	(1)
Fm.: St-Irénée	Litho.: Sandstone	Cf	Aq	3.3 ~ 3.5	3.4 (3)	125.4 ~ 137.0	130.5 (4)		calcareous		
		Bf	Aq	2.8 ~ 2.9	2.9 (2)	116.4 ~ 117.8	117.1 (2)		shale		
No.: 98MAL1-6	Area: La Malbaie	Cp1	Aq	4.1	4.1 (1)	67.5	67.5 (1)	(1)	Deschamb.	1.11 (52)	(1)
Fm.: Black River	Litho.: Limestone	Cp2	Aq	7.0 ~ 26.5	16.4 (7)	55.6 ~ 119.4	96.3 (9)		limestone		
			Oil			39.6 ~ 42.0	40.8 (2)				
No.: 98MAL1-7	Area: La Malbaie	Cp1	Aq	6.4 ~ 7.3	6.9 (2)	<50? ~ 80.3		(1)	Same fm.	1.11 (52)	(1)
Fm.: Deschambault	Litho.: Calcarenite		CH_4			-74.2 (V)	-74.2 (V) (1)		limestone		
		Cp2	Aq	8.0 ~ 18.6	13.3 (2)	86.1 ~ 98.4	91.9 (3)				
No.: 97LKA-MY-320	Area: Monmagny	Cf	Aq	19.3 ~ 20.5	19.9 (4)	104.2 ~ 131.4	120.6 (6)	(1, 2)	Rv-Ouelle	2.85 (41)	(1)
Fm.: Kamouraska	Litho.: Sandstone								black		
									mudstone		
No.: 97LKA-MY-17C	Area: Monmagny	Qf2	Light HC			-49.5 ~ -65.2	-57.4 (2)	(1, 2)	St-Damase	2.65 (49)	(1)
Fm.: Kamouraska	Litho.: Sandstone	Cf2	Aq	14.0	14.0 (1)	133.9	133.9 (1)		black		
			CH_4			-88.4 (V)	-88.4 (V) (1)		mudstone		
			Light HC			-43.9 ~ -74.6	-59.3 (2)				
No.: 98CSI6-1	Area: Cap St-Ignace	Cf	Aq	2.3 ~ 4.8	3.7 (3)	110.6 ~ 114.9	113.3 (3)	(1)	Same fm.	2.13 (31)	(1)
Fm.: St-Roch	Litho.: Sandstone	Qf	Aq	5.0	5.0 (1)	176.0	176.0 (1)		siltstone/		
									mudstone		
No.: 98LI14-1	Area: Les Ilets	Qf	Aq	2.7 ~ 2.9	2.8 (3)	180.1 ~ 197.4	186.9 (3)	(1)	Same fm.	2.97 (45)	(1)
Fm.: Rivière-du-Loup	Litho.: Sandstone								shale/		
									sandstone		
No.: 98SJPJ1-2	Area: St-Jean-Port-Joli	Qp	Aq	2.7 ~ 3.2	2.9 (3)	153.0 ~ 190.4	174.9 (3)	(1)	Same fm.	1.95 (45)	(1)
Fm.: St-Roch	Litho.: Sandstone	Cp	Aq	2.7 ~ 3.2	2.9 (7)	105.7 ~ 130.9	113.0 (8)		mudstone/		
		Qf	Aq	2.2 ~ 2.7	2.5 (2)	173.4 ~ 173.6	173.5 (2)		sandstone		
			CH_4			-84.5 (V)	-84.5 (V) (1)				
		Cf	Aq	1.8 ~ 1.9	1.9 (2)	148.7 ~ 148.8	148.8 (2)				
No.: 98SJPJ13-1	Area: St-Jean-Port-Joli	Qd	CH_4			-102.5 ~ -120.9	-112.9 (3)	(1)	Same fm.	sterile	(1)
Fm.: Rivière-du-Loup	Litho.: Conglomerate	Qp	Aq			165.0	165.0 (1)		grey		
			CH_4			-108.1 ~ -121.7	-114.9 (2)		shale		
		Cp	Aq	1.6 ~ 2.3	1.9 (6)	117.9 ~ 173.1	143.7 (8)				
No.: 98SJPJ17-1	Area: St-Jean-Port-Joli	Qf	Aq	3.4 ~ 3.7	3.6 (4)	160.1 ~ 183.3	167.8 (4)	(1)	Same fm.	2.89 (40)	(1)
Fm.: Kamouraska	Litho.: Sandstone		CH_4			-92.1	-92.1 (1)		shale/		
									sandstone		
No.: 983P6-1	Area: Trois-Pistoles	Qd	CH_4			-89.4	-89.4 (1)	(1)	Same fm.	3.22 (35)	(1)
Fm.: Kamouraska	Litho.: Sandstone	Qp	Aq	5.1 ~ 6.1	5.7 (3)	87.6 ~ 249.8	189.5 (4)		black		
		Qf1	Aq	5.4 ~ 7.0	6.4 (7)	163.9 ~ 285.2	222.0 (7)		mudstone/		
		Cf1	Aq	5.1 ~ 6.1	5.5 (6)	92.6 ~ 191.5	148.4 (7)		sandstone		
No.: 983P24-1	Area: Trois-Pistoles	Qp	Aq	9.1	9.1 (1)	57.8 ~ 221.6	140.3 (4)	(1)	Same fm.	3.65 (64)	(1)
Fm.: Kamouraska	Litho.: Sandstone	Cp	Aq	10.3 ~ 16.7	14.4 (3)	107.5 ~ 234.2	193.0 (4)		grey		
		Qf1	Aq	13.6 ~ 14.7	14.2 (2)	215.5 ~ 240.6	228.1 (2)		mudstone/		
			CH_4			-106.9 ~ -127.0	-117.9 (4)		sandstone		
		Cf1	CH_4			-115.9 ~ -122.1	-119.5 (4)				
		Cf2	Aq	6.4 ~ 8.4	7.6 (3)	174.1 ~ 261.3	212.7 (8)				
No.: 983P25-1	Area: Trois-Pistoles	Cf1	Aq	8.1	8.1 (1)	274.7	274.7 (1)	(1)	Same fm.	2.89 (12)	(1)
Fm.: Rivière-Ouelle	Litho.: Limestone	Cf2	Aq	7.1	7.1 (1)	257.9	257.9 (1)		calcareous		
		Cf3	Aq	7.6	7.6 (1)	257.6	257.6 (1)		shale		
No.: 98IV1-1	Area: Ile-Verte	Cp1	Aq	4.1	4.1 (1)	124.6	124.6 (1)	(1)	Same fm.	sterile	(1)
Fm.: Rivière-Ouelle	Litho.: Grainstone	Cp2	Aq	4.5 ~ 10.8	7.8 (5)	107.6 ~ 180.9	142.1 (7)		green		
									shale		
No.: 98IV11-1	Area: Ile-Verte	Qf1	Aq	2.9 ~ 3.2	3.0 (3)	160.2 ~ 257.0	193.3 (4)	(1)	Rv-du-Loup	3.91 (3)	(1)
Fm.: Kamouraska	Litho.: Sandstone		CH_4			-106.9 ~ -119.7	-114.7 (5)		grey shale/		
									sandstone		
No.: 97LKA-MT-223	Area: Matane	Qp	Aq			<50? ~ 141.7		(1, 2)	Same fm.	4.02 (11)	(1)
Fm.: Kamouraska	Litho.: Sandstone	Qf	Aq	6.4	6.4 (1)	71.4 ~ 184.1	124.0 (3)		mudstone		
No.: 97LKA-MT-224	Area: Matane	Qp	Aq	2.1	2.1 (1)	54.4 ~ 194.0	121.5 (4)	(1, 2)	Same fm.	4.02 (11)	(1)
Fm.: Kamouraska	Litho.: Sandstone	Qf	Aq	2.1	2.1 (1)	171.0	171.0 (1)		mudstone		
No.: 97LKA-MT-e	Area: Matane	Qp	Aq			<50? ~ 148.0		(1, 2)	Same fm.	4.02 (11)	(1)
Fm.: Kamouraska	Litho.: Sandstone	Qf	Aq	2.7	2.7 (1)	197.4	197.4 (1)		mudstone		
No.: 97LKA-MT-2C	Area: Matane	Cp2	Aq	2.7 ~ 14.0	9.5 (6)	102.4 ~ 168.1	122.8 (6)	(1, 2)	Same fm.	2.80 (67)	(1)
Fm.: Rivière-Ouelle	Litho.: Limestone	Cf	Aq	3.2 ~ 4.8	4.0 (2)	145.1 ~ 193.7	167.3 (3)		limestone		
			CH_4			-94.0	-94.0 (1)				

Table 2. Continued

Sample		Fluid-inclusion microthermometry							Organic matter reflectance		
		Host mineral*	Type	Salinity (wt.% NaCl equiv.) Range	Salinity Mean (n)**	T_h (°C) Range	T_h Mean (n)**	Ref. ***	Formation/ rock	$R_{o\ vi\text{-}eq}$(%) Mean (n)	Ref. ***
No.: 97LKA-RM-24A	Area: Rv. Madeleine	Qp	Aq	1.9	1.9 (1)	58.3 ~ 117.3	75.3 (4)	(1, 2)	Rv-Ouelle	2.48 (43)	(1)
Fm.: Kamouraska	Litho.: Sandstone	Qf	Aq	2.2 ~ 3.1	2.7 (2)	138.5 ~ 178.8	156.3 (3)		Original mudstone	3.55 (65)	
No.: 97LKA-RM-25A	Area: Rv. Madeleine	Qf	Aq	6.8	6.8 (1)	195.8	195.8 (1)	(1, 2)	Rv-Ouelle	2.48 (43)	(1)
Fm.: Kamouraska	Litho.: Sandstone								Original mudstone	3.55 (65)	
No.: 97LKA-RM-26A	Area: Rv. Madeleine	Qp	Aq	2.6 ~ 8.0	5.3 (2)	145.2 ~ 159.5	152.4 (2)	(1, 2)	Rv-Ouelle	2.48 (43)	(1)
Fm.: Kamouraska	Litho.: Sandstone	Qf	Aq	2.9	2.9 (1)	195.7	195.7 (1)		Original mudstone	3.55 (65)	
No.: 97LKA-RM-26B	Area: Rv. Madeleine	Qp	Aq	4.0	4.0 (1)	157.8	157.8 (1)	(1, 2)	Rv-Ouelle	2.48 (43)	(1)
Fm.: Kamouraska	Litho.: Sandstone	Qf	Aq	4.3	4.3 (1)	193.6	193.6 (1)		Original mudstone	3.55 (65)	
No.: 97LKA-PV-4B	Area: Petite-Vallée	Cf	Aq	0.9 ~ 1.7	1.3 (2)	62.5 ~ 118.0	101.2 (4)	(1, 2)	Same fm.	2.69 (70)	(1)
Fm.: Rivière-Ouelle	Litho.: Limestone		CH_4			-91.3	-91.3 (1)		calcareous shale	2.79 (24)	
Area:	Drill Well: NACP-44	Dr3	Aq	13.3 ~ 25.5	21.1 (14)	73.2 ~ 116.5	103.1 (19)	(3)	Mingan	1.17 (60)	(4)
Anticosti Island	Interval:	Dp1	Aq	18.1 ~ 23.7	20.9 (2)	82.9 ~ 105.1	96.7 (4)		limestone		
Fm.: Romaine	1701.39 ~ 1748.10 m	Dp2	Aq	21.4 ~ 24.8	22.3 (6)	101.4 ~ 131.4	121.5 (6)		(NACP-44		
Litho.: Dolostones		Cp2	Aq	16.0 ~ 27.5	23.9 (13)	60.3 ~ 120.8	90.4 (13)		1341 m)		
			Oil			72.8 ~ 88.7	80.2 (3)				
		Bp	Aq	22.3 ~ 25.3	22.9 (7)	59.9 ~ 96.9	80.5 (6)				
			Oil			58.9	58.9 (1)				
Area:	Cambrian to	Qf	Oil			-20 ~ 130	55 (mode)	(5)	Same fm.	1.0 ~ 2.3	(6)
Quebec City	Ordovician nappes										
Area:	Fm.: White Head	Cf1	Aq	2.6 ~ 5.9	4.1 (3)	<50?		(1, 7)			
St-Jean Anticline	Litho.: Limestone	Qf2	Aq	4.0 ~ 6.3	4.8 (4)	124.4 ~ 209.3	168.2 (5)				
			CH_4			-92.1 ~ -93.1	-92.6 (9)				
Area:	Fm.: West Point	Cf	Aq	3.4 ~ 10.0	6.7 (3)	70.3 ~ 126.7	98.8 (5)	(8)	Same fm.	1.94 (60)	(4)
Rivière Madeleine	Litho.: Limestone		CH_4			-89.6 (V)	-89.6 (V) (1)		limestone		
Area:	Fm.: Indian Cove	Cf2	Aq	21.5	21.5 (1)	<50?		(1, 9)	Same fm.	0.81 (45)	(4)
Rivière Mississippi	Litho.: Limestone		Oil			41.8 ~ 63.1	50.3 (11)		limestone	0.76 (55)	

Litho. = lithology; Fm. = formation.

* Cp = pore-filling calcite; Cf = fracture-filling calcite; Qd = detrital quartz; Qp = pore-filling quartz; Qf = fracture-filling quartz; Bf = fracture-filling barite; Dr = replacement dolomite; Dp = pore-filling dolomite. More detailed paragenesis is described in the text.

** The number in parentheses (n) indicates the number of fluid inclusion assemblages being studied, not the number of individual fluid inclusions; the latter is shown in the Appendix.

*** References: (1) this study; (2) Chi and Lavoie (1998a); (3) Chi and Lavoie (1998b); (4) Bertrand (1987); (5) Levine *et al.* (1991);

Table 3. Fluid pressures calculated from coexisting aqueous and hydrocarbon fluid inclusions

Tectonic zones	Sample No. / Locality	Formation	Host mineral	Composition of hydrocarbon inclusions	Th (°C) HC inclusion	Th (°C) Aq. inclusion	Fluid pressure (bars)
St. Lawrence Platform	98MAL1-6	Black River	Cp2	Oil (API 40.6)	40.8 (L)	96.3	565.1
	/NACP, Anticosti	Romaine	Cp2	Oil (API 41.1)	80.2 (L)	90.4	345.3
			Bp	Oil (API 41.2)	58.9 (L)	80.5	392.4
Humber Zone	97LKAMY-17C	Kamouraska	Qf	CH_4	-88.4 (V)	133.9	162.6
	98SJPJ1-2	St-Roch	Qf	CH_4	-84.5 (V)	173.5	246.7
	98SJPJ13-1	Rivière-du-Loup	Qp	CH_4	-114.9 (L)	165.0	1678.6
	98SJPJ17-1	Kamouraska	Qf	CH_4	-92.1 (L)	167.8	964.6
	983P24-1	Kamouraska	Qf1	CH_4	-117.9 (L)	228.1	2127.0
	98IV11-1	Kamouraska	Qf1	CH_4	-114.7 (L)	193.3	1820.8
	97LKA-MT-2C	Rivière-Ouelle	Cf	CH_4	-94.0 (L)	167.3	1025.1
	97LKA-PV-4B	Rivière-Ouelle	Cf	CH_4	-91.3 (L)	101.2	731.7
Gaspé Belt	/ St-Jean Anticline	White Head	Qf2	CH_4	-92.6 (L)	168.2	982.3
	/ Rivière Madeleine	West Point	Cf	CH_4	-89.6 (V)	98.8	134.4
	/ Rivière Mississippi	Indian Cove	Cf2	Oil (API 40.0)	50.3 (L)	>50.3	>265.8

overlying Deschambault Formation at the same locality and is only a few metres above 98MAL1-6. It is inferred that 98MAL1-6 has an $R_{O\ vi\text{-}eq}$ (%) value similar to that of 98MAL1-7 (*i.e.* 1.11).

The St. Lawrence Platform – Anticosti Island

Previous studies of petrography, fluid inclusions and stable isotopes were conducted on a number of dolostone samples of the Romaine Formation from several drill wells on Anticosti Island (Chi and Lavoie, 1998b). Numerous oil inclusions were observed in one of the drill wells (NACP), and the fluid-inclusion microthermometric data from this particular well are summarized in Table 2. Additional fluorescence spectrometry was carried out in this study, and the results were used to construct the isochores of the oil inclusions.

The Romaine Formation is of Early to Middle Ordovician age, and was formed in the passive–margin stage of the St. Lawrence Platform (Fig. 2). It is overlain by the Mingan, Macasty and Vauréal formations and the Anticosti Group, ranging in age from Middle Ordovician to Early Silurian. The samples from the NACP well were collected from drill depths of between 1701 and 1748 m.

The dolostones of the Romaine Formation consist of four different replacement dolomites (Dr1-4), and two phases of pore-filling dolomites (Dp1-2). Remnants of limestone and early pore-filling calcite (Cp1) were occasionally seen. Dr1-2 were probably formed in the early stages of diagenesis, whereas Dr3-4 were formed in a late stage of diagenesis, and were probably related to hydrothermal activities (Chi and Lavoie, 1998b). Significant porosity was generated during the formation of Dr3-4, which were then partly to completely filled by saddle dolomite (Dp1-2), followed by calcite (Cp2) and barite (Bp). Fluid inclusions were studied in Dr3, Dp1-2, Cp2 and Bp.

Homogenization temperatures of aqueous fluid inclusions increased from 73.2~116.5°C in Dr3, 82.9~105.1°C in Dp1, to 101.4~131.4°C in Dp2, and then decreased to 60.3~120.8°C in Cp2 and 59.9~96.9°C in Bp. Salinities were fairly high (13.3~27.5 wt% NaCl equivalent) in all the mineral phases, and no systematic changes were observed (Table 2).

Oil inclusions occur in Cp2 and Bp, and commonly show greenish white fluorescence. The L_{max} and Q values of the fluorescence spectrum are 510 nm and 0.044, respectively, for Cp2, and 510 nm and 0.040, respectively, for Bp. The average API values, estimated from the method described above, are 41.1 and 41.2 for Cp2 and Bp, respectively. Both oils were modeled by mixing 57% black oil (API= 34.3) and 43% volatile oil (API=50.1). Using the Th values of oil inclusions (80.2°C for Cp2 and 58.9°C for Bp) and coexisting aqueous inclusions (90.4°C for Cp2 and 80.5°C for Bp) (Table 2), the trapping pressures were calculated to be 345.3 and 392.4 bars for Cp2 and Bp, respectively (Table 3).

The overall range of $R_{O\ vi\text{-}eq}$ (%) values of the Romaine Formation on Anticosti Island is from 0.8 to 1.5 (Bertrand, 1987, 1990b). However, no sample from the Romaine Formation was analyzed for R^o at NACP. The nearest sample is located at a drill depth of 1341 m in the Mingan Formation, which has an $R_{O\ vi\text{-}eq}$ (%) value of 1.17 (Table 2) (Bertrand, 1987). The R_O values of the Romaine Formation at NACP are likely higher than 1.17.

The Humber Zone

Samples from the Humber Zone were collected from the Saint-Roch, Rivière-du-Loup, Kamouraska and Rivière-Ouelle formations, ranging in age from Early Cambrian to early Middle Ordovician (Fig. 2). These strata were commonly deformed and fractured during the Taconian Orogeny.

The samples for fluid-inclusion studies were mainly sandstones; some were limestone intercalated in clastic rocks. The sandstones are cemented by variable amounts of quartz overgrowth (Fig. 6A) and, to a lesser extent, by calcite cement. The limestones were cemented by one or more phases of calcite cement. Both sandstone and limestone samples commonly

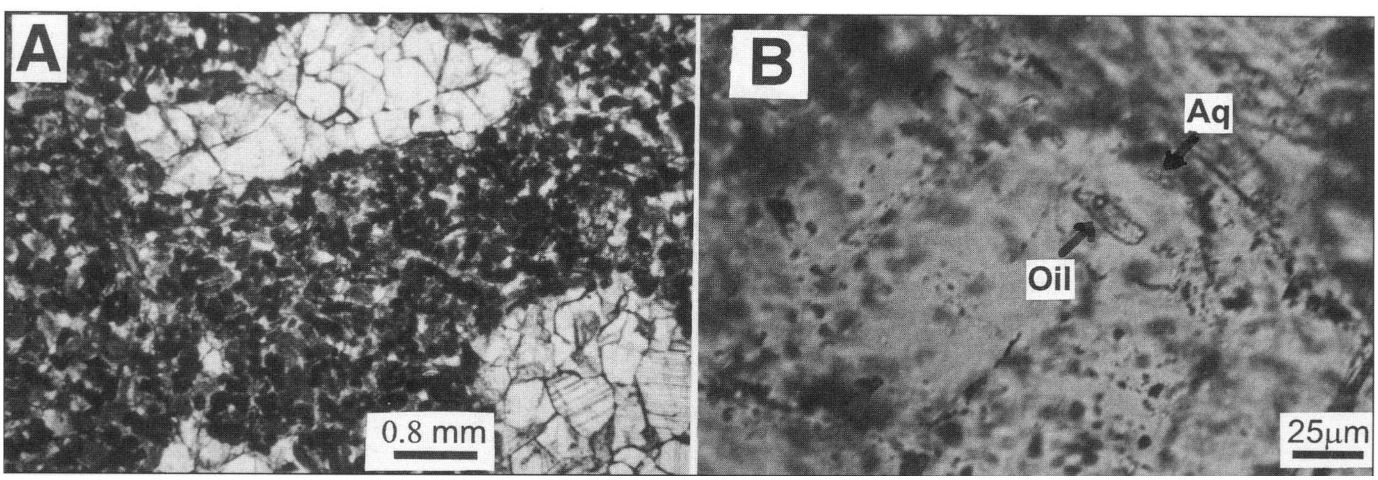

Fig. 3. (A) Calcite cement fills pores in a limestone sample from the Black River Group, La Malbaie, Charlevoix area, sample 98MAL1-6. Calcite cement filling the centre of the pores (Cp2) contains oil inclusions. **(B)** An isolated oil inclusion and an isolated aqueous inclusion occurring in pore-filling calcite (Cp2), sample 98MAL1-6.

contained one or more sets of fractures filled by quartz and/or calcite (Figs. 6B, C). The paragenetic sequences of diagenetic mineral phases are summarized in Table 1. Although workable fluid inclusions can be found in pore-filling cements, most microthermometric data were obtained from the fracture-filling mineral phases (Figs. 6D, E, F), which are generally the latest in the paragenetic sequence. Some of these fracture-filling minerals show uniform extinction under the microscope (Fig. 6B) and are believed to postdate major deformation, whereas others show undulate extinction (Fig. 6C), and probably predate or overlap major deformation. In the latter case, fluid inclusions were selected from relatively nondeformed domains (Figs. 6E, F and 7A) in order to minimize the effect on deformation on fluid inclusions.

Preliminary results of fluid-inclusion microthermometry for samples from Montmagny, Matane and Grande-Vallée were reported in Chi and Lavoie (1988a). Detailed microthermometric data of these samples, together with other samples from the Humber Zone, are listed in the Appendix for individual fluid-inclusion assemblages, and summarized in Table 2 for each mineral phase studied. Although homogenization temperatures are fairly consistent (with a range <20°C) within individual clusters, and to a lesser extent within a scattered population in a crystal, significant variation in T_h may occur within a randomly and densely distributed population in a crystal (see Appendix). This variation in T_h might reflect the variation of fluid temperature and/or pressure during the growth of the crystal, although the possibility of a stretching effect and the involvement of unrecognized secondary fluid inclusions could not be ruled out. The mean values of T_h and salinity of individual fluid-inclusion assemblages (including randomly distributed fluid inclusions) are used to calculate the mean and range for individual mineral phases (Table 2). However, in the case of coexistence of methane and aqueous fluid inclusions (Figs. 7A, B), the extremely large variation in T_h values (Fig. 8) was attributed to the effect of heterogeneous trapping, and the minimum of the T_h spectrum is used as the representative T_h (double asterisk in Appendix).

As shown in Figure 9, the homogenization temperatures of aqueous fluid inclusions are highly variable. Values of T_h are especially variable for those in quartz overgrowth (Qp), ranging from probably <50°C (all-liquid inclusions) to as high as 221.6°C. T_h values of fluid inclusions from fracture-filling quartz (Qf) and calcite (Cf) are generally higher than, and partly overlap those from quartz overgrowth (Fig. 9). Samples from the Trois-Pistoles area show T_h values significantly higher than other areas, reaching 285.2°C (Table 2 and Fig. 9). Fluid salinities are generally lower than 10 wt%, mainly between 2 and 8 wt% NaCl equivalent, although a few samples show salinities between 10 and 20 wt% NaCl equivalent (Table 2).

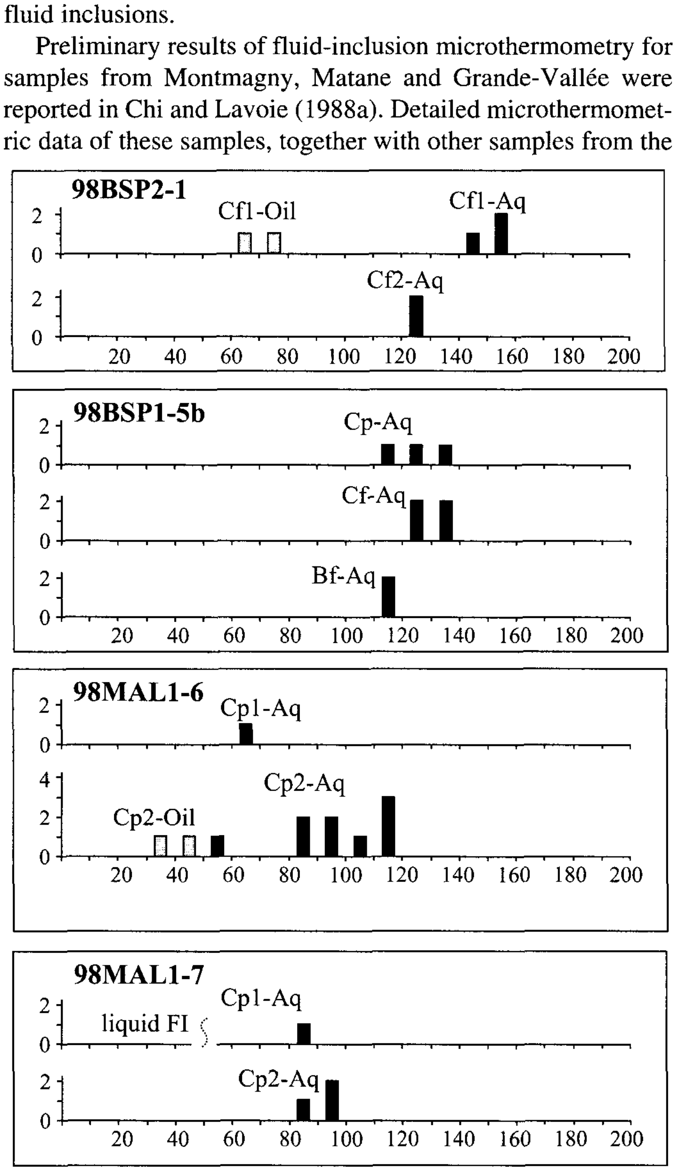

Fig. 4. Histograms of homogenization temperatures of fluid inclusions from diagenetic mineral phases from the Charlevoix area. Cp = pore-filling calcite; Cf = fracture-filling calcite; Bf = fracture-filling barite. The paragenetic sequences are described in the text and Table 1. Aq = aqueous inclusion; Oil = oil inclusion.

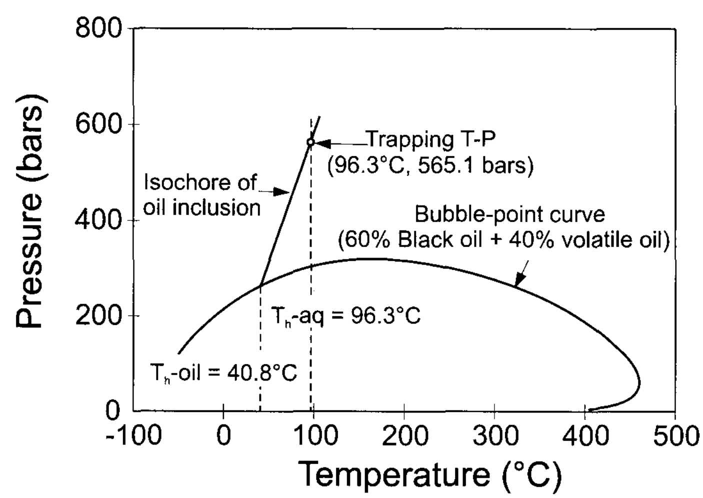

Fig. 5. Bubble-point curve and isochore of oil inclusions from calcite cement (Cp2) of sample 98MAL1-6, Charlevoix area. The trapping temperature is assumed to be equal to the homogenization temperature of aqueous inclusions, and the trapping pressure is estimated from the isochore at the trapping temperature. The bubble-point curve and isochore were constructed using the VTFLINC program of Calsep A/S, with the oil composition (API=40.6) being modeled by mixing 60% black oil (API= 34.3) and 40% volatile oil (API=50.1).

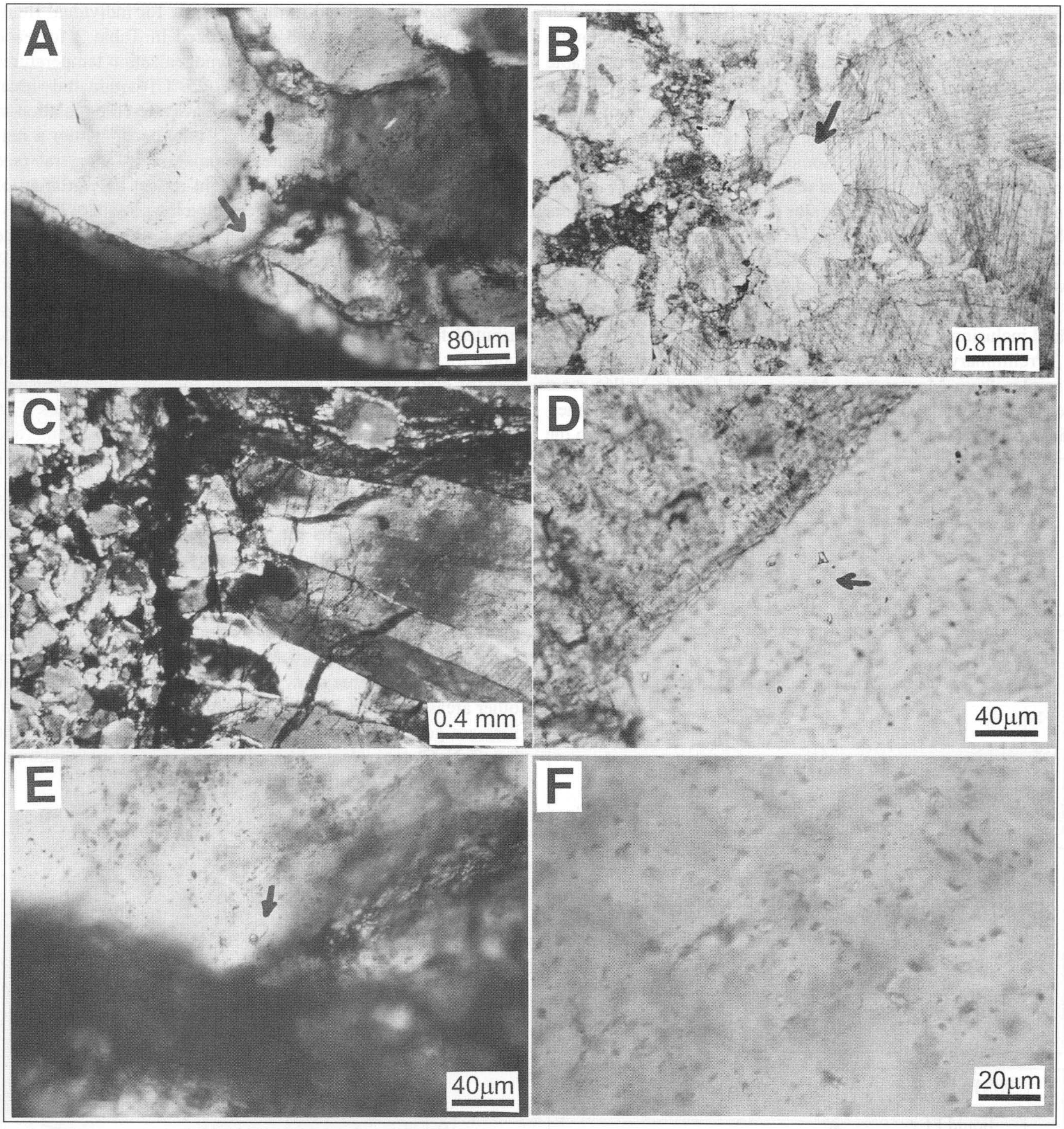

Fig. 6. (A) Quartz overgrowth (arrow) in the sandstone of the Kamouraska Formation, Matane, sample 97LKA-MT-e, crossed polarizer; **(B)** Nondeformed fracture-filling quartz (arrow) and calcite from the St-Roch Formation, St-Jean-Port-Joli, sample 98SJPJ1-2; **(C)** Fracture-filling quartz showing undulate extinction, from the Kamouraska Formation, Matane, sample 97LKA-MT-224, crossed polarizer; **(D)** A cluster of fluid inclusions (arrow) in a quartz crystal from a nondeformed quartz-calcite vein, sample 98SJPJ1-2; **(E)** An isolated fluid inclusion in a relatively nondeformed quartz crystal from a deformed quartz vein, sample 97LKA-MT-224; **(F)** Randomly distributed fluid inclusions in a relatively nondeformed quartz crystal from a deformed quartz vein, sample 97LKA-MT-224.

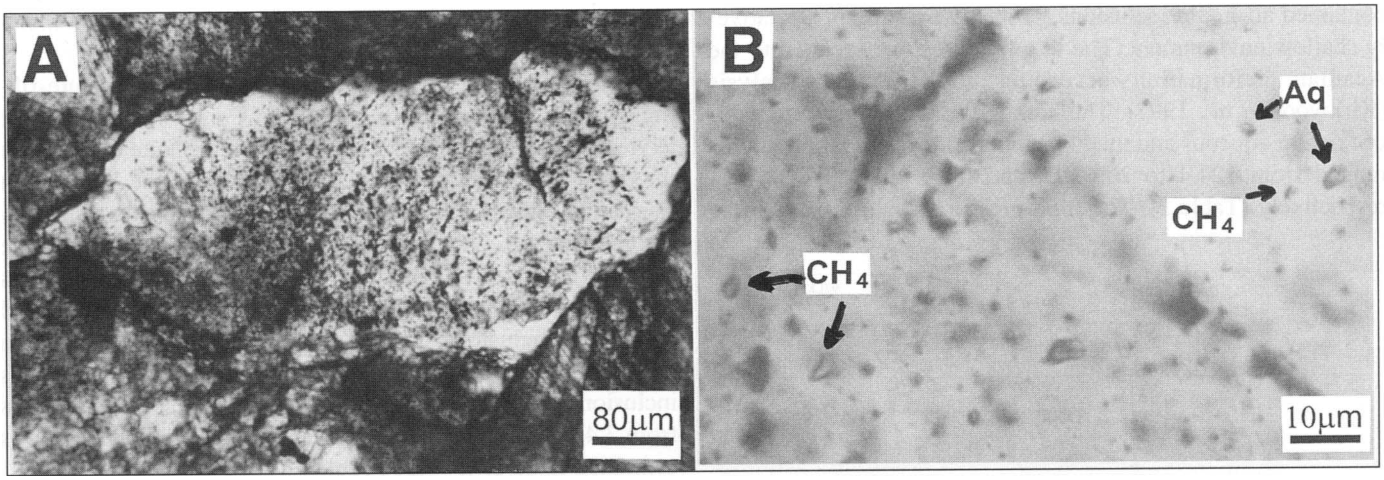

Fig. 7. (A) Randomly distributed fluid inclusions in a quartz crystal with a relatively clean rim. The quartz crystal occurs in a quartz-calcite vein cutting sandstone of the Kamouraska Formation. The vein has experienced certain deformation, but this particular crystal is relatively free of deformation. Sample 983P24-1. **(B)** Enlarged from A, near the edge of the quartz crystal, showing coexistence of methane and aqueous inclusions.

Methane inclusions were observed in many of the samples from the Humber Zone, mainly in fracture-filling quartz and calcite. A few samples contain methane inclusions in quartz overgrowth (Qp) and detrital quartz (Qd); in the latter case, methane inclusions occur as secondary inclusions (98SJPJ13-1, 983P6-1; Table 2 and Appendix). Hydrocarbon inclusions with T_h values between –43.9 and –76.4°C (Table 2) were found in fracture-filling quartz and calcite cutting the sandstone of the Kamouraska Formation in the Montmagny area (Chi and Lavoie, 1998a). These inclusions show very weak fluorescence (white), and are likely mainly composed of methane and other light hydrocarbons. Ettner *et al.* (1996) reported similar inclusions in the Bidjovagge gold-copper deposit in Norway and detected the presence of CH_4, C_2H_6, C_3H_8 and C_4H_{10} using the Raman microprobe and gas chromatography. A large number of oil inclusions, which are strongly fluorescent under UV light and show T_h values ranging from –20 to +130 (mode 55, Table 2), were reported for quartz veins cutting the Cambro-Ordovician rocks of the Humber Zone in the Quebec City area (Levine *et al.*, 1991).

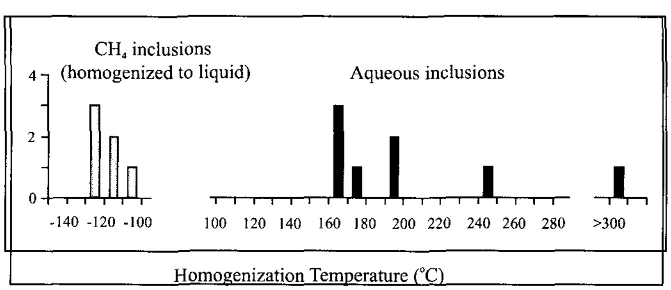

Fig. 8. Histogram of homogenization temperatures of methane and aqueous inclusions, which coexist and are randomly distributed in a crystal of fracture-filling quartz (Qf1). Sample 98IV11-1. The minimum of the Th spectrum of aqueous inclusions (160.2°C) is interpreted to represent the trapping temperature, with the higher part of the spectrum being attributed to heterogeneous trapping.

Fluid pressures were calculated from the isochores of the methane inclusions, with the trapping temperatures being equal to the homogenization temperatures of coexisting aqueous inclusions (Fig. 10). The calculated fluid pressures range from 162.6 to 2127.0 bars for the Humber Zone as a whole (Table 3). The two relatively low values (162.6 and 246.7 bars) were obtained from fracture-filling quartz that postdates major deformation (see Table 1). The rest of the data set, ranging from 731.7 to 2127.0 bars, was obtained from pore- or fracture-filling minerals that predate or overlap major deformation (Table 1). These latter values are significantly higher than those from the platform areas.

The $R_{O\ vi\text{-}eq}$ (%) values of organic matter in the host rocks corresponding to fluid-inclusion samples range from 1.0 to 4.02 for the Humber Zone (Table 2). The lowest values were from the Quebec City area (1.0 ~ 2.3) (Ogunyomi *et al.*, 1980). The highest values were obtained from the Matane (4.02) and Trois-Pistoles areas (2.89 ~ 3.65) (Table 2). The $R_{O\ vi\text{-}eq}$ (%) values of the St-Jean-Port-Joli area range from 1.95 to 2.97. No R_O values corresponding to the fluid-inclusion samples are available in the Montmagny and Grande-Vallée (Rivière Madeleine) areas, but according to the R_O values from the neighbouring strata (Table 2), they likely fall in the range from 2.65 to 2.85, and from 2.48 to 3.55, respectively.

The Gaspé Belt

Microthermometric studies of fluid inclusions from diagenetic mineral phases in the White Head and West Point formations and the Upper Gaspé Limestone were carried out previously (Kirkwood *et al.*, 1997; Savard *et al.*, 1997; Lavoie and Chi, 1997). The results for the areas where hydrocarbon fluid inclusions were observed are compiled in Table 2.

Abundant methane inclusions were observed in fracture-filling quartz (Qf2) cutting the White Head Formation in the St-Jean Anticline area. An earlier set of fracture-filling calcite contained all-liquid inclusions, probably forming in a relatively shallow environment. The late fractures were related to the Acadian deformation according to structural analysis (Kirkwood *et al.*, 1997). The homogenization temperatures of coexisting aqueous and methane inclusions in the late fractures ranged from 124.4 to 209.3°C, and from –92.1 to –93.1°C, respectively (Table 2). The fluid pressure was estimated to be

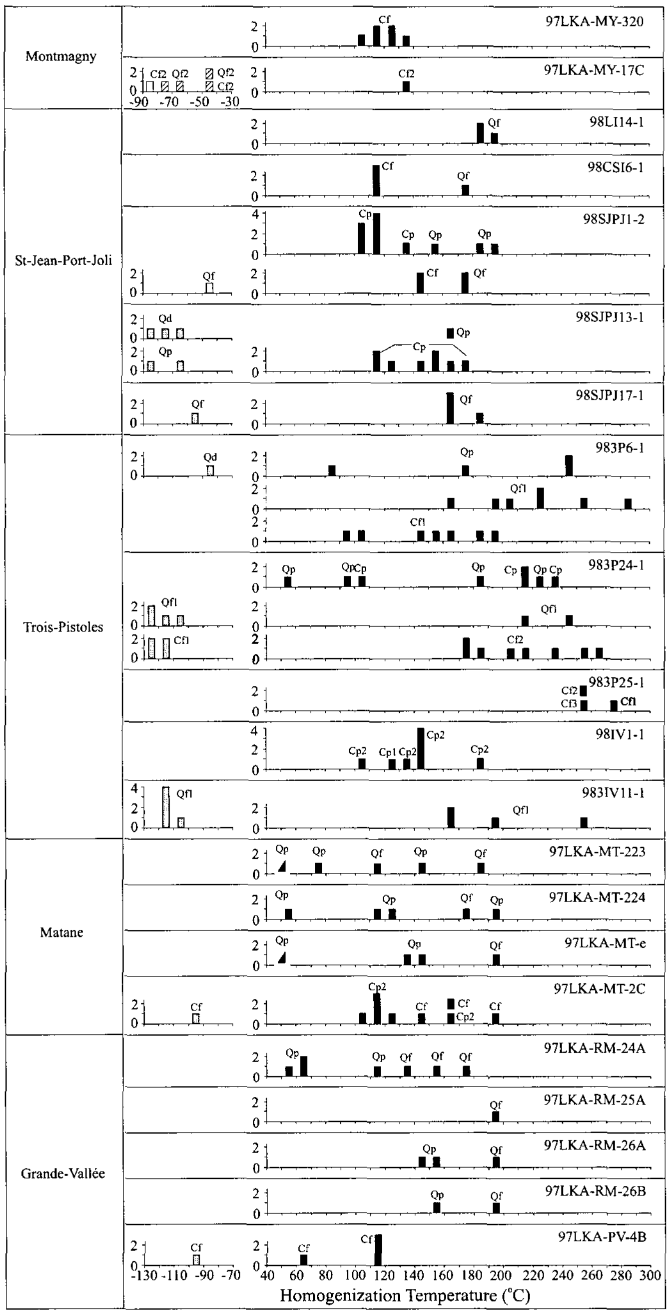

Fig. 9. Histograms of homogenization temperatures of hydrocarbon and aqueous inclusions from various diagenetic mineral phases in samples from the Humber Zone. Abbreviations of minerals are the same as in Table 1 and the Appendix. The pattern of diagonal lines represents methane + light hydrocarbons; white represents methane inclusions homogenized to vapour phase; gray represents methane inclusions homogenized to liquid phase, and black indicates aqueous inclusions (all-liquid inclusions are represented by triangles).

982.3 bars (Table 3). The salinities of the aqueous fluid inclusions is from 4.0 to 6.3 wt% NaCl equivalent.

Methane, oil and aqueous inclusions coexist in fracture-filling calcite and quartz cutting the West Point Formation in the Rivière Madeleine area. The fracture-filling calcite is similar to the latest pore-filling calcite cement found in the West Point Formation (Savard *et al.*, 1997). The oil inclusions are strongly fluorescent (greenish yellow) and show highly variable vapour/liquid ratios, probably resulting from heterogeneous trapping or leaking. No microthermometric data were obtained from these inclusions. The Th value of one methane inclusion is –89.6°C (homogenized to vapour). Coexisting aqueous inclusions have Th values from 70.3 to 126.7 and salinities from 3.4 to 10.0 wt% NaCl equivalent. The fluid pressure was estimated to be 134.4 bars (Table 3).

Abundant oil inclusions were observed in fracture-filling calcite cutting the Indian Cove Formation in the Rivière Mississippi area. This fracture-filling calcite was the latest during paragenesis (Lavoie and Chi, 1997). The oil inclusions show greenish white fluorescence, and a fluorescence spectrum characterized by an L_{max} value of 510 nm and a Q value of 0.121 (seven measurements). The API value was estimated to be 40.0. The T_h values of the oil inclusions range from 41.8 to 63.1°C, whereas coexisting aqueous inclusions contain only liquid at room temperature. The salinity value of one measured inclusion was 21.5 wt% NaCl equivalent. The fluid pressure must be higher than, but may not be too far from, the saturation pressure, which was calculated at 265.8 bars (Table 3).

The $R_{O\ vi\text{-}eq}$ (%) values of organic matter in the West Point and Indian Cove formations from the studied areas were 1.94 and 0.76 ~ 0.81, respectively (Bertrand, 1987). R_O data were unavailable for the White Head Formation in the St-Jean Anticline area, but according to data in neighbouring strata and areas (Bertrand, 1987), the samples studied for fluid inclusions likely have $R_{O\ vi\text{-}eq}$ (%) values higher than 2.5.

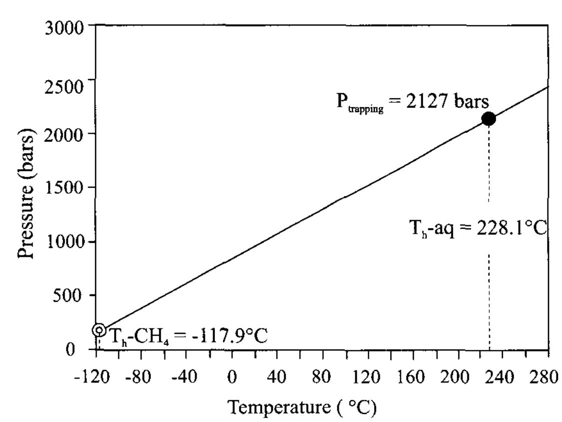

Fig. 10. Isochore of a methane inclusion that homogenizes into liquid phase at –117.9°C. A coexisting aqueous inclusion is assumed to be saturated with methane at entrapment, and its homogenization temperature (228.1°C) is equal to the trapping temperature. The trapping pressure is calculated to be 2127 bars. Sample 983P24-1, from fracture-filling quartz (Qf1).

Discussion and Conclusions

The data presented above indicate that regional-scale variation exists in the type of hydrocarbon fluid inclusions, homogenization temperatures and salinities of associated aqueous inclusions, fluid pressures and reflectance of organic matter in the host rocks. The characteristics of this variation and its implications on petroleum exploration are discussed in this section.

Figure 11 shows that the type of hydrocarbon fluid inclusion is broadly related to the tectonic zone. Oil inclusions occur in the St. Lawrence Platform (the Charlevoix area and Anticosti Island) and the Gaspé Belt (the Rivière Mississippi area), whereas methane inclusions are predominant in the Humber Zone. Within the Humber Zone, there is a trend of change in the type of hydrocarbon fluid inclusions from methane (St-Jean-Port-Joli area and northeastward) to methane + light hydrocarbons (Montmagny area) to oil (Quebec City area) from northeast to southwest. In the Gaspé Belt, there is apparently a trend of change from methane (White Head Formation) through methane + oil (West Point Formation) to oil inclusions (Indian Cove Formation) from lower to upper stratigraphic positions. The occurrence of oil inclusions is commonly associated with relatively low homogenization temperatures and high salinities of aqueous inclusions (Fig. 11).

In parallel with the variation in the type of hydrocarbon fluid inclusions, there is a systematic change in organic matter reflectance. $R_{O\ vi\text{-}eq}$ values are relatively low in the platform areas (Charlevoix and Anticosti Island) and high in the Humber Zone, although $R_{O\ vi\text{-}eq}$ of the platform successions may reach fairly high values to the southwest of the studied region (the Montreal area) and in the subsurface of the southern part of Anticosti Island (Héroux and Bertrand, 1991; Bertrand, 1990b). Within the Humber Zone, $R_{O\ vi\text{-}eq}$ values are the highest in the Matane area, slightly decrease toward the northeast (Grande-Vallée), and gradually decrease southwestward through Trois-Pistoles, St-Jean-Port-Joli, Montmagny to the Quebec City area. In the Gaspé Belt, $R_{O\ vi\text{-}eq}$ values apparently increase from upper to lower stratigraphic levels.

A positive correlation was observed between the reflectance of organic matter in the host rocks ($R_{O\ vi\text{-}eq}$) and the highest homogenization temperatures of aqueous fluid inclusions recorded in diagenetic minerals (Fig. 12). Oil inclusions mainly occur in the oil zone, whereas methane inclusions mainly occur in the dry gas and anchimetamorphism zones (Héroux *et al.*, 1979). The samples of the Romaine Formation from the NACP well on Anticosti Island and that from the Kamouraska Formation in the Montmagny area, which contain oil inclusions or methane + light hydrocarbon inclusions, were plotted on the figure with $R_{O\ vi\text{-}eq}$ values being approximated by neighbouring strata. These samples would probably fall in the condensate or dry gas zone (indicated by the horizontal arrows). The Cambrian-Ordovician rocks from the south shore of Quebec City, which contain oil inclusions but are not plotted in the diagram due to the lack of T_h data for aqueous inclusions, span from oil zone to the threshold between condensate and dry gas zones (Levine *et al.*, 1991; Ogunyomi *et al.*, 1980).

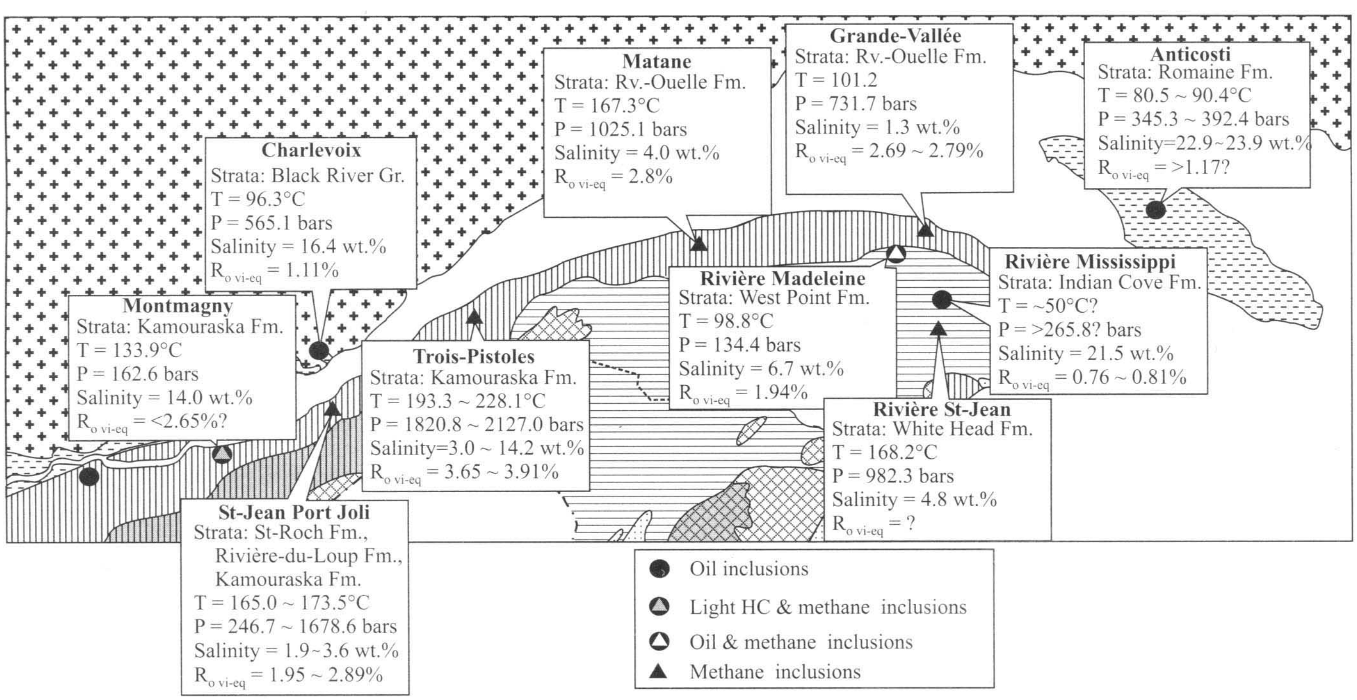

Fig. 11. Regional variation of temperature, pressure, and salinity of aqueous fluid inclusions associated with hydrocarbon fluid inclusions, as well as the reflectance values (standardized to vitrinite reflectance) of organic matter in the host rocks. Data of aqueous fluid inclusions that are not associated with hydrocarbon fluid inclusions are not shown in this figure.

The diagenetic minerals that host oil inclusions in this study are generally the latest in the paragenetic sequences. In the Charlevoix area, the pore- or fracture-filling calcite that contains oil inclusions shows the highest homogenization temperatures of aqueous inclusions and fairly high fluid pressure (565 bars), which possibly reflects the maximum burial conditions. In other cases, the oil inclusions appear to have been entrapped after maximum burial of the host rocks. The pore-filling calcite and barite from the NACP well on Anticosti Island, which host oil inclusions, show lower homogenization temperatures of aqueous inclusions than replacement and pore-filling dolomites that are paragenetically earlier (Table 2). In addition, the host rocks appear to have been subjected to thermal conditions (condensate zone; Bertrand, 1990b) higher than those indicated by fluid inclusions in the pore-filling calcite and barite. Therefore, the entrapment of oil inclusions likely took place after the maximum heating of the host rocks. Whether the oil was derived from the source rocks in the overlying Macasty Formation (Bertrand, 1990b) or from other source rocks is still an open question. In the Quebec City area, it has been demonstrated that oil inclusions hosted in quartz veins in the Cambrian-Ordovician nappes were entrapped after host rocks were heated beyond the oil window and postdated the emplacement of the nappes (Levine *et al.*, 1991). It was further proposed that strata underlying the nappes contained probable source rocks that were in the oil window, from which petroleum was derived and migrated into the overlying, overmatured rocks through fractures (Levine *et al.*, 1991). Further studies of the geochemical features of the oil inclusions and constraints on the timing need to be carried out in order to refine this model.

Although oil inclusions can occur in host rocks heated beyond the oil window, *i.e.* in the condensate zone, they were not found in rocks that have gone through the dry gas zone. In the Humber Zone, oil inclusions were only found in the Quebec City area, where the host rocks were mainly in the condensate zone. The Montmagny area, where hydrocarbon fluid inclusions contain light hydrocarbons apart from methane, is also characterized by relatively low thermal maturation of the host rocks. The major part of the Humber Zone was heated beyond the condensate zone, and only methane inclusions were found. The absence of oil inclusions in the dry gas zone rocks suggests that these rocks are farther from, thus less likely connected to, young source rocks than the less mature rocks.

Methane inclusions were entrapped at highly variable pressures. Methane inclusions indicating relatively high pressures (most of the Humber Zone) were probably entrapped before or during major deformation, which may have taken place at or near maximum burial. Those showing relatively low pressures were probably entrapped after major deformation. The existence of methane inclusions in different fracture-filling minerals within an area with very different pressures (*e.g.* St-Jean-Port-Joli) suggests multiple-stage migration of methane. Some methane inclusions may have been entrapped at maximum burial of the host rock, others may have been entrapped when the host rocks were thrust to shallower depths. The absolute age of the fracture-filling minerals needs to be determined in order to know the timing of hydrocarbon migration events.

Based on the data summarized in this paper, we suggest that part of the St. Lawrence Platform (especially the Anticosti Island and surrounding areas) and the Gaspé Belt have the thermal conditions for the formation of oil reservoirs, as testified

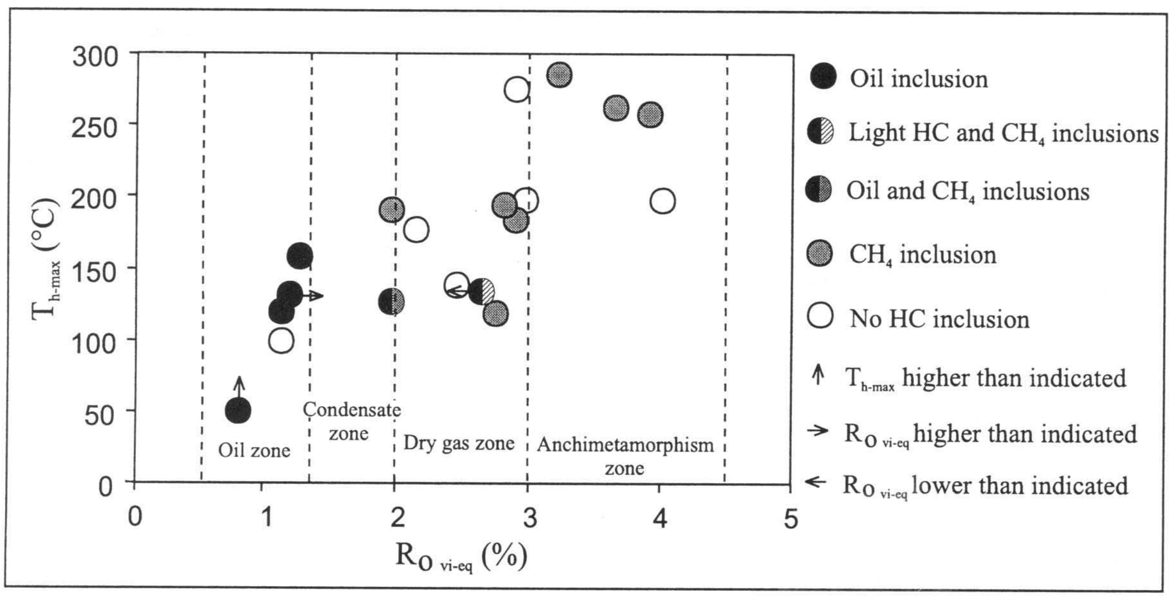

Fig. 12. A positive correlation between the maximum homogenization temperatures of fluid inclusions and the $R_{O\ vi\text{-}eq}$ values of organic matter in the host rocks (from Table 2). Organic maturation zone division is adopted from Héroux *et al.* (1979). Note oil inclusions occur mainly in the oil zone, whereas methane inclusions mainly in the dry gas and anchimetamorphism zones. The samples of the Romaine Formation from the NACP well on Anticosti Island and that from the Kamouraska Formation in the Montmagny area, which contain oil or methane + light hydrocarbon inclusions but lack corresponding R_O values, probably fall in the condensate or dry gas zone (indicated by the horizontal arrow).

by the presence of oil inclusions. The major part of the Humber Zone has been heated to and beyond the dry gas zone, and any oil reservoirs that could have formed before maximum burial would have been destroyed. However, the possibility of natural gas reservoirs forming exists, as testified by the ubiquitous occurrence of methane inclusions in various fracture-filling minerals. Some sectors of the Humber Zone, which have not been heated beyond the condensate zone, *e.g.* near the Quebec City area, may have been thrust over, after maximum burial, or overlain by, rocks that were within the oil window. These sectors cannot be excluded from the possibility of forming oil reservoirs, provided other conditions are satisfied.

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Appendix: Fluid-inclusion microthermometric data

Sample	Host mineral*	Occurrence	Size (μm)	Type	T_{m-ice}(°C) Range	T_{m-ice}(°C) Mean (n)	Salinity (wt.% NaCl equiv.) Range	Salinity (wt.% NaCl equiv.) Mean (n)	T_h (°C) Range	T_h (°C) Mean (n)
No.: 98BSP2-1	Cf1	Random	4 ~ 5	Oil					72.9 ~ 79.5	76.2 (2)
Fm.: Moulin River		Random	8	Aq	-10.9	-10.9 (1)	14.9	14.9 (1)	152.7	152.7 (1)
Litho.: Limestone		Random	5	Oil					67.1	67.1 (1)
Area: Baie St-Paul			5	Aq	-11.1	-11.1 (1)	15.1	15.1 (1)	157.8	157.8 (1)
UTMx: 390050 (19)		Random	6	Aq					142.3	142.3 (1)
UTMy: 5253300	Cf2	Isolated	13	Aq	-0.2	-0.2 (1)	0.4	0.4 (1)	126.0	126.0 (1)
		Isolated	8	Aq					129.3	129.3 (1)
No.: 98BSP1-5b	Cp	Scattered	6 ~ 10	Aq	-1.4	-1.4 (1)	2.4	2.4 (1)	101.5 ~ 116.2	110.6 (3)
Fm.: St-Irénée		Scattered	6 ~ 7	Aq	-0.8 ~ -1.2	-1.0 (2)	1.4 ~ 2.1	1.8 (2)	111.5 ~ 130.1	121.1 (4)
Litho.: Sandstone		Isolated	9	Aq	-0.5	-0.5 (1)	0.9	0.9 (1)	137.6	137.6 (1)
Area: Baie St-Paul	Cf	Cluster	6 ~ 10	Aq	-2.1	-2.1 (1)	3.5	3.5 (1)	134.8 ~ 139.1	137.0 (2)
UTMx: 402200 (19)		Cluster	6 ~ 9	Aq	-1.9 ~ -2.0	-2.0 (2)	3.2 ~ 3.4	3.3 (2)	123.0 ~ 127.6	125.4 (4)
UTMy: 5257750		Isolated	6	Aq					127.9	127.9 (1)
		Isolated	10	Aq	-2.0	-2.0 (1)	3.4	3.4 (1)	131.5	131.5 (1)
	Bf	Random	6 ~ 10	Aq	-1.7	-1.7 (1)	2.9	2.9 (1)	101.0 ~ 133.0	117.8 (5)
		Random	4 ~ 8	Aq	-1.6 ~ -1.8	-1.7 (3)	2.7 ~ 3.0	2.8 (2)	107.8 ~ 123.5	116.4 (5)
No.: 98MAL1-6	Cp1	Cluster	5 ~ 6	Aq	-2.1 ~ -2.8	-2.5 (2)	3.5 ~ 4.6	4.1 (2)	65.4 ~ 69.7	67.5 (4)
Fm.: Black River	Cp2	Cluster	5 ~ 6	Aq	-26.3 ~ -26.8	-26.6 (2)	26.0 ~ 26.5	26.3 (2)	115.6 ~ 123.2	119.4 (2)
Litho.: Limestone		Cluster	7 ~ 8	Aq					109.2 ~ 110.9	110.1 (2)
Area: La Malbaie		Cluster	5 ~ 11	Aq	-21.5 ~ -22.4	-22.1 (3)	23.4 ~ 23.9	23.7 (3)	52.4 ~ 58.5	55.6 (3)
UTMx: 417817 (19)		Cluster	6 ~ 12	Oil					33.8 ~ 54.0	42.0 (8)
UTMy: 5279616		Cluster	6 ~ 11	Aq	-12.7 ~ -13.2	-13.0 (2)	16.7 ~ 17.1	16.9 (2)	109.2 ~ 122.5	114.3 (3)
		Cluster	8 ~ 12	Aq	-4.6	-4.6 (1)	7.3	7.3 (1)	94.7 ~ 98.5	96.6 (2)
			6	Oil					39.6	39.6 (1)
		Isolated	7	Aq					86.8	86.8 (1)
		Isolated	8	Aq	-28.1	-28.1 (1)	26.5	26.5 (1)	103.0	103.0 (1)
		Isolated	12	Aq	-4.4	-4.4 (1)	7.0	7.0 (1)	93.4	93.4 (1)
		Isolated	7	Aq	-4.6	-4.6 (1)	7.3	7.3 (1)	87.5	87.5 (1)
No.: 98MAL1-7	Cp1	Random	7 ~ 8	Aq					all liquid	all liquid (2)
Fm.: Deschambault			8	CH_4					-74.2 (V)	-74.2 (V) (1)
Litho.: Calcarenite		Random	5	Aq	-4.6	-4.6 (1)	7.3	7.3 (1)	all liquid	all liquid (1)
Area: La Malbaie		Random	7	Aq	-4.0	-4.0 (1)	6.4	6.4 (1)	80.3	80.3 (1)
UTMx: 417817 (19)	Cp2	Cluster	9 ~ 10	Aq	-10.8 ~ -20.1	-15.5 (2)	14.8 ~ 22.4	18.6 (2)	85.1 ~ 87.1	86.1 (2)
UTMy: 5279616		Cluster	5 ~ 13	Aq	-5.0 ~ -5.2	-5.1 (3)	7.9 ~ 8.1	8.0 (3)	87.3 ~ 106.8	98.4 (8)
		Isolated	14	Aq					91.2	91.2 (1)

Appendix: Continued

Sample	Host mineral*	Occurrence	Size (μm)	Type	$T_{m\text{-}ice}$(°C)		Salinity (wt.% NaCl equiv.)		T_h (°C)	
					Range	Mean (n)	Range	Mean (n)	Range	Mean (n)
No.: 97LKA-MY-320	Cf	Cluster	7 ~ 10	Aq	-16.8	-16.8 (1)	20.1	20.1 (1)	123.8 ~ 142.1	131.4 (3)
Fm.: Kamouraska		Cluster	7 ~ 9	Aq	-17.4	-17.4 (1)	20.5	20.5 (1)	112.3 ~ 116.4	114.4 (2)
Litho.: Sandstone		Cluster	5 ~ 6	Aq	-13.7 ~ -18.2	-16.0 (2)	17.5 ~ 21.1	19.3 (2)	117.4 ~ 142.7	127.5 (3)
Area: Montmagny		Isolated	8	Aq	-16.2	-16.2 (1)	19.6	19.6 (1)	116.6	116.6 (1)
UTMx: 380932 (19)		Isolated	5	Aq					104.2	104.2 (1)
UTMy: 5197921		Isolated	6	Aq					129.4	129.4 (1)
No.: 97LKA-MY-17C	Qf2	Random	6 ~ 7	Ligh HC					-36.8 ~ -62.2	-49.5 (2)
Fm.: Kamouraska		Random	3 ~ 6	Ligh HC					-58.9 ~ -69.9	-65.2 (5)
Litho.: Sandstone	Cf2	Random	14	CH_4					-88.4 (V)	-88.4 (V) (1)
Area: Montmagny		Random	4 ~ 15	Ligh HC					-56.9 ~ -82.4	-74.0 (6)
UTMx: 366266 (19)		Random	6 ~ 12	Aq	-9.6 ~ -10.5	-10.0 (3)	13.6 ~ 14.5	14.0 (3)	116.8 ~ 142.5	133.9 (5)
UTMy: 5187126			6 ~ 11	Ligh HC					-32.4 ~ -54.2	-43.9 (4)
No.: 98LI14-1	Qf	Random	8 ~ 13	Aq	-1.4 ~ -1.8	-1.6 (3)	2.4 ~ 3.0	2.7 (3)	151.0 ~ 250.3	197.4 (7)
Fm.: Rivière-du-Loup		Random	6 ~ 8	Aq	-1.6	-1.6 (1)	2.7	2.7 (1)	153.5 ~ 209.4	180.1 (6)
Litho.: Sandstone		Random	4 ~ 11	Aq	-1.7 ~ -1.7	-1.7 (2)	2.9 ~ 2.9	2.9 (2)	164.0 ~ 240.1	183.1 (10)
Area: Les Ilets										
UTMx: 401034 (19)										
UTMy: 5212112										
No.: 98CSI6-1	Cf	Cluster	5 ~ 11	Aq	-1.3 ~ -1.4	-1.4 (2)	2.2 ~ 2.4	2.3 (2)	106.6 ~ 130.7	114.9 (4)
Fm.: St-Roch		Cluster	7 ~ 12	Aq	-2.4	-2.4 (1)	4.0	4.0 (1)	109.6 ~ 123.6	114.4 (3)
Litho.: Sandstone		Cluster	5 ~ 6	Aq	-2.9	-2.9 (1)	4.8	4.8 (1)	107.0 ~ 115.2	110.6 (4)
Area: Cap St-Ignace	Qf	Random	5 ~ 9	Aq	-2.2 ~ -4.6	-3.0 (6)	3.7 ~ 7.3	5.0 (6)	147.1 ~ 208.0	176.0 (13)
UTMx: 391531 (19)										
UTMy: 5209833										
No.: 98SJPJ1-2	Qp	Scattered	4 ~ 6	Aq	-1.4 ~ -1.7	-1.6 (2)	2.4 ~ 2.9	2.7 (2)	137.7 ~ 181.6	153.0 (5)
Fm.: St-Roch		Cluster	4 ~ 9	Aq	-1.6 ~ -1.7	-1.7 (2)	2.7 ~ 2.9	2.8 (2)	167.8 ~ 195.2	181.2 (6)
Litho.: Sandstone		Cluster	5 ~ 7	Aq	-1.9	-1.9 (1)	3.2	3.2 (1)	130.7 ~ 198.6	190.4 (4)
Area: St-Jean-Port-Joli	Cp	Isolated	11	Aq	-1.6	-1.6 (1)	2.7	2.7 (1)	110.1	110.1 (1)
UTMx: 409200 (19)		Cluster	6 ~ 6	Aq	-1.7	-1.7 (1)	2.9	2.9 (1)	106.1 ~ 107.7	106.9 (2)
UTMy: 5234450		Cluster	7 ~ 8	Aq	-1.8 ~ -1.9	-1.9 (2)	3.0 ~ 3.2	3.1 (1)	101.6 ~ 110.8	105.7 (3)
		Cluster	6 ~ 7	Aq					100.5 ~ 113.3	106.9 (2)
		Cluster	5 ~ 9	Aq	-1.6	-1.6 (1)	2.7	2.7 (1)	111.0 ~ 122.8	117.4 (4)
		Cluster	6 ~ 8	Aq	-1.6 ~ -1.7	-1.7 (2)	2.7 ~ 2.9	2.8 (2)	113.2 ~ 118.7	115.0 (3)
		Scattered	7 ~ 10	Aq	-1.9	-1.9 (1)	3.2	3.2 (1)	91.9 ~ 127.1	111.2 (5)
		Scattered	5 ~ 11	Aq	-1.7 ~ -1.9	-1.8 (2)	2.9 ~ 3.2	3.1 (2)	115.5 ~ 141.8	130.9 (5)
	Qf	Cluster	6 ~ 9	Aq	-1.5 ~ -1.7	-1.6 (3)	2.6 ~ 2.9	2.7 (3)	163.2 ~ 186.1	173.4 (5)
			6 ~ 12	CH_4					-82.7 ~ -86.5 (V)	-84.5 (V) (3)
		Random	4 ~ 7	Aq	-1.0 ~ -1.7	-1.3 (5)	1.7 ~ 2.9	2.2 (5)	145.2 ~ 210.1	173.6 (12)
	Cf	Cluster	5 ~ 9	Aq	-1.0 ~ -1.2	-1.1 (4)	1.7 ~ 2.1	1.9 (4)	136.1 ~ 153.9	148.8 (5)
		Cluster	6 ~ 9	Aq	-1.0 ~ -1.1	-1.0 (3)	1.7 ~ 1.9	1.8 (3)	138.4 ~ 158.0	148.7 (4)
No.: 98SJPJ13-1	Qd	Fracture	7 ~ 8	CH_4					-113.1 ~ -129.2	-120.9 (5)
Fm.: Rivière-du-Loup		Fracture	7 ~ 9	CH_4					-98.9 ~ -106.8	-102.5 (4)
Litho.: Conglomerate		Fracture	7 ~ 10	CH_4					-112.3 ~ -120.1	-115.4 (3)
Area: St-Jean-Port-Joli	Qp	Random	4 ~ 10	CH_4					-103.1 ~ -114.5	-108.1 (7)
UTMx: 414462 (19)		Cluster	5 ~ 8	CH_4					-113.1 ~ -132.6	-121.7 (8)
UTMy: 5227261		Isolated	3	Aq					165.0	165.0 (1)
	Cp	Cluster	6 ~ 8	Aq	-1.3 ~ -1.4	-1.4 (2)	2.2 ~ 2.4	2.3 (2)	132.4 ~ 147.4	141.5 (3)
		Isolated	7	Aq	-1.3	-1.3 (1)	2.2	2.2 (1)	129.1	129.1 (1)
		Cluster	5	Aq					119.4	119.4 (1)
		Cluster	5	Aq	-1.0	-1.0 (1)	1.7	1.7 (1)	150.8	150.8 (1)
		Cluster	9	Aq	-0.9	-0.9 (1)	1.6	1.6 (1)	151.6	151.6 (1)
		Cluster	5	Aq					165.9	165.9 (1)
		Isolated	13	Aq	-1.0	-1.0 (1)	1.7	1.7 (1)	173.1	173.1 (1)
		Scattered	4 ~ 6	Aq	-1.1	-1.1 (1)	1.9	1.9 (1)	104.7 ~ 132.0	117.9 (3)
No.: 98SJPJ17-1	Qf	Cluster	6 ~ 8	Aq	-2.0 ~ -2.1	-2.1 (2)	3.4 ~ 3.5	3.5 (2)	159.2 ~ 171.9	164.0 (3)
Fm.: Kamouraska		Cluster	4 ~ 5	Aq	-2.2	-2.2 (1)	3.7	3.7 (1)	171.1 ~ 195.6	183.3 (3)
Litho.: Sandstone		Cluster	5 ~ 10	Aq	-2.0 ~ -2.2	-2.1 (2)	3.4 ~ 3.7	3.6 (2)	140.8 ~ 206.2	160.1 (6)
Area: St-Jean-Port-Joli		Cluster	6 ~ 9	Aq	-1.9 ~ -2.1	-2.0 (4)	3.2 ~ 3.5	3.4 (4)	163.9 ~ 239.2	163.9 (9)**
UTMx: 418995 (19)			4 ~ 12	CH_4					-89.5 ~ -95.7	-92.1 (8)
UTMy: 5222125										
No.: 983P6-1	Qd	Fracture	4 ~ 10	CH_4					-83.6 ~ -98.6	-89.4 (3)
Fm.: Kamouraska	Qp	Isolated	6	Aq	-3.6	-3.6 (1)	5.8	5.8 (1)	245.0	245.0 (1)
Litho.: Sandstone		Isolated	5	Aq	-3.8	-3.8 (1)	6.1	6.1 (1)	249.8	249.8 (1)
Area: Trois-Pistoles		Isolated	4	Aq					175.5	175.5 (1)
UTMx: 489099 (19)		Isolated	6	Aq	-3.1	-3.1 (1)	5.1	5.1 (1)	87.6	87.6 (1)
UTMy: 5327768	Qf1	Cluster	5 ~ 12	Aq	-3.7 ~ -3.9	-3.8 (3)	6.0 ~ 6.3	6.2 (3)	212.7 ~ 242.3	229.3 (6)
		Cluster	5 ~ 10	Aq	-4.0 ~ -4.3	-4.2 (4)	6.4 ~ 6.9	6.7 (4)	221.7 ~ 244.0	229.3 (9)
		Cluster	7 ~ 12	Aq	-3.8 ~ -4.0	-3.9 (2)	6.1 ~ 6.4	6.3 (2)	280.2 ~ 290.2	285.2 (2)
		Cluster	9 ~ 9	Aq	-3.3	-3.3 (1)	5.4	5.4 (1)	250.3 ~ 250.9	250.6 (2)
		Cluster	8 ~ 10	Aq	-4.2 ~ -4.4	-4.3 (2)	6.7 ~ 7.0	6.9 (2)	219.0 ~ 241.1	205.2 (4)
		Isolated	8	Aq	-3.8	-3.8 (1)	6.1	6.1 (1)	163.9	163.9 (1)
		Isolated	5	Aq	-4.4	-4.4 (1)	7.0	7.0 (1)	190.7	190.7 (1)

Appendix: Continued

Sample	Host mineral*	Occurrence	Size (µm)	Type	$T_{m\text{-}ice}$(°C) Range	Mean (n)	Salinity (wt.% NaCl equiv.) Range	Mean (n)	T_h (°C) Range	Mean (n)
No.: 983P6-1	Cf1	Scattered	6 ~ 12	Aq	-2.9 ~ -3.5	-3.2 (2)	4.8 ~ 5.7	5.3 (2)	82.4 ~ 141.9	100.7 (4)
Fm.: Kamouraska		Cluster	8 ~ 15	Aq	-3.6 ~ -3.8	-3.7 (2)	5.8 ~ 6.1	6.0 (2)	143.8 ~ 152.9	147.4 (4)
Litho.: Sandstone		Cluster	10 ~ 10	Aq	-3.4	-3.4 (1)	5.5	5.5 (1)	179.7 ~ 189.5	184.6 (2)
Area: Trois-Pistoles		Cluster	6 ~ 11	Aq	-3.8 ~ -3.8	-3.8 (3)	6.1 ~ 6.1	6.1 (3)	156.6 ~ 168.0	163.3 (4)
UTMx: 489099 (19)		Isolated	11	Aq	-3.1	-3.1 (1)	5.1	5.1 (1)	158.6	158.6 (1)
UTMy: 5327768		Isolated	7	Aq	-3.1	-3.1 (1)	5.1	5.1 (1)	92.6	92.6 (1)
		Isolated	9	Aq					191.5	191.5 (1)
No.: 983P24-1	Qp	Isolated	3	Aq					57.8	57.8 (1)
Fm.: Kamouraska		Isolated	5	Aq					98.7	98.7 (1)
Litho.: Sandstone		Isolated	5	Aq	-5.9	-5.9 (1)	9.1	9.1 (1)	182.9	182.9 (1)
Area: Trois-Pistoles		Cluster	3 ~ 3	Aq					214.4 ~ 228.8	221.6 (2)
UTMx: 485486 (19)	Cp	Isolated	9	Aq					107.5	107.5 (1)
UTMy: 5326115		Isolated	10	Aq	-6.8	-6.8 (1)	10.3	10.3 (1)	211.6	211.6 (1)
		Isolated	5	Aq	-12.2	-12.2 (1)	16.2	16.2 (1)	218.6	218.6 (1)
		Isolated	7	Aq	-12.8	-12.8 (1)	16.7	16.7 (1)	234.2	234.2 (1)
	Qf1	Random	4 ~ 6	CH_4					-118.0 ~ -125.6	-121.6 (6)
		Random	6 ~ 9	CH_4					-123.5 ~ -130.7	-127.0 (6)
		Random	3 ~ 8	Aq	-10.2 ~ -11.2	-10.7 (2)	14.2 ~ 15.2	14.7 (2)	240.0 ~ 349.6	240.0 (6)**
			5 ~ 6	CH_4					-104.3 ~ -109.5	-106.9 (2)
		Cluster	3 ~ 6	Aq	-9.6	-9.6 (1)	13.6	13.6 (1)	198.8 ~ 228.7	215.5 (4)
			6 ~ 7	CH_4					-114.8 ~ -117.0	-115.9 (2)
	Cf1	Cluster	3 ~ 6	CH_4					-116.5 ~ -124.3	-120.4 (3)
		Isolated	6	CH_4					-115.9	-115.9 (1)
		Isolated	5	CH_4					-122.1	-122.1 (1)
		Random	4 ~ 6	CH_4					-115.2 ~ -123.6	-119.4 (2)
	Cf2	Scattered	9 ~ 12	Aq					170.2 ~ 195.8	183.0 (2)
		Isolated	8	Aq					174.1	174.1 (1)
		Isolated	8	Aq	-4.0	-4.0 (1)	6.4	6.4 (1)	179.5	179.5 (1)
		Isolated	7	Aq					202.0	202.0 (1)
		Isolated	12	Aq	-5.4	-5.4 (1)	8.4	8.4 (1)	232.1	232.1 (1)
		Isolated	12	Aq	-5.2	-5.2 (1)	8.1	8.1 (1)	261.3	261.3 (1)
		Isolated	6	Aq					212.2	212.2 (1)
		Isolated	8	Aq					257.0	257.0 (1)
No.: 983P25-1	Cf1	Cluster	5 ~ 10	Aq	-5.2	-5.2 (1)	8.1	8.1 (1)	260.2 ~ 289.2	274.7 (2)
Fm.: Rivière-Ouelle	Cf2	Cluster	7 ~ 12	Aq	-4.2 ~ -4.8	-4.4 (3)	6.7 ~ 7.6	7.1 (3)	250.2 ~ 266.7	257.9 (5)
Litho.: Limestone	Cf3	Scattered	6 ~ 10	Aq	-4.0 ~ -5.3	-4.8 (3)	6.4 ~ 8.3	7.6 (3)	234.3 ~ 284.0	257.6 (8)
Area: Trois-Pistoles										
UTMx: 487132 (19)										
UTMy: 5325130										
No.: 98IV1-1	Cp1	Random	4 ~ 6	Aq	-2.0 ~ -2.9	-2.4 (4)	3.4 ~ 4.8	4.1 (4)	110.9 ~ 135.7	124.6 (8)
Fm.: Rivière-Ouelle	Cp2	Cluster	5 ~ 7	Aq	-3.4 ~ -3.5	-3.5 (2)	5.5 ~ 5.7	5.6 (2)	134.6 ~ 151.7	143.2 (2)
Litho.: Grainstone		Isolated	5	Aq					141.9	141.9 (1)
Area: Ile-Verte		Isolated	7	Aq	-5.6	-5.6 (1)	8.7	8.7 (1)	107.6	107.6 (1)
UTMx: 477439 (19)		Cluster	3 ~ 8	Aq	-2.7	-2.7 (1)	4.5	4.5 (1)	125.7 ~ 141.3	134.2 (3)
UTMy: 5315584		Scattered	5 ~ 8	Aq	-5.9 ~ -6.0	-6.0 (2)	9.1 ~ 9.2	9.2 (2)	172.2 ~ 190.9	180.9 (5)
		Isolated	12	Aq	-7.2	-7.2 (1)	10.8	10.8 (1)	140.2	140.2 (1)
		Isolated	5	Aq					146.7	146.7 (1)
No.: 98IV11-1	Qf1	Random	6 ~ 7	Aq					257.0 ~ 295.3	257.0 (2)**
Fm.: Kamouraska			7 ~ 12	CH_4					-110.4 ~ -125.3	-119.7 (4)
Litho.: Sandstone		Isolated	6	CH_4					-112.5	-112.5 (1)
Area: Ile-Verte		Isolated	7	CH_4					-106.9	-106.9 (1)
UTMx: 483063 (19)		Isolated	5	Aq	-1.7	-1.7 (1)	2.9	2.9 (1)	165.8	165.8 (1)
UTMy: 5310590		Isolated	5	Aq	-1.7	-1.7 (1)	2.9	2.9 (1)	190.2	190.2 (1)
		Random	4 ~ 11	Aq	-1.9 ~ -1.9	-1.9 (2)	3.2 ~ 3.2	3.2 (2)	162.8 ~ 247.9	160.2 (7)**
			4 ~ 6	CH_4					-105.1 ~ -127.0	-117.8 (6)
		Random	5 ~ 8	CH_4					-111.0 ~ -123.3	-116.8 (3)
No.: 97LKA-MT-223	Qp	Cluster	3	Aq					all liquid	all liquid (1)
Fm.: Kamouraska		Cluster	3	Aq					141.7	141.7 (1)
Litho.: Sandstone	Qf	Random	6	Aq					71.4	71.4 (1)
Area: Matane		Random	5	Aq					116.4	116.4 (1)
UTMx: 610853 (19)		Cluster	4 ~ 8	Aq	-3.7 ~ -4.2	-4.0 (2)	6.0 ~ 6.7	6.4 (2)	156.2 ~ 204.6	184.1 (6)
UTMy: 5395271										
No.: 97LKA-MT-224	Qp	Cluster	6	Aq	-1.2	-1.2 (1)	2.1	2.1 (1)	194.0	194.0 (1)
Fm.: Kamouraska		Isolated	4	Aq					54.4	54.4 (1)
Litho.: Sandstone		Isolated	4	Aq					126.8	126.8 (1)
Area: Matane		Isolated	3	Aq					110.7	110.7 (1)
UTMx: 611067 (19)	Qf	Random	5 ~ 14	Aq	-1.2 ~ -1.3	-1.2 (3)	2.1 ~ 2.2	2.1 (3)	131.4 ~ 233.1	171.0 (9)
UTMy: 5395439										

Appendix: Continued

Sample	Host mineral*	Occurrence	Size (μm)	Type	T_{m-ice}(°C) Range	Mean (n)	Salinity (wt.% NaCl equiv.) Range	Mean (n)	T_h (°C) Range	Mean (n)
No.: 97LKA-MT-e	Qp	Cluster	4 ~ 4	Aq					all liquid	all liquid (2)
Fm.: Kamouraska		Isolated	3	Aq					138.7	138.7 (1)
Litho.: Sandstone		Isolated	4	Aq					148.0	148.0 (1)
Area: Matane	Qf	Random	5 ~ 12	Aq	-1.4 ~ -1.8	-1.6 (4)	2.4 ~ 3.0	2.7 (4)	163.8 ~ 243.6	197.4 (12)
UTMx: 611067 (19)										
UTMy: 5395439										
No.: 97LKA-MT-2C	Cp2	Cluster	7	Aq	-10.0	-10.0 (1)	14.0	14.0 (1)	123.9	123.9 (1)
Fm.: Rivière-Ouelle		Cluster	8	Aq	-8.0	-8.0 (1)	11.7	11.7 (1)	112.6	112.6 (1)
Litho.: Limestone		Cluster	4 ~ 9	Aq	-3.2 ~ -3.6	-3.4 (2)	5.2 ~ 5.8	5.5 (2)	104.9 ~ 126.3	117.1 (4)
Area: Matane		Cluster	5 ~ 8	Aq	-8.2 ~ -8.6	-8.3 (3)	12.0 ~12.4	12.1 (3)	94.1 ~ 108.7	102.4 (3)
UTMx: 607650 (19)		Cluster	9 ~ 10	Aq	-7.2 ~ -7.4	-7.3 (2)	10.8 ~ 11.0	10.9 (2)	106.8 ~ 118.0	112.4 (2)
UTMy: 5408480		Isolated	9	Aq	-1.6	-1.6 (1)	2.7	2.7 (1)	168.1	168.1 (1)
	Cf	Cluster	13	Aq	-2.1	-2.1 (1)	3.5	3.5 (1)	145.1	145.1 (1)
		Isolated	7	Aq	-1.9	-1.9 (1)	3.2	3.2 (1)	193.7	193.7 (1)
		Isolated	10	Aq	-2.9	-2.9 (1)	4.8	4.8 (1)	163.0	163.0 (1)
		Random	4 ~ 4	CH_4					-90.4 ~ -97.5	-94.0 (2)
No.: 97LKA-RM-24A	Qp	Isolated	3	Aq					64.7	64.7 (1)
Fm.: Kamouraska		Isolated	4	Aq					60.8	60.8 (1)
Litho.: Sandstone		Isolated	5	Aq					58.3	58.3 (1)
Area: Rv. Madeleine		Isolated	12	Aq	-1.1	-1.1 (1)	1.9	1.9 (1)	117.3	117.3 (1)
UTMx: 327536 (20)	Qf	Cluster	12 ~ 14	Aq					129.8 ~ 147.2	138.5 (2)
UTMy: 5443104		Cluster	6 ~ 15	Aq	-1.3	-1.3 (1)	2.2	2.2 (1)	147.3 ~ 155.8	151.6 (2)
		Cluster	8 ~ 16	Aq	-1.4 ~ -2.1	-1.8 (4)	2.4 ~ 3.5	3.1 (4)	149.1 ~ 216.6	178.8 (6)
No.: 97LKA-RM-25A	Qf	Random	7 ~ 15	Aq	-4.0 ~ -4.6	-4.3 (3)	6.4 ~ 7.3	6.8 (3)	180.2 ~ 205.2	195.8 (9)
Fm.: Kamouraska										
Litho.: Sandstone										
Area: Rv. Madeleine										
UTMx: 327546 (20)										
UTMy: 5442993										
No.: 97LKA-RM-26A	Qp	Cluster	3 ~ 4	Aq	-1.4 ~ -1.6	-1.5 (2)	2.4 ~ 2.7	2.6 (2)	138.5 ~ 151.9	145.2 (2)
Fm.: Kamouraska		Isolated	5	Aq	-5.1	-5.1 (1)	8.0	8.0 (1)	159.5	159.5 (1)
Litho.: Sandstone	Qf	Scattered	5 ~ 12	Aq	-1.6 ~ -1.9	-1.7 (4)	2.7 ~ 3.2	2.9 (4)	180.5 ~ 221.9	195.7 (7)
Area: Rv. Madeleine										
UTMx: 327389 (20)										
UTMy: 5442973										
No.: 97LKA-RM-26B	Qp	Cluster	4 ~ 4	Aq	-2.4	-2.4 (1)	4.0	4.0 (1)	148.2 ~ 167.4	157.8 (2)
Fm.: Kamouraska	Qf	Random	5 ~ 9	Aq	-2.5 ~ -2.7	-2.6 (3)	4.2 ~ 4.5	4.3 (3)	175.9 ~ 201.3	193.6 (8)
Litho.: Sandstone										
Area: Rv. Madeleine										
UTMx: 327389 (20)										
UTMy: 5442973										
No.: 97LKA-PV-4B	Cf	Random	6 ~ 8	Aq	-0.5	-0.5 (1)	0.9	0.9 (1)	100.2 ~ 126.8	111.4 (3)
Fm.: Rivière-Ouelle		Random	4 ~ 5	Aq	-1.0	-1.0 (1)	1.7	1.7 (1)	103.5 ~ 132.8	118.0 (4)
Litho.: Limestone		Random	5	Aq					62.5	62.5 (1)
Area: Petite Vallée		Cluster	6 ~ 10	Aq					106.9 ~ 118.9	112.9 (2)
UTMx: 351828 (20)		Random	5 ~ 8	CH_4					-84.0 ~ -97.4	-91.3 (10)
UTMy: 5449397										

Litho. = lithology; Fm. = formation.

* Cp = pore-filling calcite; Cf = fracture-filling calcite; Qd = detrital quartz; Qp = pore-filling quartz; Qf = fracture-filling quartz; Bf = fracture-filling barite.

** Possible heterogeneous trapping; minimum T_h values adopted.