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Microstructural analysis and geochemical vein characterization of the Salinic event and Acadian Orogeny: evaluation of the hydrocarbon reservoir potential in eastern Gaspé

DONNA KIRKWOOD
Département de géologie et de génie géologique
Université Laval
Québec, QC
G1K 7P4

MARTINE M. SAVARD AND GUOXIANG CHI
Centre Géoscientifique de Québec
Geological Survey of Canada (Québec)
Québec, QC
G1V 4C7

ABSTRACT

For the past century, eastern Gaspé Peninsula has generated an interest in oil and gas exploration. This paper examines the fractured reservoir play in the Upper Ordovician to Lower Silurian limestones of the White Head Formation. The White Head Formation is strategically important for play concepts in eastern Gaspé because of its stratigraphic position, overlying potential source rocks of Cambrian and Ordovician age, and underlying Silurian and Devonian rocks that host oil seeps. Combined microstructural and petrographic evidence, as well as isotope geochemistry, helped in proposing a genetic link between fracture sets and the Salinic event and Acadian Orogeny. The proposed tectonic model involves three distinct events beginning with shallow to moderate burial, followed by fracturing and uplift as a result of normal faulting during the Salinic disturbance, and deeper burial, fracturing, folding and strike-slip faulting during the Acadian Orogeny. Fractures that developed within the White Head limestones during the Salinic event and the Acadian Orogeny contributed to enhance porosity and permeability to some extent at different stages during the entire tectonic history of the rocks. The presence of liquid hydrocarbon inclusions in Salinic veins and methane inclusions in the Acadian veins indicates that hydrocarbon-rich fluids migrated through the fracture network. The Salinic fracture network could therefore have provided a pathway for expulsion of liquid hydrocarbons from source rocks before they became overmature.

RÉSUMÉ

Au cours du dernier siècle, l'Est de la Gaspésie a suscité l'intérêt pour l'exploration de l'huile et du gaz. Cet article évalue le potentiel en réservoirs fracturés dans les calcaires ordoviciens supérieurs à siluriens inférieurs de la Formation de White Head. Cette dernière est stratégiquement importante pour cette démarche d'évaluation à cause de sa position stratigraphique au-dessus de roches cambriennes et ordoviciennes potentiellement roches-mères, et en-dessous de roches siluriennes et dévoniennes dans lesquelles on a répertorié des sources d'huile. Une combinaison d'évidences venant de l'analyse microstructurale et pétrographique et de la géochimie isotopique conduit à proposer l'existence d'un lien génétique entre des ensembles de fractures, la pulsation salinique et l'orogénie acadienne. Le modèle tectonique proposé implique trois événements distincts: d'abord un enfouissement peu profond à intermédiaire, suivi par de la fracturation et du soulèvement reliés à du faillage normal durant la pulsation salinique, puis finalement un enfouissement plus profond, de la fracturation, du plissement et du faillage de décrochement durant l'orogénie acadienne. Des fractures se sont développées dans les calcaires de White Head pendant l'événement salinique; l'orogénie acadienne a par la suite contribué à améliorer dans une certaine mesure la porosité et la perméabilité à différents stades pendant toute l'histoire tectonique de la formation. La présence d'inclusions d'hydrocarbures liquides dans des veines saliniques et d'inclusions de méthane dans des veines acadiennes indique que des fluides riches en hydrocarbures ont migré à travers le réseau de fractures. Le réseau de fractures salinique a pu conséquemment présenter une voie d'expulsion des hydrocarbures liquides de la roche-mère, avant qu'ils ne deviennent trop matures.

Traduit par les auteurs.

Introduction

For the past century, an interest in oil and gas exploration in eastern Gaspé Peninsula has existed (Immerz, 1997). Although oil shows and seeps are abundant, hydrocarbon production has been minor, and no major hydrocarbon resources have been found. In this part of the Gaspé Peninsula the hydrocarbon potential is restricted to Upper Ordovician to Lower Devonian rocks of the Gaspé Belt. Different play concepts have been applied for years: depositional plays in porous reservoir rocks such as the Val-Brillant, Gascons and Gaspé sandstones; diagenetic plays in the West Point reef complexes (Bourque, 2001, this issue); structural traps in anticlinorial structures (Rocksandic and Granger, 1981); and fractured reservoir plays. Geochemical analyses from recovered oils in northeastern Gaspé indicate that oils and source rocks belong to the same family of oils and compare well with Ordovician oil and source rocks from western Newfoundland (Idiz et al., 1997; Rodgers et al., 1998). This paper examines the genetic link between the fracture sets and geological and diagenetic events that could possibly have enhanced the porosity, permeability and reservoir capacity of the Upper Ordovician to Lower Silurian limestones of the White Head Formation. The White Head Formation is an important play in eastern Gaspé, because of its stratigraphic position overlying potential source rocks of Cambrian and Ordovician age (Bertrand and Malo, 2001, this issue), and underlying Silurian and Devonian rocks that yield oil seeps. Field work at selected sites within the White Head Formation, petrography, isotope geochemistry, and fluid inclusion microthermometry were performed in order to verify: 1) how diagenetic and tectonic processes interacted during the evolution of limestones of the White Head Formation and controlled their porosity and permeability; 2) whether the fracture network was enhanced by meteoric diagenesis (karstification) related to the Salinic event; and 3) if hydrocarbons migrated through the fracture network and, if so, during which tectonic event. This study presents new structural and geochemical evidence toward a better definition of the Salinic event and a more complete picture of the deformation history of the White Head Formation, and establishes its reservoir potential.

Tectonic History of the White Head Formation in Gaspé

Three tectonic events affected rocks of the Gaspé Peninsula: the Late Ordovician Taconian Orogeny (St-Julien and Hubert, 1975), the Late Silurian to Early Devonian Salinic disturbance (Boucot, 1962), and the Middle Devonian Acadian Orogeny (Malo and Kirkwood, 1995). In northeastern Gaspé, the White Head Formation was subjected to the last two tectonic events. A detailed tectono-diagenetic study was initiated to distinguish between different fracture sets within the White Head Formation in northeastern Gaspé, to establish a chronological sequence of their development and to relate them to tectonic events. In view of renewed interest in hydrocarbon exploration in northeastern Gaspé, it is important to evaluate the effect of the Salinic extensional tectonic regime and its influence on the development of deformation features, particularly brittle faulting and related fracturing.

For the past two decades, regional studies and more detailed structural analysis in the Gaspé Peninsula have focussed mainly on structural features related to the Acadian Orogeny. Consequently, an impressive database is available and has helped to establish a well-constrained model for the development of these Acadian structures (Malo and Kirkwood, 1995). More recently, the widespread recognition of the Late Silurian–Early Devonian Salinic disturbance has prompted geologists to put forward new models for the tectonic evolution of the northern Appalachians. Some workers have proposed a two-phase scenario for the period spanning the Late Silurian to Middle Devonian in Newfoundland, Nova Scotia and New Brunswick, arguing that both tectonic pulses represent distinct orogenic phases that can be clearly separated in time, hence the introduction of the Late Silurian Salinic Orogeny (Dunning et al., 1990; Lin et al., 1994; van Staal and de Roo, 1995). Nevertheless, these two phases are also recognized in the Gaspé part of the orogen and are recorded as a first phase of extensional faulting, minor folding and a resulting unconformity that is well documented and clearly of Late Silurian–Early Devonian age (Bourque et al., 1993; Malo and Bourque, 1993). This was followed by a second phase of dextral transpression during the Middle Devonian. The model proposed by Bourque (2001, this issue) and based on sedimentological analysis of the Gaspé Belt rocks in the northeastern part of the Gaspé Peninsula (Bourque, 1977; Lavoie, 1992) and seismic data (Roksandic and Granger, 1981) proposes that the Bras Nord-Ouest and Troisième Lac faults (Fig. 1) were active as normal faults during Late Silurian to Early Devonian sedimentation. Bourque (2001, this issue) relates the Ludlovian–Pragian Salinic unconformity to the interplay between normal faulting and sea-level changes resulting in erosion on topographically high blocks and erosional surfaces within the Chaleurs Group in marginal basin facies. In more basinal sequences of the Chaleurs Group, evidence for the Salinic disturbance is the presence of conglomeratic facies, such as the Owl Capes and the Griffon Cove River members of the West Point Formation (Fig. 2). In such a scenario, NW-trending folds are interpreted as extensionally induced folds that formed over faulted blocks delineated by Late Silurian–Early Devonian extensional faults (Malo, 2001, this issue; Malo and Kirkwood, 1995). All these events suggest that the Late Silurian to Early Devonian period corresponded to an episode of regional extension in the Gaspé Peninsula that we will refer to herein as the Salinic event. The postulated Late Silurian normal faults were reactivated as strike-slip faults during the Acadian Orogeny.

Even though the Salinic event is well documented in the Gaspé, neither diagenetic nor deformation features have yet been identified as clearly resulting from this tectonic event. Regional stratigraphic evidence suggests that the Upper Ordovician to Upper Silurian rocks within the Gaspé Basin were tectonically exhumed and brought to near surface conditions during the Late Silurian–Early Devonian Salinic event (Bourque et al., 1993). In this study we present new microstructural data that attest to deformation features developed within rocks of the White Head Formation during the Salinic event—features that could have acted as conduits for hydrocarbon-rich fluids.

Regional Geology

In the Gaspé Peninsula, evidence of the Appalachian Orogen occurs in Paleozoic rocks that can be divided into three temporal rock assemblages: Cambro-Ordovician rocks of the Humber and Dunnage zones; Siluro-Devonian rocks of the Gaspé Belt, a post-Taconian successor basin; and Carboniferous rocks (Figs. 1, 2).

Cambro-Ordovician Rocks

Cambro-Ordovician rocks of the Gaspé Peninsula comprise the two westernmost tectono-stratigraphic zones of the Canadian Appalachians: the Humber and Dunnage zones (Fig. 1). The Humber Zone, which is made up of lower Paleozoic, slope-and-rise deposits of the Laurentian continental margin, occupies mainly the northern part of the Gaspé Peninsula. The regional deformation and greenschist-grade metamorphism (locally up to amphibolite grade) within the Humber Zone is mainly related to the Taconian Orogeny and is viewed as the result of the emplacement of northwest-verging thrust sheets over the autochthonous cover rocks of the St. Lawrence platform (St-Julien and Hubert, 1975). Rocks of the Dunnage Zone include ophiolitic rocks, mélanges, arc and back-arc volcanics and forearc basin deposits (Tremblay et al., 1995) and are found in inliers close to the Baie Verte–Brompton Line (BBL) in the northern and southern parts of the Gaspé Peninsula. In the Québec Appalachians, allochthonous rocks of the Dunnage Zone rest unconformably on rocks of the Humber Zone to the northwest (St-Julien et al., 1983; Slivitzky et al., 1991). Regional deformation and the lower greenschist-grade metamorphism of the Dunnage rocks in the Gaspé Peninsula are clearly associated with the Middle Devonian Acadian Orogeny (Malo and Bourque, 1993).

Siluro-Devonian Rocks

Siluro-Devonian rocks of the Gaspé Peninsula form a single depositional belt, known as the Gaspé Belt, which occupies the central and southern parts of the peninsula (Fig. 1). Rocks of the Gaspé Belt are deposited unconformably on, or are in fault contact with, rocks of the Humber and Dunnage zones (Malo and

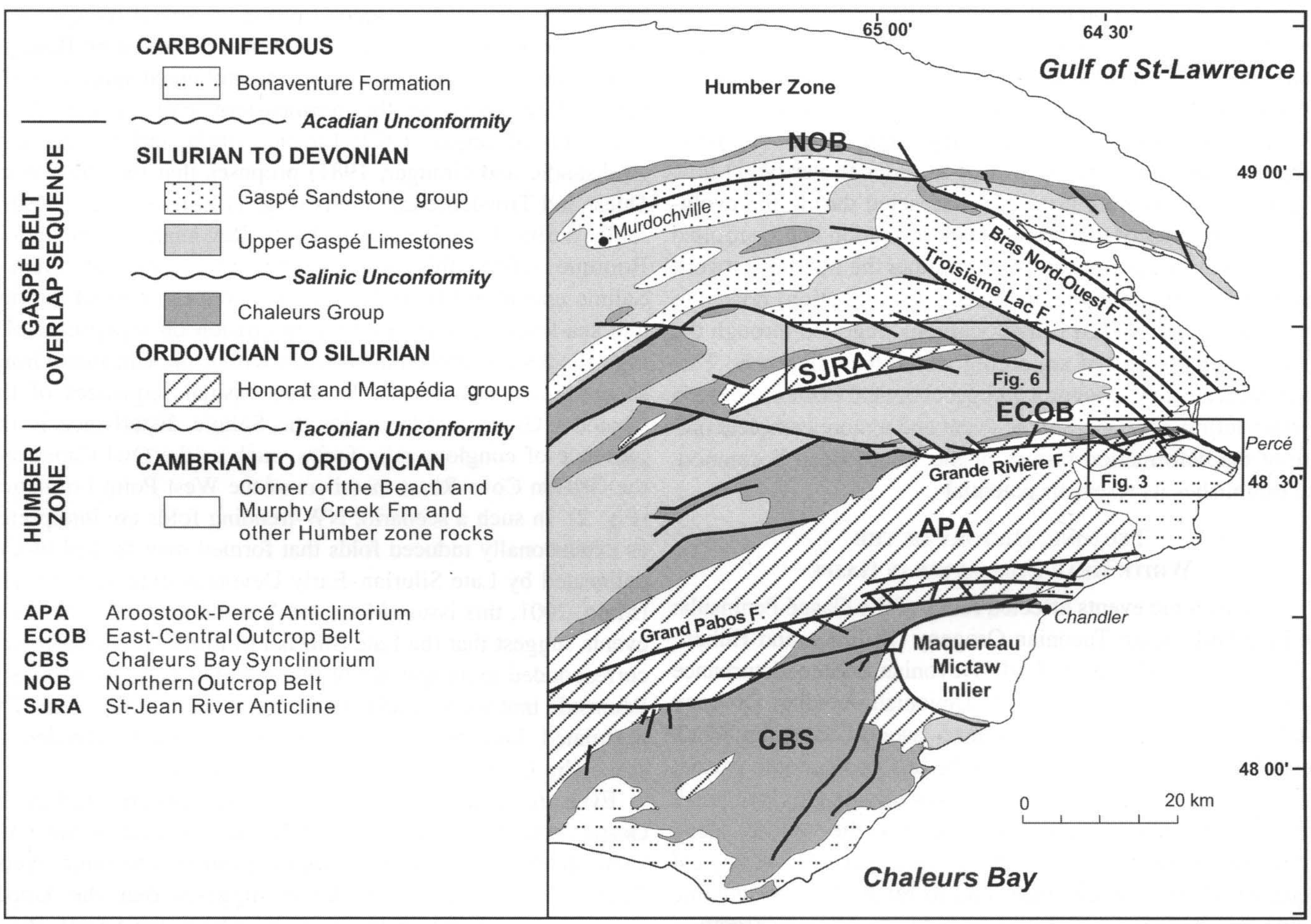

Fig. 1. Geological map of eastern Gaspé Peninsula.

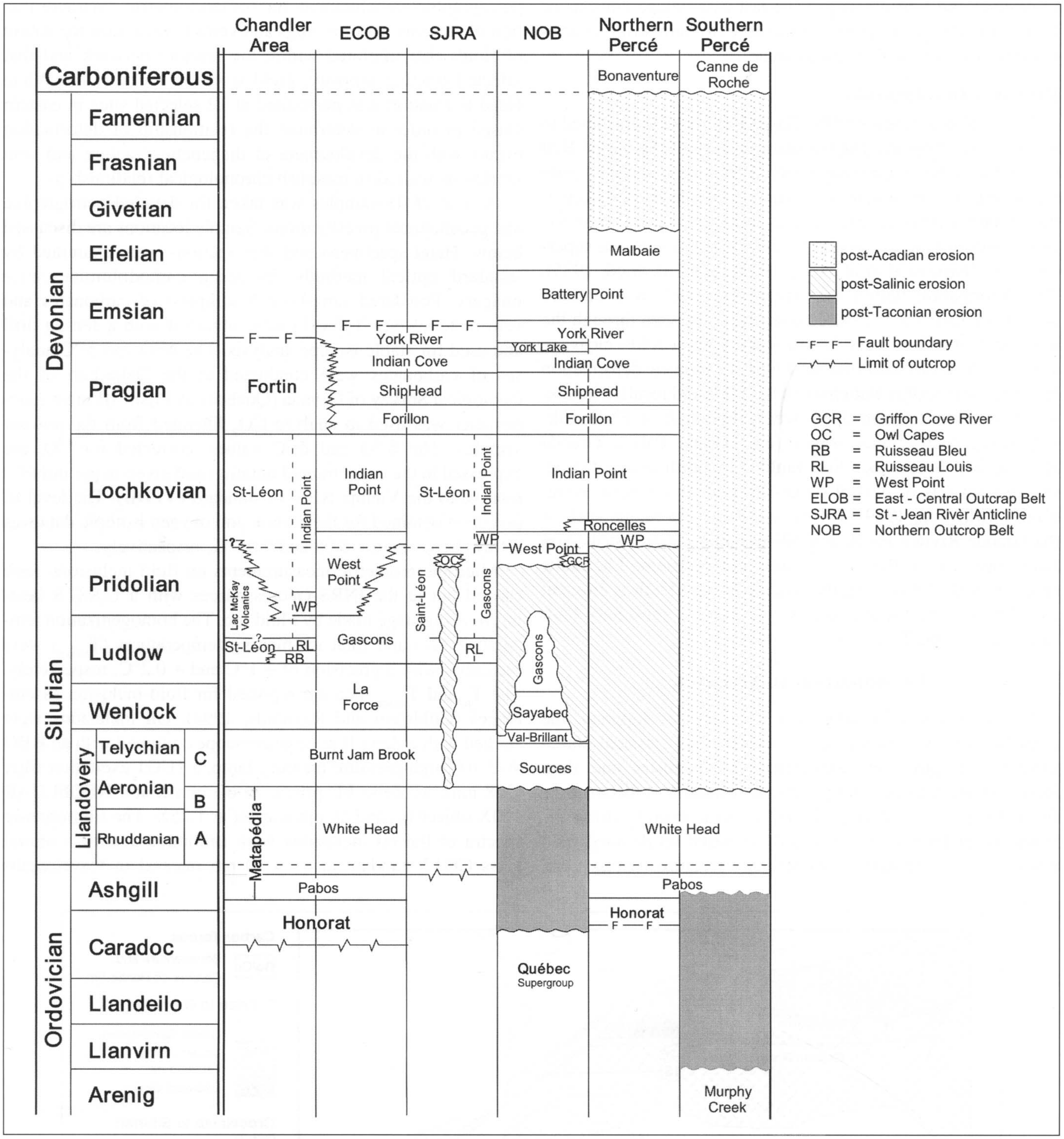

Fig. 2. Correlation chart showing distribution of Gaspé Belt rocks for northeastern Gaspé. Modified from Bourque et al. (2000, Fig. 4).

Bourque, 1993). The Gaspé Belt comprises four broad temporal and lithological rock assemblages (Bourque et al., 2001, this issue) that were deposited after the Taconian Orogeny and before the Acadian Orogeny (Fig. 2). The first lithological rock assemblage consists of Upper Ordovician to lowermost Silurian, deep-water, fine-grained, siliciclastic and carbonate facies of the Honorat and Matapedia groups. The second rock assemblage is characterized by shallow- to deep-water shelf facies of the Chaleurs Group, deposited during the Silurian to lowermost Devonian. The third rock assemblage consists of Lower Devonian, mixed siliciclastic and carbonate, fine-grained, deep shelf and basin facies of the Upper Gaspé

Limestone and Fortin groups. The last assemblage consists of Lower to Middle Devonian nearshore to terrestrial coarse-grained facies of the Gaspé sandstone.

Regional Deformation

Regional deformation of the Gaspé Belt rocks is attributed to the Acadian Orogeny. The structural history of the Gaspé Belt during the Acadian Orogeny evolved from an essentially pure shortening deformation to a dominantly simple shear deformation within a transpressive setting during the oblique convergence between the composite Laurentia and Gondwana supercontinent (Kirkwood et al., 1995; Malo and Kirkwood, 1995). The deformation within the transpressive belt was initially accommodated and distributed over the entire area through the development of compressive structures, such as folds, cleavage and reverse faults (Kirkwood, 1995). Continued deformation brought about further flattening of the folds and resulted in dextral transcurrent faulting along steeply dipping E- to ENE-striking, brittle-ductile shear zones (e.g., Grand Pabos, Grande Rivière, and Shickshock-Sud faults). In northeastern Gaspé, two distinct sets of dextral strike-slip faults have been recognized (Kirkwood, 1989): E-trending strike-slip faults, such as the Grande Rivière Fault, and NE-trending, dextral strike-slip faults, such as the Bras-Nord Ouest and Troisième Lac faults (Fig. 1). In the Percé area, the Grande Rivière Fault is crosscut and displaced by the Ruisseau Blanc Fault, a subsidiary fault subparallel to the Troisième Lac Fault (Fig. 3).

Methodological Approach

In the context of conduit and reservoir development, the combined use of mesotectonic, microtectonic, classical diagenetic petrography, low temperature geochemistry and fluid inclusion microthermometry help to establish a better time frame for the main diagenetic and tectonic events within the White Head Formation. This study is based on detailed field work to distinguish different fracture sets and petrographic–geochemical–microthermometric characterization of cements in pores, vugs and veins to recognize the nature of fluids that migrated within the fracture network and that affected fracture porosity. Field work on rocks of the White Head Formation was performed at 12 selected sites in eastern Gaspé in order to determine the relationship of deformation events with the development of diagenetic, fracture and vein fabrics, as well as to establish chronological relationships.

A total of 48 samples was taken for detailed petrographic and geochemical investigations. Sample locations are discussed below. Hand specimens and thin sections were examined by standard optical methods, including cathodoluminescence imagery. Powdered samples (78 samples) of carbonates and vein material (see Table 1) were obtained with a Jensen drill and used for stable isotope analysis. The $\delta^{18}O$ and $\delta^{13}C$ analyses of carbonates were conducted at the Delta-Lab of the Geological Survey of Canada (Québec). A Prism-III mass spectrometer was used to analyze CO_2 liberated from the powder samples. The $\delta^{18}O$ and $\delta^{13}C$ values, corrected for ^{17}O, are expressed in the conventional notation and given in per mil (‰) relative to the Vienna NBS-19 standard (VPDB). The level of precision obtained for the carbon and oxygen isotopic data was always better than + 0.05 and 0.06 ‰, respectively.

Microthermometric measurements on fluid inclusions were carried out at the INRS-Géoressources with a U.S.G.S heating/freezing stage made by Fluid Inc. The homogenization temperature (T_h) and final ice-melting temperatures ($T_{m\text{-}ice}$) were measured with a precision of + 1°C and + 0.2°C, respectively. The T_h and $T_{m\text{-}ice}$ data are reported for fluid-inclusion assemblages (Goldstein and Reynolds, 1994). 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), an 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

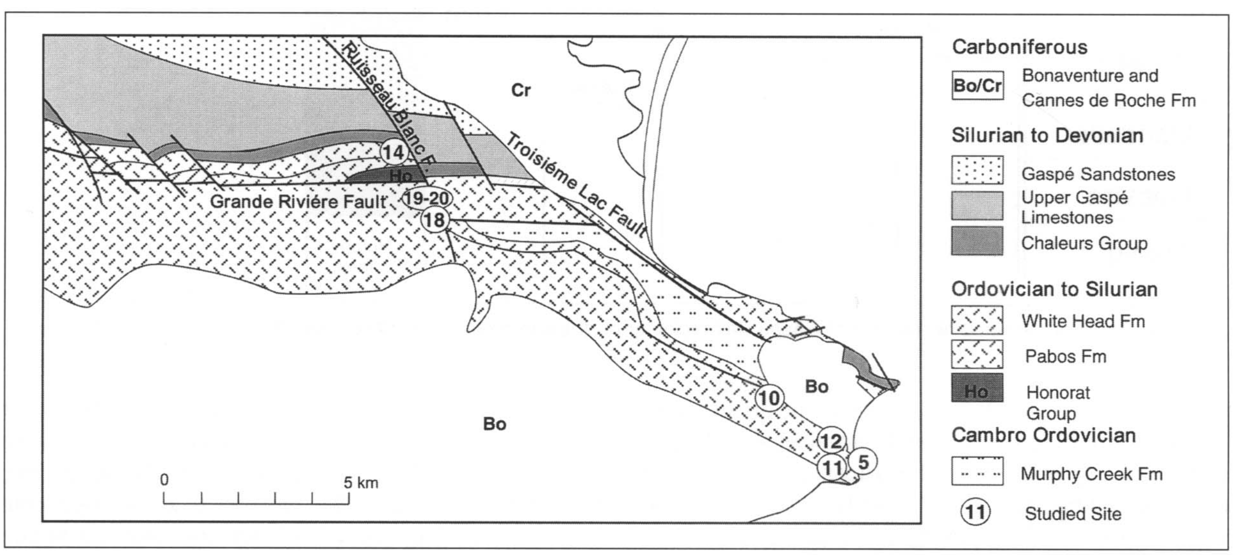

Fig. 3. Geological map of the Percé area and the East-Central Outcrop Belt showing locations of sites studied.

Table 1. Stable isotope data of samples from the White Head Formation.

Thin section	Vein* No. or m=matrix	$\delta^{13}C$	$\delta^{18}O$
Rivière St-Jean Anticline			
SH8-1a	5	-0.35	-8.25
SH8-1b	2	-0.85	-3.46
SH8-1c	c	-0.43	-9.37
SH8-1e	2	-0.91	-4.34
SH8-1f	2	-0.91	-3.56
SH8-1A	4		
SH8-1B	4	-0.62	-5.96
SH8-2-R	2b	-1.18	-7.99
SH8-3AA	2	-1.35	-8.08
SH8-3AB	5	-1.63	-4.38
SH8-3AC	m	-1.40	-8.42
SH8-3bA	2	-0.76	-4.58
SH8-3bB	5	-0.75	-7.74
SH8-3BC	m	-1.10	-7.50
SH8-4A	2	-0.20	-5.62
SH8-4B	4	-0.41	-6.04
SH8-4C	m	-0.83	-7.27
SH8-6A	5	-1.14	-7.51
SH8-6B	m	-0.81	-6.66
SH8-B3A	2	-0.39	-3.61
SH8-B3B	m	-1.13	-7.29
SH8-B4A	2	-0.49	-6.45
SH8-B4B	m	-0.46	-6.33
SH8-B51A	4	-0.03	-6.36
SH8-B51B	m	-0.51	-6.32
SH8-B51C	2	1.53	-2.76
SH8-B52A	4	-0.70	-6.60
SH8-B52B	m	-0.32	-5.94
SH8-B5A	4	-0.46	-5.95
SH8-B5B	m	-0.57	-6.48
SH9-1	5	0.65	-8.13
	m	0.67	-7.67
SH9-2			
SH9-3	5	0.92	-7.67
SH9-4	5	1.18	-7.48
East Centre Outcrop Belt			
SH14-2		0.28	-9.67
SH14-3		0.43	-8.43
SH14-4	2	0.60	-6.22
SH14-5	5	0.52	-8.25
	5	0.53	-8.20
SH14-6	5	-0.29	-8.68
	m	-0.15	-8.31
376-f		0.14	-6.50
376-g		-0.09	-6.15
214-f1		0.40	-7.18
214-f2		0.34	-7.03
214		0.82	-5.01
239		-0.35	-6.06

Thin section	Vein* No. or m=matrix	$\delta^{13}C$	$\delta^{18}O$
W Percé area - Ruisseau Blanc			
SH18-28-f		-0.20	-6.63
SH18-28		0.69	-4.68
SH18-28b		0.84	-5.48
SH19-1	4	0.38	-6.96
SH20-1	4-5	-0.79	-6.35
SH20-2	m	-0.74	-4.83
Eastern Percé area			
SH5Karst-P1		-2.06	-10.70
		-0.79	-9.93
SH5Karst-P2		1.63	-7.48
		-2.29	-9.67
		-5.66	-9.37
SH5Karst-P5		-2.16	-10.35
		-4.30	-9.27
		-5.26	-10.13
SH5Karst-P6		-1.11	-7.97
SH5-4j-1a		1.12	-4.63
SH5-4j		1.67	-6.93
SH5-4j-2		1.24	-5.56
SH5-15-3a		0.65	-5.38
SH10-1			
SH10-1B	2	-0.20	-7.38
	m	0.31	-4.95
SH10-5		0.08	-7.74
SH10-6	4	0.07	-8.30
	m	0.24	-5.67
	4	0.04	-8.17
SH10-7A	4	0.01	-8.69
SH10-7B2	4	0.25	-7.02
	4	0.10	-8.22
SH10-10		0.72	-7.43
SH11-1	5	-0.14	-9.21
	m	0.93	-7.26
	2	0.90	-7.29
	c	0.91	-6.94
SH11-3	5	0.68	-9.61
SH11-4	2	0.55	-6.60
SH12-1	5	0.23	-7.06
	m	0.55	-5.38
SH12-95		0.97	-5.44
SH13-1	3	0.17	-6.00
	m	0.40	-4.83
SH13-2	3	0.10	-7.32

*Vein generation is based on vein shape, orientation, geometry and crosscutting relationships in hand specimens, where available.

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, with API values of the oil being estimated from the fluorescence spectra (Stasiuk and Snowdon, 1997). A more detailed description of the research methods of aqueous and hydrocarbon inclusions can be found in Chi et al. (2000).

Stratigraphy of the White Head Formation

The White Head Formation is the upper formation of the Matapédia Group in the Gaspé (Malo, 1988). It crops out mainly in the Aroostook–Percé Anticlinorium in southern Gaspé and along the East Central Outcrop Belt (ECOB) and in the Saint-Jean River Anticline in eastern Gaspé (Fig. 1). Limestones of the White Head Formation overlie rocks of the Upper Ordovician Pabos Formation, which in turn overlie rocks of the Upper Ordovician Honorat Group (Fig. 2). In the Percé area, unlike in southern Gaspé, rocks of the Pabos rest unconformably on polydeformed rocks of the Upper Cambrian Murphy Creek Formation, which have been correlated with rocks of the Québec Supergroup of the Humber Zone exposed in northern Gaspé (Kirkwood, 1989). The observed unconformity in the Percé area corresponds to the Taconic unconformity. North of the Grande Rivière Fault, in the Saint-Jean River Anticline for example, underlying rocks of the White Head are not exposed, but one can speculate that the White Head overlies either the Pabos–Honorat stratigraphic sequence or the Pabos–Québec Supergroup sequence (Fig. 2).

In eastern Gaspé, the White Head Formation crops out in two areas southeast of the Troisième Lac Fault and north of the Grande Rivière Fault (Fig. 1) the axial region of the Saint-Jean River Anticline, and north of the Grande-Rivière Fault within the East Central Outcrop Belt in the Connecticut Valley–Gaspé Synclinorium. The White Head is a carbonate-dominated sequence consisting of thin-bedded calcilutite with mudshale partings and a few thin beds of calcarenite, dark green calcareous mudstones, and thinly bedded silty and argillaceous limestones. In the Percé area, where type sections have been defined, the White Head consists of four members, which are, from bottom to top, the Burmingham, Côte de la Surprise, l'Irlande and Des Jean members (Fig. 4) (Lespérance et al., 1987). The lower two members are Upper Ordovician (Ashgillian) whereas the upper two are Lower Silurian (Llandoverian) (Malo, 1988). The minimum measured thickness of the White Head Formation in the type area is 850 m.

In the study area in eastern Gaspé, the Grande Rivière Fault separates two stratigraphically distinct zones (Kirkwood, 1989), the Percé area to the south and the East Central Outcrop Belt (ECOB) to the north. Stratigraphic sections are slightly dissimilar in both zones; rocks of the ECOB are typical of a more basinal environment whereas rocks of the Percé area are representative of deposition in shallower water. North of the Grande Rivière Fault in the ECOB, rocks of the Honorat Group are overlain by the Pabos and White Head formations. Rocks of the Chaleurs Group overly the l'Irlande Member of the White Head Formation and the Des Jean Member is either absent or missing. In the Percé area, the entire stratigraphic sequence of the White Head is present (Fig. 4). Thicknesses are also slightly different in both areas, individual members of the White Head at the type section in the Percé area are thinner than stratigraphically equivalent units north of the Grande Rivière Fault, and elsewhere in the peninsula. A general lack of shelly faunas, the presence of graptolites, deep-water trace fossil assemblages and turbiditic facies indicate that the White Head Formation occupies a relatively deep-water marine basin everywhere within the Gaspé Peninsula, except in the Percé area where unique faunas reflect shallower water deposition (Lespérance et al., 1987).

Observed Features at Sites Studied

The White Head crops out in three areas in northeastern Gaspé. Studied sites were chosen for detailed analysis of the microfracture network within the White Head limestones in the Percé area, the Saint-Jean River Anticline and the East Central Outcrop Belt (Fig. 1).

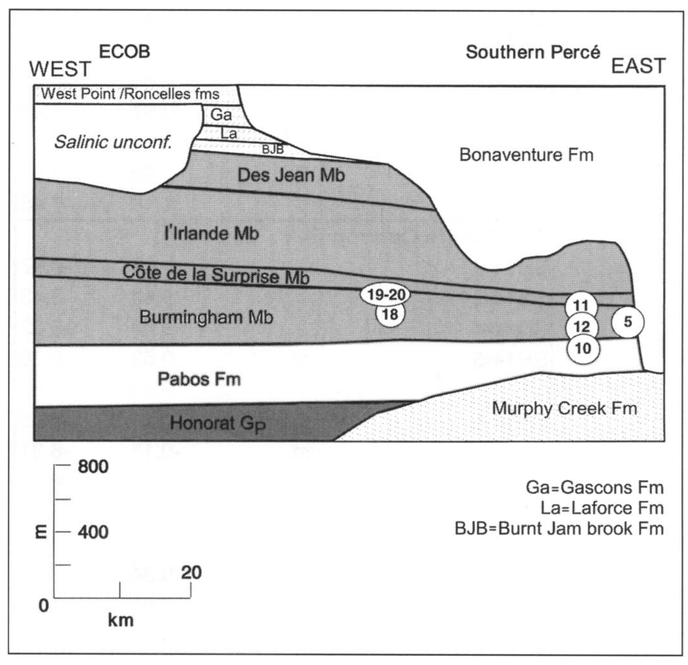

Fig. 4. Schematic lithostratigraphic profile of the East-Central Outcrop Belt and Percé area.

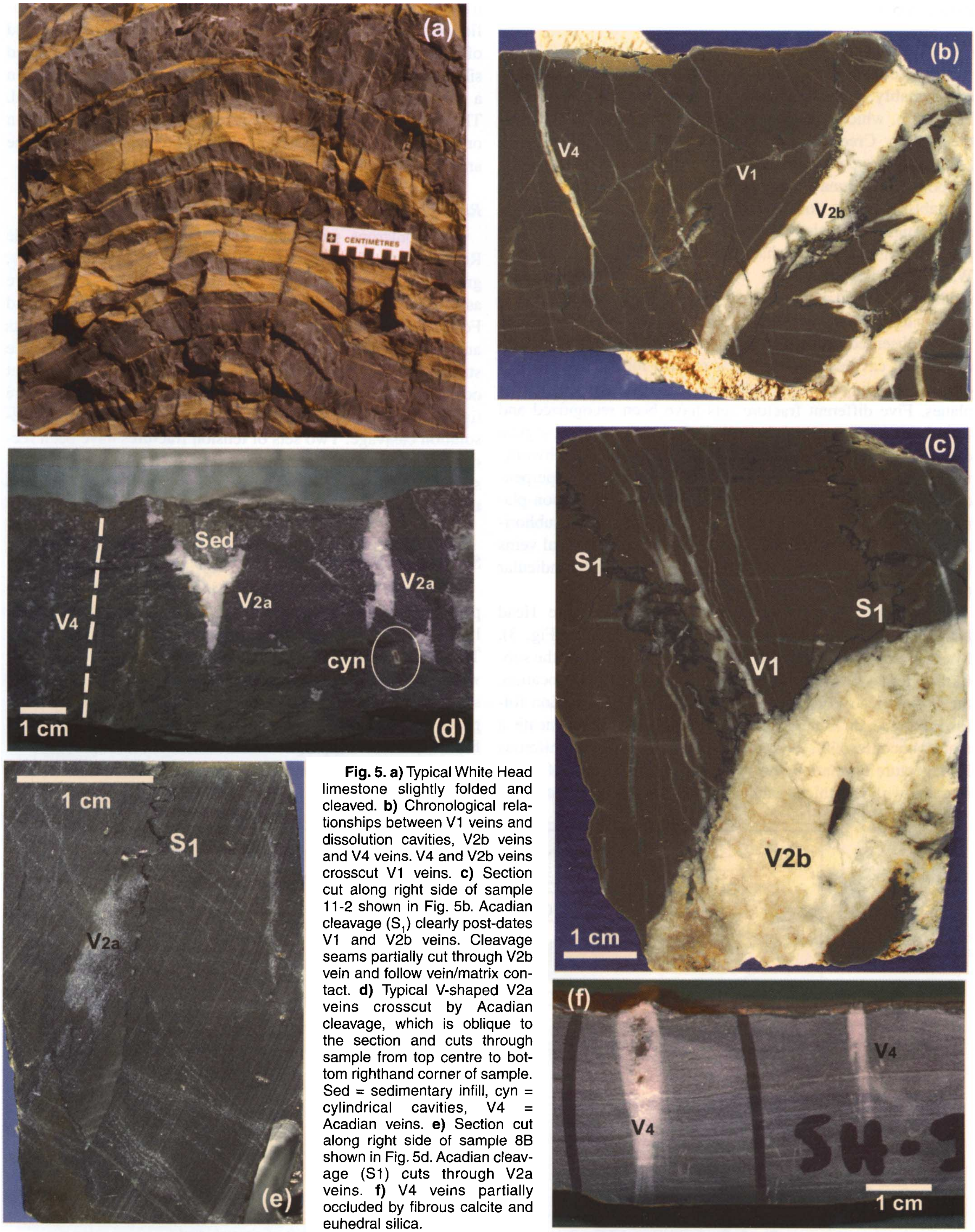

Fig. 5. a) Typical White Head limestone slightly folded and cleaved. **b)** Chronological relationships between V1 veins and dissolution cavities, V2b veins and V4 veins. V4 and V2b veins crosscut V1 veins. **c)** Section cut along right side of sample 11-2 shown in Fig. 5b. Acadian cleavage (S_1) clearly post-dates V1 and V2b veins. Cleavage seams partially cut through V2b vein and follow vein/matrix contact. **d)** Typical V-shaped V2a veins crosscut by Acadian cleavage, which is oblique to the section and cuts through sample from top centre to bottom righthand corner of sample. Sed = sedimentary infill, cyn = cylindrical cavities, V4 = Acadian veins. **e)** Section cut along right side of sample 8B shown in Fig. 5d. Acadian cleavage (S1) cuts through V2a veins. **f)** V4 veins partially occluded by fibrous calcite and euhedral silica.

Percé Area

Eastern Percé Area (Sites 5, 10–12)

In the eastern Percé area, the White Head limestone rests conformably over calcareous mudstones of the Pabos Formation, which rests unconformably on Cambrian rocks of the Murphy Creek Formation (Kirkwood, 1989) (Figs. 3, 4). Subhorizontal conglomerates and coarse sandstones of the Carboniferous Bonaventure Formation were deposited unconformably over the folded and faulted Cambrian to Silurian stratigraphic succession. Four localities were studied and sampled within the Burmingham and l'Irlande members of the White Head Formation (Fig. 4). The well-bedded limestone is moderately folded and affected by the regional Acadian cleavage, a 5 to 10 cm spaced solution cleavage (Fig. 5a) (Kirkwood, 1989). Observed features at the outcrop scale include 1 to 4 mm cylindrical cavities that contain a reddish infill, cement-filled cavities, bedding-parallel stylolites, and irregular dissolution planes. Five different fracture sets have been recognized and crosscutting relationships helped decipher their chronological development. These are: a set of irregular 'patchwork' veins and cavities (V1) (Figs. 5b, c); V-shaped veins, perpendicular to bedding (blocky calcite) (V2a) (Figs. 5d, e); non-planar, oblique veins (blocky calcite) (V2b) (Figs. 5b, c); subhorizontal veins (vertical calcite fibres) (V3); and subvertical veins (horizontal calcite fibres) (V4) (Figs. 5b, f) both perpendicular to the Acadian layer-parallel shortening cleavage.

One other locality was studied within the White Head Formation at the type section at Cap Blanc (Site 5; Fig. 3). Rocks along this cliff section occur a few metres below the sub-Carboniferous angular unconformity (Fig. 4). At this location, the White Head Formation was affected by karstification following Acadian folding. The 4-m thick karst lies beneath a major unconformity, and is covered by the Carboniferous Bonaventure Formation, but the exact age of the unconformity is unknown. The thick, subhorizontal, karstified surface contrasts with the well-bedded, subvertical strata of the unkarstified White Head Formation. The karstified portion is composed of recrystallized brown calcilutite, breccia, and thickly layered silica and calcite cement crusts, mosaic calcites and pisolites in a cavity network, which is now almost completely occluded. The different types of meteoric calcite cements were sampled in order to establish the isotopic meteoric calcite curve for the area.

Ruisseau Blanc, Western Percé Area (Sites 18–20)

Two outcrops were studied 700 m south of the Grande Rivière Fault along Ruisseau Blanc (Fig. 3). At this locality, grey calcilutite, calcareous mudshale and calcarenite were assigned to undifferentiated limestones of the White Head Formation (Kirkwood, 1989). Numerous brittle-ductile faults and Riedel shear fractures crosscut the limestone beds. These structures consist of third-order Acadian strike-slip faults that occur within the Ruisseau Blanc fault zone. Limestones are tightly folded and affected by a pervasive Acadian pressure-solution cleavage. Two sets of tension fractures have been recognized at this site, a subvertical set (V3) and a subhorizontal set (V4), both filled with fibrous calcite and perpendicular to the Acadian layer-parallel shortening cleavage and folds.

Saint-Jean River Anticline (Sites 1, 3, 6, 8 and 9)

The Saint-Jean River Anticline is located within the central part of the Gaspé Peninsula (Fig. 1). The anticline trends roughly E–W, with its eastern tip originating just west of the Troisième Lac Fault, and extends laterally 50 km towards the west. It is dissected by a set of SE-trending Acadian dextral strike-slip faults (Fig. 6). The stratigraphic succession is composed of basin facies with lime turbidites of the White Head Formation outcropping within the core of the structure, followed by claystones of the Burnt Jam Brook Formation, turbidites and debrites of the Laforce Formation, fine-grained

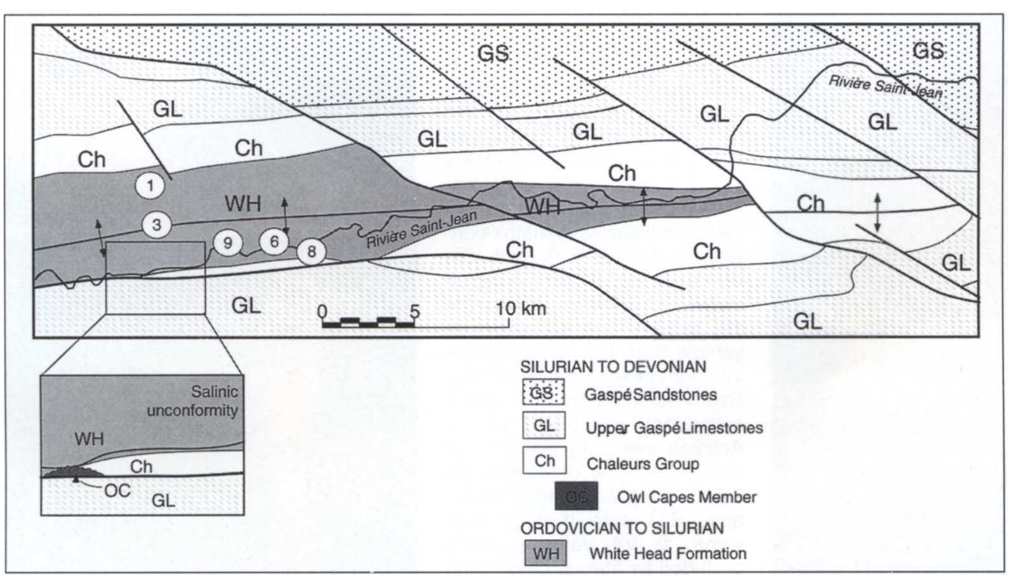

Fig. 6. Geological map of the Saint-Jean River Anticline showing locations of sites studied.

siliciclastics of the Saint-Léon Formation and turbidites of the Fortin Formation (Bourque, 2001, this issue). This succession differs from east to west with more nearshore facies occurring in the east. In the east, the Pridolian Owl Capes conglomerate rests unconformably on limestones of the White Head Formation along the southern limb of the anticline and marks the Salinic unconformity (Bourque, 1977). The conglomerate is composed of quartz pebbles and fragments of various limestones, corals, stromatoporoids, feldspathic wacke and mafic volcanic rocks, and is attributed to erosion during the Salinic event (Bourque et al., 2000). The Owl Capes is associated with the nearshore to terrestrial facies of the West Point and Indian Point formations (Bourque et al., 2001, this issue).

Four outcrops were studied within the White Head Formation at the Saint-Jean River Anticline (Fig. 6). At this site, the limestones consist of regularly bedded, 10 to 20 cm thick grey calcilutite beds with 2 to 10 cm thick calcareous mudshale interbeds, typical of either the Burmingham or l'Irlande members. Studied outcrops are located on both the northern and southern limbs of the anticline, 100 to 400 m below overlying rocks of the Chaleurs Group and beneath the Salinic unconformity (Fig. 7). Rocks are moderately to tightly folded and affected by a pervasive Acadian pressure-solution cleavage.

Observed structural features within rocks of the White Head Formation at the outcrop scale include E-trending, high-angle reverse faults, with displacements in the order of millimetres to tens of centimetres, SE-trending shear fractures and strike-slip faults, and subvertical tension fractures and/or veins. Three sets of subvertical fractures have been recognized: a first set of V-shaped veins, developed perpendicular to bedding (blocky calcite) (V2a)(Fig. 5d), a set of tension veins perpendicular to the Acadian layer-parallel shortening cleavage and folds (fibrous calcite) (V4) (Fig. 5f), and another set of tension veins parallel to the Acadian layer-parallel shortening cleavage (fibrous calcite) (V5). The V2a veins occur sporadically and do not cut through the entire beds. They thin toward the centre of the beds and some are partially filled with beige, fine-grained sediment. Other small-scale features include cylindrical cavities (2 to 4 mm in size) containing reddish infill and subhorizontal stylolitic planes.

East Central Outcrop Belt (Site 14)

The East Central Outcrop Belt is a geographic and stratigraphic subdivision of the Gaspé Belt (Bourque et al., 2000). It is located in eastern Gaspé in the southern part of the Connecticut Valley–Gaspé Synclinorium, 15 km northwest of Percé. The outcrop belt roughly follows the E-trending Grande-Rivière Fault, a major Acadian dextral strike-slip fault (Malo and Kirkwood, 1995). Deformation associated with the Grande-Rivière Fault extends as much as 400 m to the north and south of the fault (Kirkwood, 1989). Rocks of the White Head Formation were studied at one locality along the Portage River, 75 m north of the trace of the Grande Rivière Fault (Fig. 3). At this site, the limestone of the White Head Formation occurs approximately 450 m stratigraphically below rocks of the Chaleurs Group and consists of regularly bedded, 7 to 15 cm thick grey calcilutite beds with 2 to 10 cm thick calcareous mud–shale interbeds that have been correlated with the Burmingham Member (Kirkwood, 1989). Although the contact between the White Head and the West Point formations is not exposed, it is inferred to correspond to the Salinic unconformity, as most of the upper part of the White Head Formation is missing (part of the l'Irlande Member and the entire Des Jean Member) (Fig. 4).

Five outcrops were examined along the Portage River. Rocks of the White Head Formation are tightly folded and affected by a pervasive Acadian pressure-solution cleavage. At the outcrop scale, numerous dextral and sinistral faults, as well as Riedel shear fractures, were identified. These brittle features are third-order, strike-slip faults of the Grande Rivière fault zone with centimetre- to decimetre-scale displacements. Such geometry is typical of the low strain zones of Acadian strike-slip faults (Kirkwood and Malo, 1993). Bedding-parallel, brittle, east-trending faults are also frequently observed at these outcrops. Down-dip calcite slickenfibres and calcite crack-and-seal slip foliations are developed on fault planes. A coarsely developed fracture cleavage is observed within the limestone beds between closely spaced, bedding-parallel fault planes. Dextral strike-slip faults crosscut the bedding-parallel faults. Subvertical veins occur perpendicular to the bedding-parallel faults.

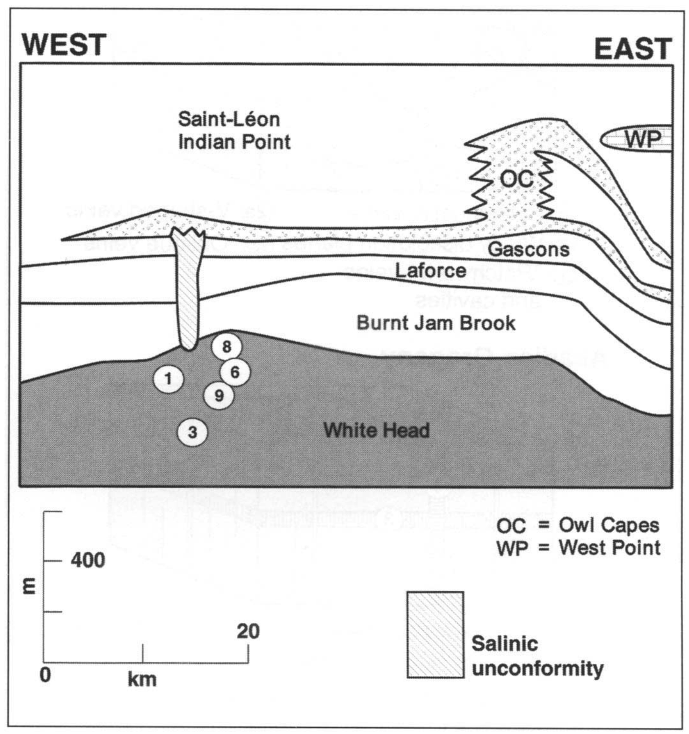

Fig. 7. Schematic lithostratigraphic profile of the Saint-Jean River Anticline area. Modified from Bourque et al. (2000), Fig. 7.

Timing of Tectonic Events

Timing of diagenetic and tectonic events within the White Head Formation was deduced through careful observation of deformation features on outcrops, hand specimens and in thin section. The observed features, mesostructures and microstructures can be related to three distinct sets of processes/events that have affected rocks of the White Head Formation: diagenesis, the Salinic event and the Acadian Orogeny (Fig. 8). Bedding-parallel stylolites observed in limestones of the Percé and Saint-Jean River areas are crosscut by every other feature and microstructure. We relate the bedding-parallel stylolites to vertical stress developed during compaction and burial. Several fracturing episodes (V1 to V5) can be differentiated based on their mutual crosscutting relationship and their relationship to bedding-parallel stylolites and the Acadian layer-parallel shortening cleavage (Fig. 8).

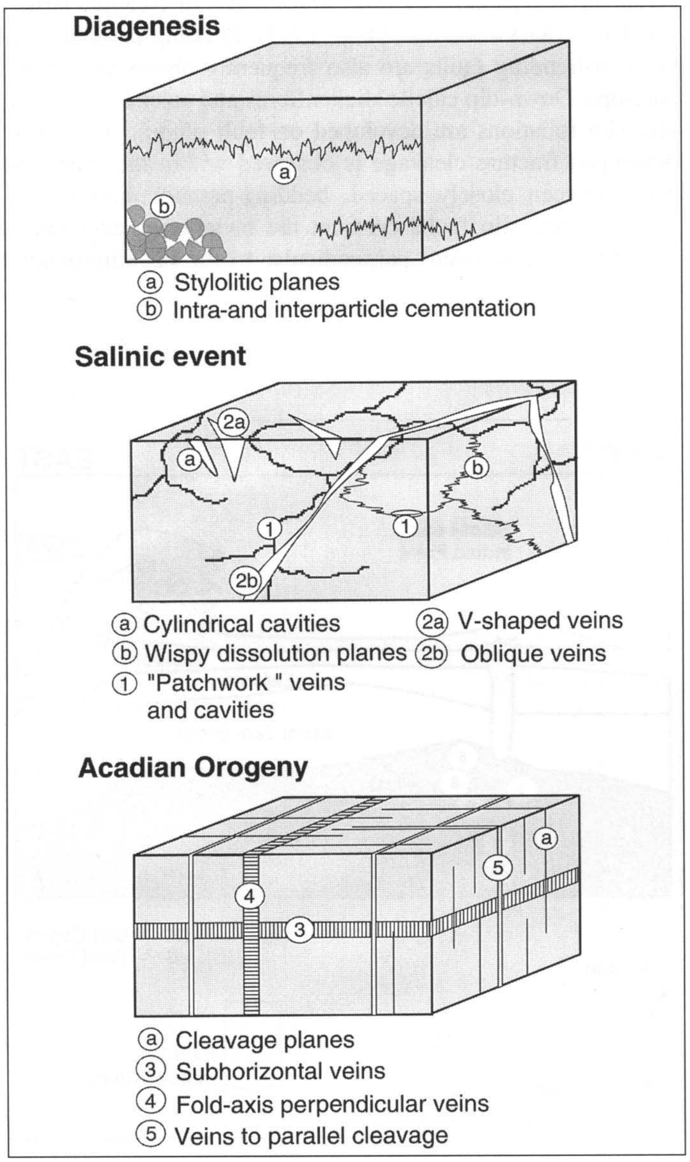

Fig. 8. Pre-Salinic diagenetic features and deformation features developed during the Salinic event and the Acadian Orogeny.

Microfracturing, dissolution of host rock and precipitation of calcite veins and veinlets have been observed in limestones of the Percé and Saint-Jean River areas. These features are post-bedding-parallel stylolites and pre-layer-parallel shortening cleavage (Figs. 5b–e). Dissolution of host carbonate rocks occurs along irregular seams and within cylindrical cavities (with associated iron oxides) that are connected to the top of the limestone beds and seem to progress toward the centre of the bed. The cylindrical cavities are locally, partially infilled by iron oxides and light brown sediments. Based on crosscutting relationships, microfracturing was coeval to dissolution and developed an irregular microfracture network that seems restricted to the upper part of beds (patchwork veining) (V1). These microfractures are very thin, less than 1 mm, and contain rare films of calcite cement too thin for sampling by mechanical separation. Two vein sets also developed during this event. These include V-shaped veins filled with blocky calcite that do not cut through the entire bed (V2a), and non-planar, oblique veins filled with blocky calcite (V2b). Crosscutting relationships indicate that the features developed during this event are post-lithification and pre-Acadian layer-parallel shortening cleavage and folding (Fig. 8). Geometrically, these veins can be distinguished from Acadian veins as they are only a few centimetres in length, are usually restricted to a single bed, and are not pervasive at the outcrop scale. These post-bedding-parallel stylolites and pre-layer-parallel shortening cleavage fractures are tension fractures that can be related to hydrofracturing (V1) and to subhorizontal extension (V2a and Vab). The widespread occurrence of these features indicates that they were formed during a tectonic event of regional importance that we relate to the Salinic event. Deformation structures attributed to the Salinic event are brittle structures implying shallow level pressure–temperature (P–T) conditions during their development.

Acadian structures are well documented in the Gaspé. In the southern peninsula, major strike-slip faults, subsidiary faults, synthetic and antithetic Riedel shear fractures, rotated oblique regional folding (F_R), high-angle reverse faults subparallel to regional F_R folding, and regional layer-parallel shortening cleavage (S_R), are all related to the same Acadian regional deformation event. This is consistent with a classic strike-slip tectonic model (Malo and Béland, 1989). As previously described, observed small-scale deformation features developed during the Acadian Orogeny are easily recognized in the field and in hand specimen. These include dextral and sinistral faults and related Riedel shear fractures, high-angle reverse faults, subvertical stylolitic cleavage planes (layer-parallel shortening) and three sets of fractures (Fig. 8). The first fracture set consists of subhorizontal veins filled with calcite fibres that attest to vertical extension during the first phase of Acadian deformation (V3) (Kirkwood, 1995). The second and third sets of vertical fractures (V4 and V5) occur either parallel or perpendicular to the Acadian layer-parallel shortening cleavage and crosscut the first set. Veins and fractures perpendicular to the V4 fold axis can be either completely filled with subhorizontal fibrous calcite or partially filled with euhedral calcite and quartz (Fig. 5f), both resulting from horizontal extension of the limestone during the second phase of Acadian deformation (Kirkwood, 1995). Less common subvertical veins parallel to the Acadian layer-parallel shortening cleavage are partially filled with fibrous calcite (V5). These deformation features clearly crosscut all previously developed features and have been observed at all sites. They are structurally compatible with the documented transpressional deformation regime during the Middle Devonian in the Gaspé Peninsula, undoubtedly relating them to the Acadian Orogeny. The brittle-ductile nature of Acadian deformation features reflects deeper levels of development within the crust (Kirkwood and Malo, 1993) and higher P–T conditions than during the Salinic event.

Low-angle reverse faults and related fracture cleavage observed only at three outcrops along the Portage River are more difficult to interpret. Downdip calcite slickenfibres and calcite crack-and-seal slip foliations are developed on the fault planes indicating bedding-parallel movement along the low-angle faults. They are crosscut by Acadian strike-slip faults so that they are pre-strike-slip. We relate these structures either to: 1) an early episode of thrust faulting during the first phase of the Acadian Orogeny (e.g. Kirkwood, 1995), which is expressed by thrusting along the Ste-Florence Fault in the western part of the Gaspé Peninsula; or 2) to low-angle thrusting during the pre-Acadian Salinic event.

Petrography

Thin sections were selected to represent features related to the deformation events described previously. Photomicrographs were used to illustrate the chronology of processes in Kirkwood et al. (1997). The main paragenetic features are described herein.

Before lithification, porosity within the calcilutites and wackestones reached 5%, whereas in the packstones and fine grainstones of the White Head Formation, porosity reached 15%. Porosity included intraparticle and minor interparticle primary pores, and secondary aragonite–mollusk moulds. Both types of pore were totally occluded during burial diagenesis by two distinct calcite cements: 1) syntaxial calcite overgrowths on crinoids, mostly coarse and anhedral, dull in cathodoluminescence (CL), sometimes bladed and luminescent; 2) bladed to anhedral crystals of calcite in mosaic, with dull to non-luminescent CL patterns, and typified by well developed sector zoning.

The next generation of cements in the V2 fractures and related features all post-date bedding-parallel stylolites, which translates vertical compression as a result of burial. In addition, their petrographic features are compatible with a burial origin. These secondary pores related to the Salinic event developed mostly by fracturing, and to a minor extent by dissolution in small cavities (Fig. 8). No petrographic evidence exists for significant karstification during the Salinic event. However, small-scale solution features with a red lining of oxides likely represent evidence of meteoric diagenesis. All pores of this stage, including V2a veins and cavities, are occluded by two types of cement: 1) inclusion-free (rarely rich), anhedral calcite crystals in mosaic, with dull CL, sometimes blotchy, locally showing crystal sector zoning (dull to non-luminescent); or 2) inclusion-free, disseminated anhedral crystals of calcite, uniformly non-luminescent or dull. These cements are locally associated with opaque minerals and iron oxides.

The V2b cement consists most commonly of inclusion-rich anhedral to fibrous calcite, dull with blotchy aspect in CL from the presence of numerous inclusions. More rarely an inclusion-free bladed to anhedral calcite cement, dull in CL, occurs within lime mud that contains fossil fragments, quartz fragments and iron oxides.

Deformation features, such as horizontal and vertical fractures, and cleavage planes, enhanced porosity during the Acadian Orogeny. The V3 horizontal fractures are infilled by inclusion-free to inclusion-rich anhedral or bladed calcite, dark in CL, locally zoned. The V3 fractures can be cut by subvertical tectonic stylolites and cleavage planes that occur perpendicular to bedding. Vertical V4 veins and fractures perpendicular to the fold axis also crosscut the V3 fractures. They are partially occluded by: 1) inclusion-rich, fibrous calcite forming fence-like layers, dull in CL; 2) clear, anhedral to rhombohedral calcite, dull to non-luminescent in CL, rich in methane inclusions; and 3) authigenic euhedral silica, non-luminescent in CL, and rich in methane inclusions. Finally, V5 veins parallel to cleavage planes are filled by inclusion-free, anhedral calcite in mosaic, dull in CL and crosscutting V4 veins and fractures.

In summary, the petrographic investigation has established the relative timing of the main features and events that affected the evolution of the White Head Formation. There is no evidence for significant dissolution or karstification related to meteoric diagenesis in the investigated sites. The V2 to V5 cements characterized by geochemistry in the next section all postdate lithification of the White Head and its vertical compression (stylolitization) as a result of burial.

Stable Isotope Geochemistry

Meteoric Calcite Curve

Different types of meteoric calcite cements were sampled in veins and vugs contained within a thick subhorizontal karstified surface occurring in the White Head limestones immediately below the Carboniferous Bonaventure Formation at Cap Blanc (Site 5, Fig. 3). Isotopic data obtained for the karst cements were used to establish the isotopic meteoric calcite curve for the area. Results follow an inverted 'J' curve (Lohmann, 1988) typical of meteoric water and marine limestone interaction (Fig. 9). The $\delta^{13}C$ values vary significantly, but the $\delta^{18}O_{VPDB}$ is practically constant (around –10.00‰) at high water:rock ratios, the opposite is found at low water:rock ratios. The line or field that follows a constant $\delta^{18}O_{VPDB}$ value is called the 'meteoric calcite line,' which can distinguish an isotopic meteoric imprint in the Siluro-Devonian carbonate sequences as the paleolatitude did not change significantly from the Silurian to the Carboniferous.

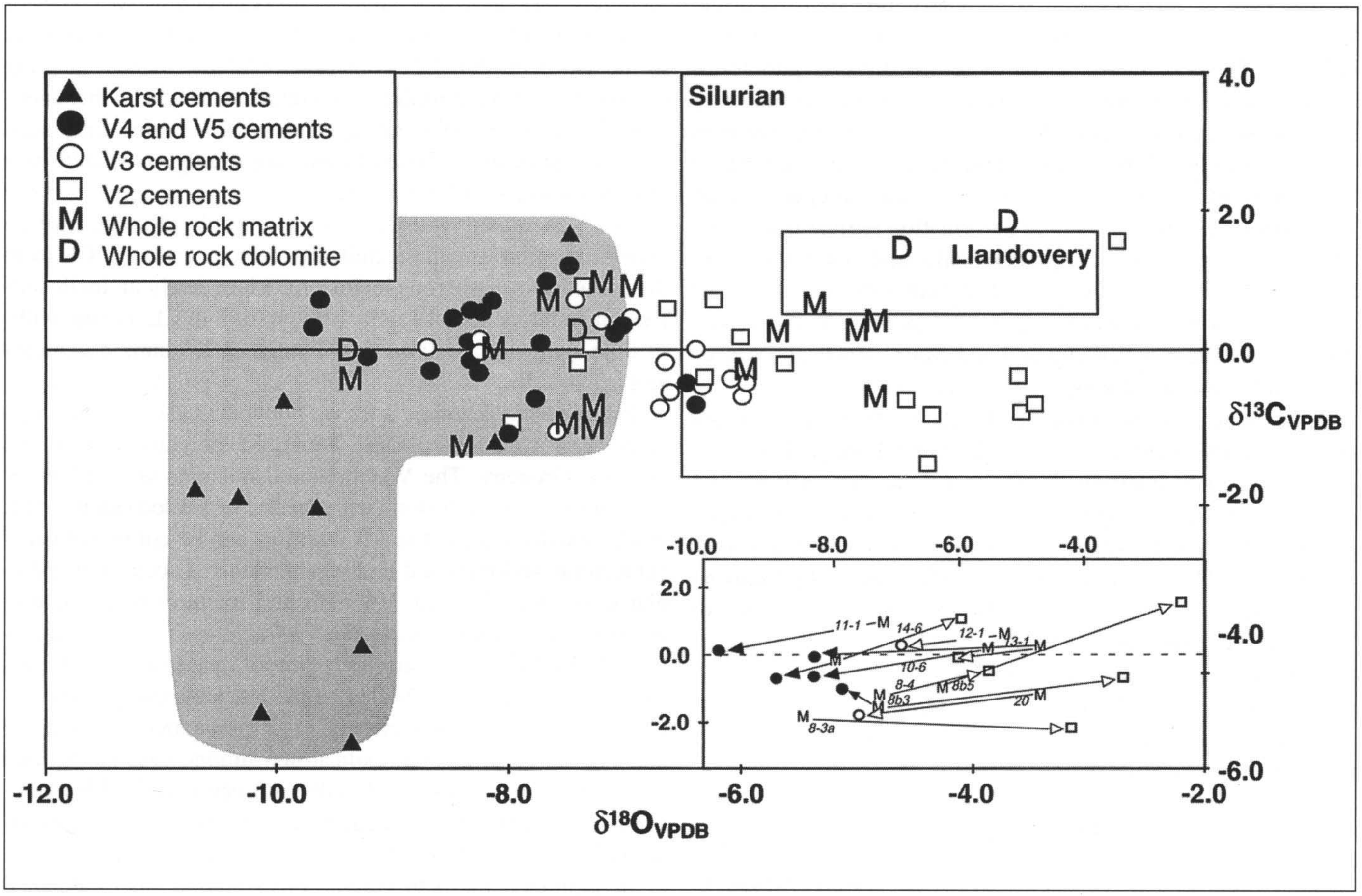

Fig. 9. Stable isotope geochemistry of sampled cements of the White Head Formation. Inset: isotopic results for cements of different events in the same sample. Arrows indicate time as established petrographically. Samples numbers in italics.

Trends in Tectonic Stages

The data for cements within the White Head Formation ranges from –9.67 to –3.46‰, and from –0.91 to 1.85‰, for $\delta^{18}O_{VPDB}$ and $\delta^{13}C$, respectively (Table 1, Fig. 9). The $\delta^{13}C$ values do not show significant variation. They mostly match the normal Silurian–Devonian marine calcite field ($\delta^{13}C$=–1.6 to +7.5‰ ; $\delta^{18}O_{VPDB}$=–6.5 to –2.5‰) taken from Azmy et al. (1998).

For all the different types of analyzed carbonates, the $\delta^{13}C$ results have a similar extent in the narrow range mentioned above. In contrast, the $\delta^{18}O$ values distinguish clearly the major cement types and events that affected the White Head Formation. Six $\delta^{18}O_{VPDB}$ values for whole rock samples plot within the marine box, whereas eight others spread from –8.42 to –7.26‰. For cements filling structures or voids formed during the Salinic event (deformation features such as solution pores and veins), $\delta^{18}O_{VPDB}$ values range from –8.08 to –2.76‰, whereas values for cements within Acadian structures (veins and fractures) vary between –9.61 and –4.38‰. Salinic cements have the highest $\delta^{18}O_{VPDB}$ values of the total trend for cements, whereas the opposite is found for the Acadian cements, their mean $\delta^{18}O_{VPDB}$ values being –5.80 and –7.50‰, respectively.

Isotopic Variation in Time Within Individual Samples

For most of the studied sites, the isotopic variation in time as based on values for cements within the same sample can be summarized by a progressive decrease of $\delta^{18}O_{VPDB}$ values as stated above (Fig. 9 inset). The only exception being Site 8 at the Saint-Jean River Anticline and Site 14 from Rivière du Portage along the ECOB, where V2 cements have anomalous $\delta^{18}O_{VPDB}$ values, as they are higher than values for their respective whole rock samples.

For most studied sites, the general diagenetic trend as revealed by the whole rock attributes can be explained by marine diagenesis followed by progressively deeper burial recrystallization and cementation. The limestone was formed in marine conditions reflected by whole rock samples plotting within the Late Ordovician to Early Silurian marine calcite box (M in Fig. 9) (Azmy, et al., 1998). The gradual depletion of $\delta^{18}O_{VPDB}$ values for whole rock samples is related to replacement or recrystallization during burial (Fig. 9). The succession of vein cements suggests progressively higher temperatures of precipitation or burial depths, i.e., conditions typical of shallow to deeper burial settings. The higher (anomalous) $\delta^{18}O_{VPDB}$ values for V2 cements from the Saint-Jean River Anticline and

ECOB could reflect either 1) an incursion of isotopically heavy, exotic fluids such as metamorphic fluids; or 2) uplift of the sequence to a cooler setting following a period of shallow burial conditions. The White Head Formation would then have been subjected to subsequent burial to much greater depths as indicated by lower $\delta^{18}O_{VPDB}$ values in Acadian veins. Field evidence and smaller-scale (hand specimen) crosscutting relationships between the observed structures clearly indicate that the V2 veins, which record exceptional conditions, are pre-Acadian, coinciding with the Salinic event further strengthening the uplift scenario.

Fluid-Inclusion Microthermometry

Samples and thin sections for the fluid inclusion study were carefully selected with the help of isotopic geochemistry criteria in order to assess the interpreted general trend of progressive burial and to determine the origin of the anomalous trend in the St-Jean River Anticline and ECOB.

Percé Area

Fluid inclusions were studied in V2 calcite veins related to the Salinic event from two samples from the eastern Percé area at Site 10. Fluid inclusions from sample 10-10 are either monophase (all liquid) or show homogenization temperatures from 43.9° to 89.1°C (Table 2 and Fig. 10), suggesting

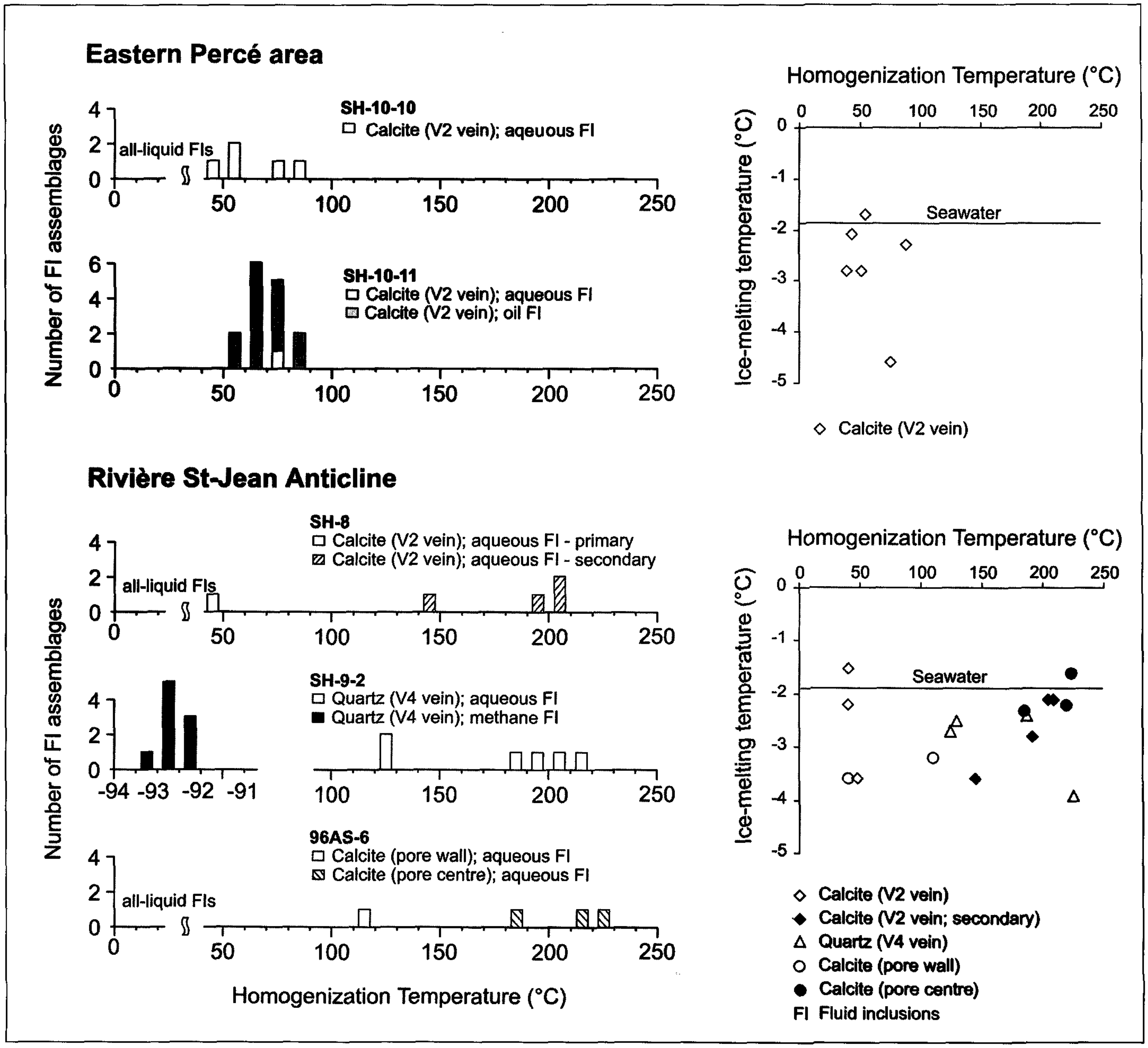

Fig. 10. Histograms of homogenization temperatures and $T_{ice\ melting}$ versus T_h diagrams of fluid inclusions from the White Head Formation for all cement types investigated, after selection based on isotopic geochemistry criteria.

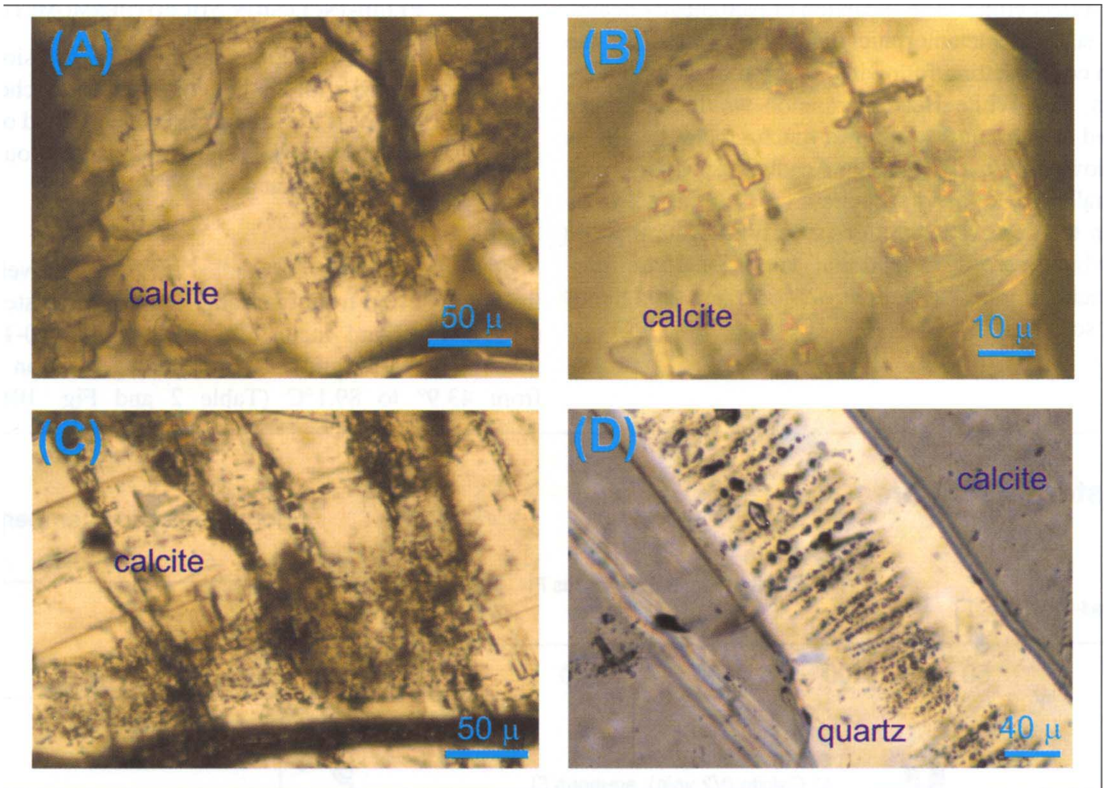

Fig. 11. (A) Cloudy core of calcite composed of fluid inclusions in a V2 vein (sample SH-8). **(B)** A close-up view of the fluid inclusions shown in A. **(C)** Primary inclusions superimposed by secondary inclusions in a V2 vein (sample SH-8). **(D)** Methane inclusions in the core of a quartz crystal from a V4 vein (sample SH-9-2).

relatively shallow burial conditions. Fluid salinity values range from 2.9 to 4.6 wt % NaCl equivalent (Table 2), which are near those of seawater (~ 3.5 wt %).

Sample 10-11 contains numerous oil inclusions, showing homogenization temperatures ranging from 50.4 to 87.2°C (Table 2, Fig. 10), with an average of 68.6°C. Only one group of workable aqueous inclusions was found, this group shows a homogenization temperature of 76.1°C (Table 2 and Fig. 10) and a salinity of 7.3 wt % NaCl equivalent (Table 2). The average (n = 8) fluorescence spectrum of the oil inclusions has an L_{max} value of 510 nm and a Q value of 0.042. The average API value was calculated at 41.2. An isochore was constructed for the average oil inclusion using the VTFLINC program of Calsep A/S. With the trapping temperature being approximated by the average T_h of the aqueous inclusions (76.1°C), the fluid pressure was estimated to be 330 bars. This pressure value corresponds to a depth of 1300 m, assuming lithostatic loading (2.7 g/cm^3).

Saint-Jean River Anticline

Three samples from the Saint-Jean River Anticline were studied for fluid inclusions. The sample from location 8 contains the anomalous V2 calcite. Fluid inclusions occurring in the cloudy core of this calcite are predominantly monophase (all liquid) (Figs. 11A, B). Some liquid + vapour inclusions also occur in the cloudy core, and show low homogenization temperatures (47.8°C) (Figs. 10, 11D, Table 2). Fluid salinity values vary from 2.6 to 5.8 wt % NaCl equivalent, and the T_h-salinity scatterplot suggests a mixing line between high-salinity water and below-marine salinity water. Secondary fluid inclusions distributed along intercrystal fractures or fractures ending at the crystal edges (Fig. 1D) show homogenization temperatures ranging from 144.5 to 208.2°C and salinities from 3.5 to 4.6 wt % NaCl equivalent (Table 2 and Fig. 10).

Near the pore walls, fluid inclusions in interparticle calcite cement of the grainstone 96AS-6 (location 9) are monophase (all liquid) or show relatively low homogenization temperatures (110.0°C) (Table 2 and Fig. 10). Fluid salinities range from 4.9 to 5.8 wt % NaCl equivalent (Table 2). In the centre of the pores, fluid inclusions in calcite cement of the same sample show relatively high homogenization temperatures, ranging from 185.3 to 222.5°C (Table 2 and Fig. 10). Fluid salinities range from 2.7 to 3.8 wt % NaCl equivalent (Table 2). Sample 9-2 contains quartz + calcite V5 veins developed during the Acadian Orogeny. Both aqueous and methane inclusions occur in the cloudy core of quartz crystals (Fig. 11D) or are scattered in calcite crystals. The wide range in homogenization temperatures of aqueous inclusions within individual cloudy cores of quartz crystals are interpreted as indicating heterogeneous trapping, and the minimum T_h value is used to represent the trapping temperature (Table 2). However, the variation between different crystals, from 124.4 to 225.2°C (Table 2 and Fig. 12) probably reflects the real variation in fluid temperature. Fluid salinities range from 4.0 to 6.3 wt % NaCl equivalent. Methane inclusions co-existing with aqueous inclusions in the cloudy core of quartz crystals show homogenization temperatures ranging from –93.1 to –92.1°C to liquid (Table 2 and Fig. 12), with an average of –92.6°C. An isochore was constructed for the average methane inclusion using the FLINCOR program of Brown (1989). With the trapping temperature being approximated by the average T_h of the aqueous inclusions (177.7°C), the fluid pressure was estimated to be 1010 bars. This pressure value corresponds to a depth of 3800 m, assuming lithostatic loading (2.7 g/cm^3).

The relatively high T_h values of the primary aqueous fluid inclusions in the interparticle pore-filling calcite, in the Acadian vein (V5) and in secondary inclusions in the Salinic vein (V2) reflect the usual evolution to progressively higher burial conditions. In contrast, the relatively low values for the anomalous Salinic V2 calcite suggest that the vein was formed under relatively shallow burial conditions (probably shallower than the lithification of the rock; see below). We can infer that the host rock was subjected to either a thermal event or significant burial after development of the vein, because higher values exist in the secondary inclusion of this V2 calcite.

Table 2. Fluid-inclusion microthermometric data of samples from the White Head Formation.

Sample	Host mineral	Occurrence	Size (mm)	T_{m}- (°C) Range	Mean (n)	Salinity (wt % NaCl eq.) Range	Mean (n)	T_h (°C) Range	Mean (n)
Eastern Percé area									
SH-10-10	Calcite	Randomly distributed	4	-	-	-	-	70.7	70.7 (1)
	(T3 vein)	Isolated	18	-1.7	-1.7 (1)	2.9	2.9 (1)	54.4	54.4 (1)
		Randomly distributed	7 ~ 9	-2.3	-2.3 (1)	3.9	3.9 (1)	86.0 ~ 92.2	89.1 (2)
		Randomly distributed	5 ~ 7	-2.7 ~ -2.8	-2.8 (2)	4.5 ~ 4.6	4.6 (2)	50.9 ~ 51.2	51.1 (2)
		Isolated	6	-2.8	-2.8 (1)	4.6	4.6 (1)	all liquid	all liquid
		Isolated	7	-2.1	-2.1 (1)	3.5	3.5 (1)	43.9	43.9 (1)
SH-10-11	Calcite	Randomly distributed	4 ~ 7	-4.6	-4.6 (1)	7.3	7.3 (1)	72.0 ~ 79.4	76.1 (3)
	(T3 vein)	Cluster	3 ~ 4	-	-	-	Oil:	63.2 ~ 65.6	64.7 (3)
		Isolated	7	-	-	-	Oil:	50.4	50.4 (1)
		Isolated	3	-	-	-	Oil:	68.0	68.0 (1)
		Isolated	4	-	-	-	Oil:	70.7	70.7 (1)
		Isolated	5	-	-	-	Oil:	75.1	75.1 (1)
		Isolated	5	-	-	-	Oil:	61.6	61.6 (1)
		Isolated	5	-	-	-	Oil:	77.3	77.3 (1)
		Isolated	15	-	-	-	Oil:	74.4	74.4 (1)
		Cluster	10 ~ 14	-	-	-	Oil:	63.2 ~ 64.5	63.9 (1)
		Cluster	2 ~ 4	-	-	-	Oil:	64.2 ~ 68.4	66.3 (4)
		Cluster	5 ~ 6	-	-	-	Oil:	81.3 ~ 82.7	81.8 (3)
		Cluster	3 ~ 8	-	-	-	Oil:	63.1 ~ 65.6	64.0 (3)
		Cluster	5 ~ 10	-	-	-	Oil:	87.0 ~ 87.3	87.2 (2)
		Cluster	4 ~ 6	-	-	-	Oil:	47.8 ~ 59.0	55.2 (3)
Rivière St-Jean Anticline									
SH-8	Calcite	Cloudy core edge	6 ~ 9	-3.6	-3.6 (1)	5.8	5.8 (1)	47.3 ~ 48.3	47.8 (2)
	(T3 vein)	Cloudy core edge	10	-2.2	-2.2 (1)	3.7	3.7 (1)	all liquid	all liquid
		Cloudy core	8	-1.5	-1.5 (1)	2.6	2.6 (1)	all liquid	all liquid
		Intercrystal fracture	6 ~ 7	-3.6	-3.6 (1)	5.8	5.8 (1)	141.9 ~ 147.0	144.5 (2)
		Fracture ending at crystal edge	6 ~ 15	-2.0 ~ -2.1	2.1 (2)	3.4 ~ 3.5	3.5 (2)	200.3 ~ 213.3	208.2 (4)
		Intercrystal fracture	4 ~ 8	-2.8	-2.8 (1)	4.6	4.6 (1)	188.0 ~ 195.6	191.8 (2)
		Intercrystal fracture	10 ~ 15	-2.1	-2.1 (1)	3.5	3.5 (1)	203.3 ~ 205.6	204.5 (2)
SH-9-2	Quartz	Cloudy core	5 ~ 18	-2.0 ~ -3.0	-2.5 (3)	3.4 ~ 4.9	4.2 (3)	129.6 ~ 202.6	129.6*
	(T5 vein)	Cloudy core	12 ~ 14	-	-	-	-	178.7 ~ 202.5	190.6 (2)
		Cloudy core	9 ~ 10	-2.6 ~ -2.8	-2.7 (2)	4.3 ~ 4.6	4.5 (2)	124.4 ~ 206.7	124.4*
		Cloudy core	7	-	-	-	-	209.3	209.3 (1)
		Cloudy core	8	-3.9	-3.9 (1)	6.3	6.3 (1)	225.2	225.2 (1)
		Cloudy core	7	-2.4	-2.4 (1)	4.0	4.0 (1)	187.0	187.0 (1)
		Cloudy core	5 ~ 12	-	-	-	Methane:	-92.1 ~ -93.3 (L)	-92.7 (5)
		Cloudy core	5 ~ 11	-	-	-	Methane:	-92.3 ~ -93.5 (L)	-92.7 (5)
		Cloudy core	9 ~ 11	-	-	-	Methane:	-92.2 ~ -93.2 (L)	-92.7 (4)
		Cloudy core	5 ~ 12	-	-	-	Methane:	-91.3 ~ -92.9 (L)	-92.4 (5)
		Cloudy core	6 ~ 12	-	-	-	Methane:	-92.5 ~ -93.8 (L)	-92.9 (5)
		Cloudy core	4 ~ 11	-	-	-	Methane:	-91.2 ~ -93.6 (L)	-92.4 (6)
		Cloudy core	6 ~ 10	-	-	-	Methane:	-91.3 ~ -92.9 (L)	-92.1 (5)
		Cloudy core	5 ~ 12	-	-	-	Methane:	-92.5 ~ -93.5 (L)	-93.1 (4)
		Cloudy core	4 ~ 5	-	-	-	Methane:	-92.4 ~ -92.8 (L)	-92.6 (2)
96AS-6	Calcite	Randomly distributed	7	-3.6	-3.6 (1)	5.8	5.8 (1)	all liquid	all liquid
	(Pore wall)	Cluster	8 ~ 9	-2.8 ~ -3.5	-3.2 (2)	4.6 ~ 5.2	4.9 (2)	105.7 ~ 114.2	110.0 (2)
	Calcite	Randomly distributed	6 ~ 10	-1.9 ~ -2.6	-2.3 (4)	3.2 ~ 4.3	3.8 (4)	172.4 ~ 199.3	185.3 (4)
	(Pore centre)	Isolated	8	-1.6	-1.6 (1)	2.7	2.7 (1)	222.5	222.5 (1)
		Isolated	10	-2.2	-2.2 (1)	3.7	3.7 (1)	219.9	219.9 (1)

* The wide range in Th within a FI assemblage is interpreted to reflect heterogenous trapping; minimum Th is used to represent trapping temperature.

Fracturing, Porosity Occlusion and Migration of Hydrocarbons During the Salinic Event and the Acadian Orogeny

Combined microstructural and petrographic evidence has helped us propose a genetic link between fracture sets and the Salinic event and Acadian Orogeny that most probably enhanced the porosity and permeability at specific times in the Upper Ordovician to Lower Silurian limestones of the White Head Formation.

Salinic cements sampled in V2 veins have homogenization temperatures, T_h, ranging between 43.9 and 92.2°C and salinity between 2.6 and 5.8 wt % NaCl equivalent, suggesting a broad range of precipitation conditions. This is also indicated by the isotopic results. An informative data set is the trend from liquid-only inclusions to liquid + vapour secondary inclusions in intercrystalline fractures that crosscut V2 cements in Salinic veins. The secondary fluid inclusions also show higher T_h values, which suggests that low-temperature cementation was followed by cementation in a deeper burial setting (note that the whole rock oxygen isotopic results were much lower for calcite in Acadian veins than for V2 calcite) (Fig. 9). This supports the interpretation involving uplift of the White Head limestones and inferred on the basis of the oxygen isotope values in V2 veins, which lie within the marine calcite range. The microthermometric data in the anomalous Salinic V2 cements can be explained by the influx of marine-like water at shallow burial conditions (T2, Fig. 12). Therefore, both the isotopic data from the Saint-Jean River Anticline and the ECOB and fluid inclusion data from the Saint-Jean River Anticline and the Percé area indicate that the most plausible explanation for the development of the Salinic veins and related structural features is an uplift related to extension and block faulting during the Salinic event. This implies that the White Head Formation was buried (T1), fractured and uplifted during the Salinic event (T2), and then buried and fractured again during the Acadian Orogeny (T3) (Fig. 12).

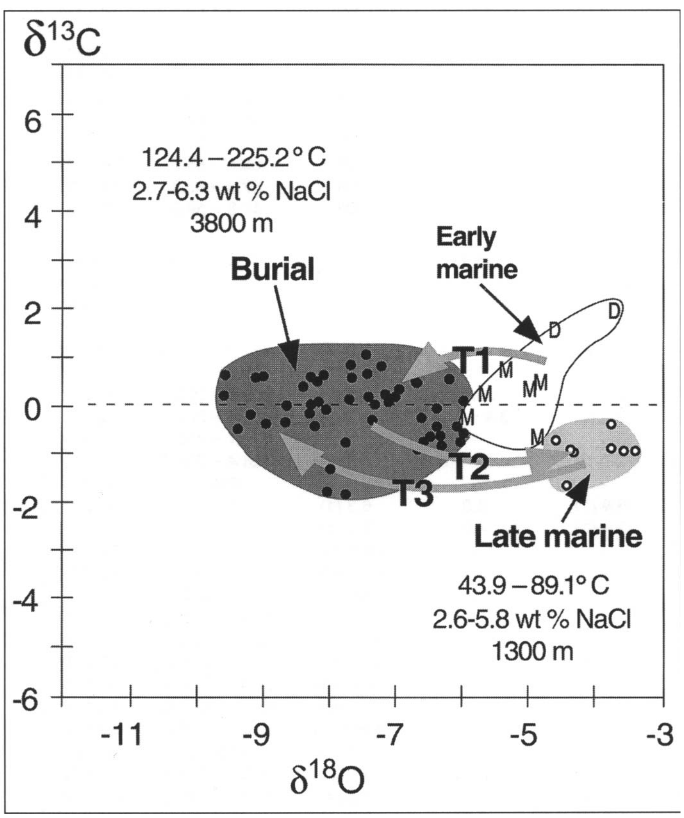

Fig. 12. P–T and geochemical conditions during geological events. T1: early burial, T2: uplift and marine flush during the Salinic event, T3: deep burial during the Arcadian Orogeny.

The proposed structural evolution (fracture sets, P–T and geochemical conditions) during fracture development in the White Head limestone sheds new light on the tectonic scenario of eastern Gaspé during the Salinic event. Salinic tension fractures related to hydrofracturing and to subhorizontal extension clearly pre-date Acadian veins, fractures and cleavage and are compatible with the development of normal faults in the Gaspé Basin as proposed by Bourque (2001, this issue) and Malo (2001, this issue). Even though the fractures are not obvious at the outcrop scale, their widespread occurrence within the study area indicates that the Salinic event is indeed a regional tectonic event. The brittle nature of these structures implies shallow level P–T conditions also confirmed by the low homogenization temperatures determined from Salinic (V2) cements. Isotopic and fluid inclusion data also indicate a late fluid flush of marine-like origin during this event.

The interplay between normal faulting and sea-level changes during the Salinic resulted in an erosional unconformity within the Silurian–Devonian sequence (Bourque, 2001, this issue) and provides a mechanism for relative uplift of the White Head limestones. However according to our data, it seems doubtful that the erosion surface cut deep enough into the sequence to reach the White Head limestones. Minimum depth estimates for the White Head limestones, obtained using isotopic and fluid inclusion data, indicate 0.7 km of overburden (see below). There is absolutely no evidence, either petrographically or based on isotopic signatures, for significant meteoric diagenesis or karst development during the Salinic event in the White Head limestones in the immediate vicinity of the studied areas. However, clear evidence for meteoric diagenesis during the Salinic event has been documented in younger strata, i.e., in the Sayabec (Lavoie and Chi, 2001, this issue) and West Point formations (Bourque et al., 2001, this issue).

Fluid inclusions in V2 calcite veins related to the Salinic event show homogenization temperatures from 43.9 to 89.1°C, suggesting relatively shallow burial conditions. Fluid pressure estimated from temperature data of aqueous and oil inclusions in Salinic cements points to a burial depth of 1.3 km. Relatively high homogenization temperatures, ranging from 124.43 to 222.5°C, have been determined from aqueous inclusions in Acadian veins, suggesting deeper burial conditions. Pressure values estimated from aqueous and oil inclusions in Acadian veins indicate a burial depth of 3.8 km.

The T_h values of cements were also used to estimate burial depth at the time they precipitated and to evaluate porosity occlusion of the different fracture sets. For some cements, fluid inclusion data were not available, thus the temperature of precipitation was calculated using the equation of O'Neil et al. (1969) and the $\delta^{18}O_{VPDB}$ of the cements. This requires that $\delta^{18}O_{SMOW}$ of the parent water is known, or calculated from available T_h and their matching $\delta^{18}O_{VPDB}$ in other cements. As suggested by the fluid inclusion data, at an early stage of burial, the formation waters very likely had $\delta^{18}O_{SMOW}$ near the signal of seawater (3.25‰, using a ratio in calcite at –4.50 ‰ and a surficial temperature of 20°C). For later stage cements, other $\delta^{18}O_{SMOW}$ values of parent waters were also calculated at 5.30 and 2.70, using the lowest and highest $\delta^{18}O_{VPDB}$ values of Salinic cements, respectively (Table 1).

These parent-water $\delta^{18}O_{SMOW}$ values were then used to evaluate the temperature of precipitation of the most ^{18}O-depleted burial cement for each tectonic stage. The parent-water values increase with the assumed level of burial, i.e., –3.20, 2.70 and 5.30 ($\delta^{18}O_{SMOW}$) for shallow burial diagenesis, the Salinic event and the Acadian Orogeny, respectively (Table 1). Finally, for each cement in structural features, an evaluation of maximum burial can be given for occlusion using a surficial temperature of 20°C and a geothermal gradient of 25°C/km, estimated from the Gulf Sunny Bank core (Bertrand, 1987). It is pertinent here to point out the limitations of this kind of depth estimate: 1) thermal gradient uncertainty; 2) uncertainty about how representative T_h is; and 3) assumptions of burial effect instead of hydrothermal activity.

Based on these calculations and according to our estimates, primary porosity in the White Head Formation was not occluded before burial depths of 0.74 km for mudstones and 6.6 km for grainstones. The T_h measurements and $\delta^{18}O$ values also indicate shallow burial conditions during early diagenesis and the Salinic event, probably at depths as low as 0.7 and 1.1 km. It is well known that mudstones become completely lithified within hundreds of metres of burial; 0.7 km is therefore an acceptable depth. However, wackestone-grainstone can contain intra-shell cavities that stay open at greater depths. These figures are in agreement with estimations of burial depth at the time of cementation based on fluid pressure estimates, i.e., burial depths of 1.3 and 3.8 km for Salinic and Acadian veins, respectively. In addition, general trends in terms of porosity occlusion are quite variable and largely depend on the tectonic (burial) history of a carbonate sequence.

The development of fractures contributed effectively to porosity development in the White Head Formation. Petrography of fluid inclusions indicates that hydrocarbon-rich fluids did migrate through the fracture network developed during both the Salinic and Acadian events. The presence of liquid hydrocarbon inclusions in V2 veins indicates that development of fractures during the Salinic event occurred while the source rocks were well within the oil window and the host rock, the White Head limestones, either within or above the oil window. On the other hand, methane inclusions in the V4 and V5 veins indicate that development of Acadian fractures occurred when source rocks and limestones of the White Head Formation were at depths greater than the oil window. Moreover, as indicated by the liquid hydrocarbon inclusions in the V2 calcite, migration of oil within the Salinic fracture network occurred before the source rocks were too mature and also suggests that pre-Salinic burial of the White Head had not surpassed depths of 1.5–2 km. The oil inclusions in Salinic veins and the observed methane in Acadian veins both indicate that source rocks were present in the Saint-Jean River Anticline and the Percé area, and that fractures in the White Head acted as conduits for hydrocarbons at different stages of maturity. However, based on field observations, fracture porosity developed during the Salinian (V1 and V2 veins) seems restricted to less than 1% of the rock volume. During the Acadian Orogeny, porosity was apparently restricted to the late fractures themselves, i.e., V4 and V5 veins and fractures that make up 5% of the total rock volume, of which approximately 1% are still presently open.

The possible source rocks for the hydrocarbon-rich inclusions could be either the Honorat Group or the Québec Supergroup rocks, which represent the underlying rocks of the White Head in different parts of the Gaspé Peninsula. The Honorat Group, which underlies the White Head in southern Gaspé and along the ECOB, contains a black shale unit of the same age as the Utica and Macastry shales, which constitute source rocks in the St. Lawrence Lowlands and Anticosti Island. In northeastern Gaspé, between the Troisième Lac and Bras Nord-Ouest faults (Fig. 1), rocks of the Québec Supergroup underly the White Head and have been suggested as possible source rocks in northeastern Gaspé on the basis of their TOC content (Bertrand and Malo, 2001, this issue).

Summary and Conclusions

This study of the White Head Formation has demonstrated that, by combining both microstructural analysis and cement characterization (petrography, stable isotope geochemistry and fluid inclusion microthermometry), a better timeframe can be established for the migration of hydrocarbon-rich fluids during diagenesis and tectonic events. The proposed tectonic model for the development of observed deformation features geochemically characterized in the White Head limestone involves three distinct events, beginning with shallow to moderate burial (T1), followed by fracturing and uplift as a result of normal faulting during the Salinic event (T2), and deeper burial, fracturing, folding and strike-slip faulting during the Acadian Orogeny (T3). The microthermometric and isotope data point toward an influx of marine-like water at shallow burial conditions during the Salinic event.

Fractures developed within the White Head limestones during the Salinic event and the Acadian Orogeny contributed to enhance porosity and permeability to some extent at different stages during the entire tectonic history of the rocks. The presence of liquid hydrocarbon inclusions in Salinic veins and methane inclusions in the Acadian veins indicates that hydrocarbon-rich fluids did migrate through the fracture network. The Salinic fracture network could therefore have provided a pathway for expulsion of liquid hydrocarbons from source rocks before they became overly mature. Acadian fractures perpendicular to the fold axis are still open and contribute to the present-day permeability of the rocks. These Acadian features are widespread within the entire Siluro-Devonian section and should be investigated more closely, especially in the area located between the Troisième Lac and Bras Nord-Ouest faults, where numerous oil seeps have been documented.

To further the evaluation of the potential plays in northeastern Gaspé, we recommend a more detailed structural investigation of Salinic fractures in pre-Salinic rocks. In view of the findings of liquid oil and methane inclusions in Salinic fractures, an evaluation of the thermal maturation history of the rocks that underly the White Head Formation in the Percé and ECOB areas, i.e., the Honorat Group, would help test their potential as source rocks.

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