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ZONATION OF DIAGENESIS AND LOW-GRADE METAMORPHISM IN CAMBRO-ORDOVICIAN FLYSCH OF GASPÉ PENINSULA, QUEBEC APPALACHIANS

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ABSTRACT

In the Taconic belt of Gaspé Peninsula Cambro-Ordovician deep-water shales yield very similar patterns of trend surfaces for both illite crystallinity (IC, based on a network of 350 sample points) and mean random reflectance of asphaltic pyrobitumen ($\bar{R}_o$, 95 samples). An epimetamorphic and higher grade aureole (IC $\leqslant$ 0.24° $\triangle 2\theta$, $\bar{R}_o \geqslant$ 5%) around the Devonian McGerrigle Mountains pluton is surrounded by concentric zones of anchizonal (0.24 < IC $\leqslant$ 0.43° $\triangle 2\theta$, 2.7% $\leqslant \bar{R}_o <$ 5%) and late diagenetic conditions (IC > 0.43° $\triangle 2\theta$, $\bar{R}_o <$ 2.7%). The epimetamorphic halo is more than twice as wide (16–20 km) as the intrusive body (8 km). The width of the alteration zone suggests that the intrusion probably extends over a much larger area at relatively shallow depth. A northeasterly deflection of the isopleths suggests that the intrusive body may plunge in this direction in the subsurface. Poor illite-crystallinity in the immediate vicinity west of the pluton is interpreted as a hydrothermal anomaly. West of the central thermal dome, maturation levels decrease northwards indicating a northward-dipping "thermal slope" in sediments that become younger, as well, in this direction. As progressively deeper tectonic units are involved in this trend, the preorogenic diagenetic grade (reached during sedimentary burial at the original site of deposition) seems to have been preserved in this region. For the Lower Ordovician Tourelle Formation, a maximum temperature of 170°C has been estimated from the observed reflectance of $\bar{R}_o$ = 1.5% by assuming an effective heating time of 25 Ma. For an average geothermal gradient of 30 to 35°C/km, this assumption would imply 5 to 6 km of burial. With a preserved thickness of 1 km of the Tourelle Formation, 4 to 5 km of younger rocks appear to have been removed. East of the thermal dome, maturation levels form a pattern that can best be described as a "thermal trough" with a central elongate low in the Cambro-Ordovician Cap-des-Rosiers Group and the Middle Ordovician Deslandes Formation. Both to the north (late Middle Ordovician Cloridorme Formation) and south (Cap-des-Rosiers Group), rocks are more highly matured. Since diagenetic grade increases northward with decreasing age, burial-diagenetic conditions appear to have been exceeded during later synorogenic heating.

Keywords: diagenetic and low-grade metamorphic zonation, illite crystallinity, reflectance of asphaltic pyrobitumen, transported (preorogenic) diagenesis, syn- and postorogenic diagenesis, Cambro-Ordovician flysch, Quebec Appalachians.

SOMMAIRE

Dans la ceinture taconique de la péninsule de Gaspé, les shales cambro-ordoviciens déposés en eau profonde montrent une concordance régionale frappante entre la cristallinité de l'illite (CI, déterminée sur 350 échantillons) et la réflectance moyenne du pyrobitume asphaltique ($\bar{R}_o$, 95 échantillons). L'auréole épimétamorphique et à facies encore plus élevés (CI $\leqslant$ 0.24° $\triangle 2\theta$, $\bar{R}_o \geqslant$ 5%) du complexe plutonique dévonien des monts McGerrigle se trouve entourée de zones concentriques marquant l'anchizone (0.24 < CI $\leqslant$ 0.43° $\triangle 2\theta$, 2.7% $\leqslant \bar{R}_o <$ 5%) et les conditions de diagenèse tardive (CI > 0.43° $\triangle 2\theta$, $\bar{R}_o <$ 2.7%). La largeur du halo épimétamorphique (16–20 km) égale plus de deux fois le diamètre du massif intrusif (8 km). La largeur de la zone d'altération fait supposer que la masse intrusive occupe une superficie beaucoup plus vaste à assez faible profondeur. Les isoplèthes, s'infléchissant vers le nord-est, indiqueraient un ennoyage du pluton dans cette direction. La présence à l'ouest du pluton de zones où la cristallinité de l'illite est imparfaite s'interprète comme anomalie hydrothermale. A l'ouest du dôme thermique central, le degré de maturation diminue vers le nord, indication d'une "pente thermique" dans cette direction, dans laquelle les sédiments deviennent, eux aussi, de plus en plus jeunes. Vu que des unités tectoniques de plus en plus profondes sont impliquées dans cette zonation, le degré de diagenèse pré-orogénique (atteint lors de l'enfouissement au site originel de déposition) semble avoir été préservé dans cette région. Pour les roches de la formation Tourelle (Ordovicien inférieur), une température maximum de 170°C a pu être estimée à partir de la réflectance observée ($\bar{R}_o$ = 1.5%), en supposant une durée effective du réchauffement de 25 Ma. Pour un gradient géothermique moyen de 30 à 35°C/km, cette hypothèse indiquerait un enfouissement de 5 à 6 km de profondeur. L'épaisseur actuelle de la formation Tourelle (1 km) requiert l'érosion de 4 à 5 km de roches plus jeunes. A l'est du dôme thermique, les résultats sur le degré de maturation définissent une "auge thermique" dont la dépression centrale s'allonge dans les roches du groupe Cap-des-Rosiers (Cambro-ordovicien) et de la formation Deslandes (Ordovicien moyen). Tant vers le nord (formation Cloridorme, Ordovicien moyen supérieur) que vers le sud (groupe Cap-des-Rosiers), les roches sont plus évoluées. Comme le degré de diagenèse s'accentue vers le nord au fur et à mesure que décroît l'âge des roches, les conditions de diagenèse lors de l'enfouissement semblent avoir été dépassées pendant le réchauffement synorogénique subséquent.

(Traduit par la Rédaction)

Mots-clés: zonation diagénétique et métamorphique, cristallinité de l'illite, réflectance du pyrobitume asphaltique, diagenèse transportée (pré-orogénique), diagenèse syn- et post-orogénique, flysch cambro-ordovicien, Appalaches québécoises.

INTRODUCTION

Progressive thermal maturation of clastic rocks with increasing time and depth of burial results in the gradual transformation of organic and inorganic compounds. Organic matter reflectance ($\bar{R}_o$) and clay mineralogy are presently used as principal tools for mapping regional variations in maturation and establishing a zonation of diagenetic and low-grade metamorphic terrains. In several orogenic belts, maturation studies of shales have led to interesting and surprising findings. For instance, in the Taconic belt of the Appalachians around Quebec City, the occurrence of preorogenic inverted diagenesis has been recognized (Ogunyomi *et al.* 1980), *i.e.*, more highly matured older rocks tectonically overlie less mature younger rocks. Inverted diagenesis has also been reported from the external part of the Alps in Switzerland and France (Frey *et al.* 1980, Kübler *et al.* 1979) and from the Northern Appenines in Italy (Reuter *et al.* 1978). This shows that, in external zones of orogenic belts, original levels of maturation reached during sedimentary burial may be preserved beyond the time of thrusting and nappe emplacement. Therefore, the phenomenon of "transported diagenesis" offers the

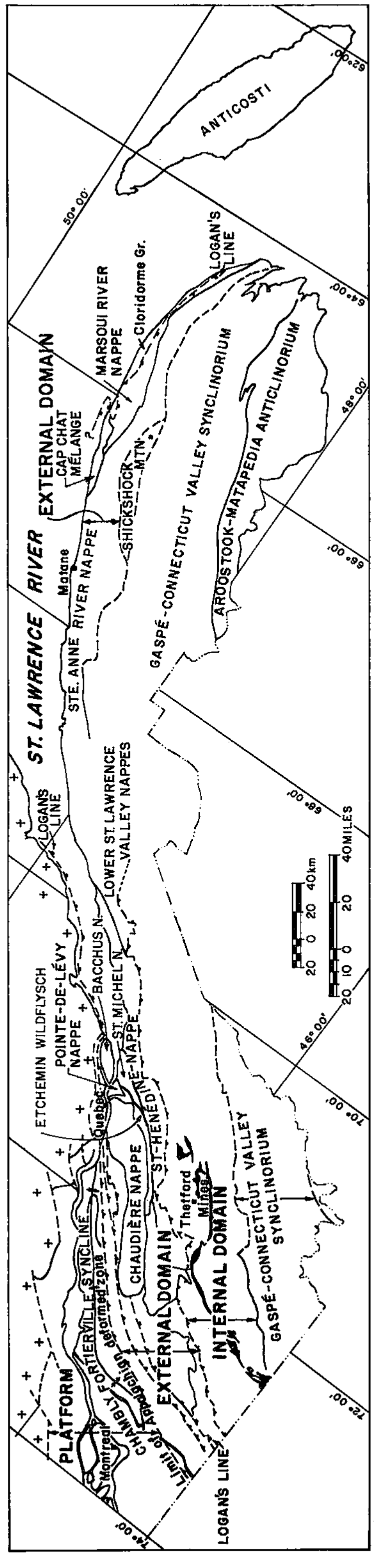


FIG. 1. Tectonic units of Quebec Appalachians (modified after St-Julien & Hubert 1975).

possibility to unravel, at least in part, the burial and subsidence history in structurally complex thrust-sheet terrains. This is a key problem in the study of ancient continental margins. The discovery and proper interpretation of transported diagenesis, however, are of interest not only from this point of view but also for the gas and oil potential of these regions.

Geological Setting

This study is part of a mapping project directed towards the regional patterns of thermal maturation in the Taconic belt of the Quebec Appalachians. Cambro-Ordovician deep-water, continental-slope and continental-rise sediments of this belt represent a portion of the early Paleozoic North American continental margin. Following Hadrynian rifting, extensive accumulation of sediment took place during the passive phase of margin evolution, which lasted until early Ordovician time. Collision with a late Cambrian to early Ordovician island arc caused foundering of the shelf and development of a retroarc basin in which the Tourelle, Deslandes and Cloridorme Formations were deposited (St-Julien & Hubert 1975, Hiscott 1977). The Taconic orogeny affected the area in late Ordovician time, reaching its peak approximately 440 Ma ago. Later deformation during the Acadian and Appalachian orogenies did not affect the Taconic belt which is, therefore, well suited for maturation studies. As shown by the results of Ogunyomi *et al.* (1980) for the Quebec City traverse, maturation levels may be expected to display coherent patterns.

Structurally the Taconic belt has been subdivided (Fig. 1) into an External and an Internal Domain (St-Julien & Hubert 1975); both are composed of allochthonous rocks that have been thrust at least 30 to 40 km over shallow-water platform rocks in the autochthonous region of the St. Lawrence Lowlands (*e.g.*, Beiers 1976). The Internal Domain consists of highly deformed and metamorphosed rocks which, in part, represent former oceanic crust. The less deformed and metamorphosed External Domain is underlain by continental crust of Grenville affinity. In the External Domain, an outer zone of thrust-imbricated structures has been differentiated from an inner zone of nappes (St-Julien & Hubert 1975) based on width of tectonic transport zone. The thrust sheets are parautochthonous, the nappes tectonically rootless. Logan's Line marks the major thrust fault separating the two zones. Along this line the Cambro-Ordovician Cap-des-Rosiers Group (Ste-Anne River nappe) and the Lower Ordovician Tourelle and Middle Ordovician Deslandes Formations (Marsoui River nappe) of the study area are thrust over the late Middle Ordovician Cloridorme Formation. The strati-

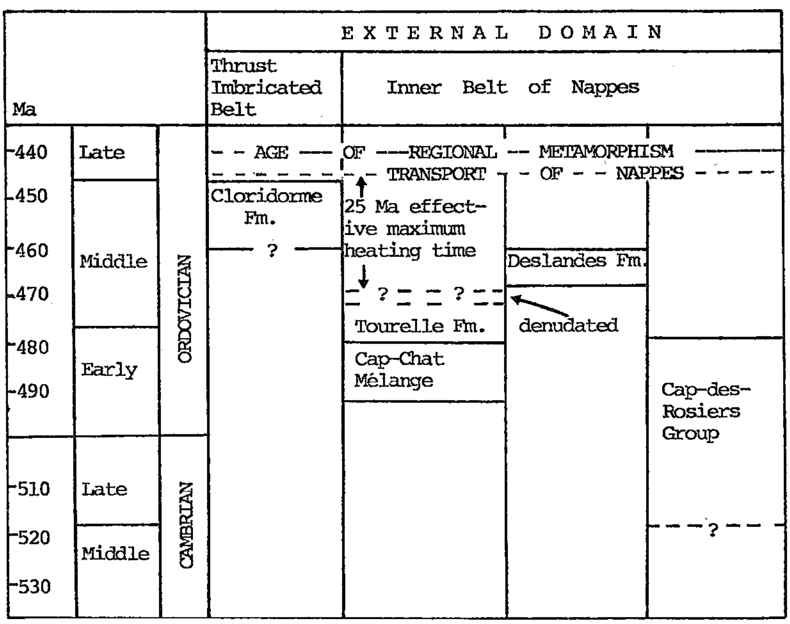


FIG. 2. Cambro-Ordovician stratigraphy, Taconic belt, Gaspé Peninsula (modified from Hiscott 1977). In the Inner Belt of Nappes, the three columns refer to increasingly higher tectonic units from left to right.

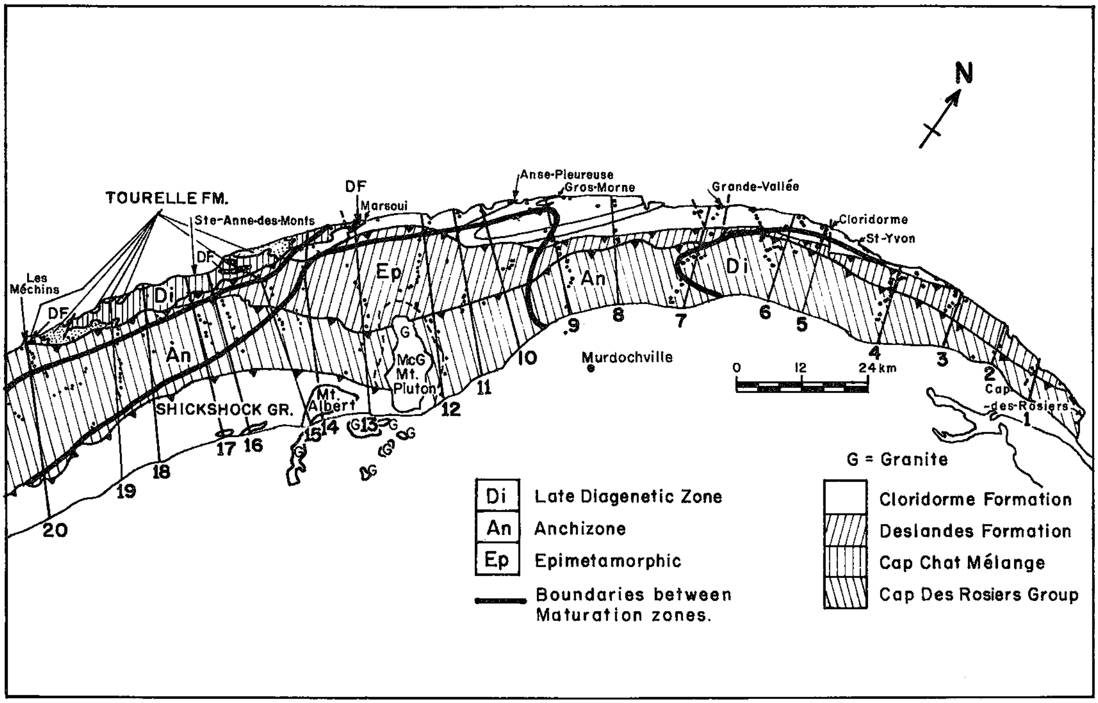


FIG. 3. Location of sections sampled for illite crystallinity and pyrobitumen reflectance: 1. Anse-au-Griffon, 2. Rivière-au-Renard, 3. Petit-Cap. 4. Fame Point, 5. Cloridorme, 6. Pointe-à-la-Frégate, 7. Grande-Vallée, 8. Manche-d'Epée, 9. Anse-Pleureuse, 10. Mont-Louis, 11. Mont-St-Pierre, 12. Rivière-à-Claude, 13. Marsoui, 14. Ste-Marthe, 15. St-Joachim-de-Tourelle, 16. Ste-Anne-des-Monts I, 17. Ste-Anne-des-Monts, II, 18. Cap-Chat I, Cap-Chat II, 20. Les Méchins.

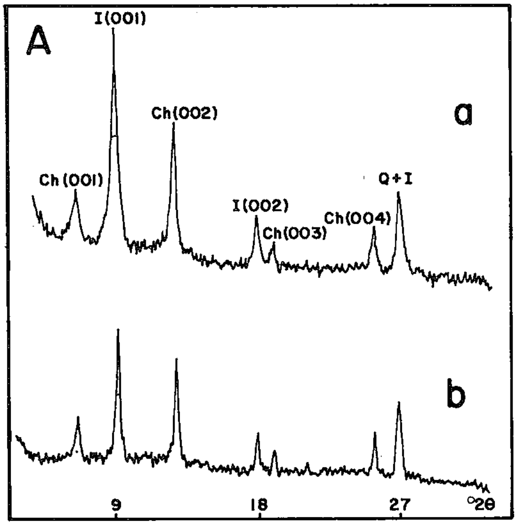
graphic range of the different units is shown in Figure 2. The area was postkinematically intruded by the Upper Devonian granitic to granodioritic McGerrigle Mountains pluton approximately 350 Ma ago (de Römer 1977).

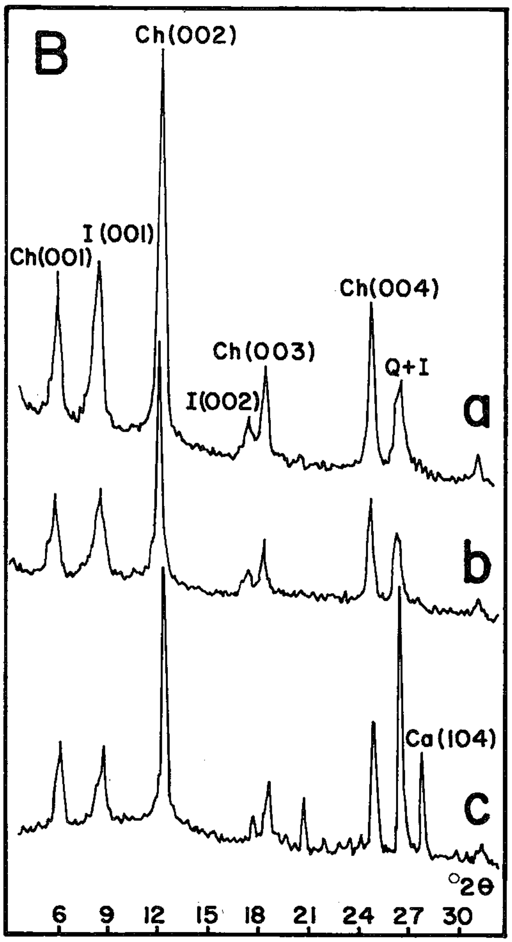
ANALYTICAL METHODS AND SAMPLING

The study area of the Taconic belt between Les Méchins in the west and Cap-des-Rosiers at the eastern tip of Gaspé Peninsula is nearly 250 km long and up to 25 to 30 km wide. From this area, 350 samples were collected along 20 sections across strike (Fig. 3) and one section along the shoreline of the Gulf of St. Lawrence. All samples were analyzed for clay-mineral content and crystallinity using X-ray diffraction; 145 samples were processed for organic matter. Of the latter, 95 samples contained sufficient numbers of organic particles to be used for reflectance measurements.

Clay mineralogy

Among the numerous cristallochemical and structural changes in clay minerals during burial, two are widely observed in fine-grained terrigenous sediments and have been used to characterize progressive stages of diagenesis: (1) the first is the transformation of smectite to illite or chlorite through a sequence of mixed-layer clay minerals that starts with random interstratification (up to 65% illite or chlorite layers) and then proceeds to short-range ordering of the smectite and illite or chlorite layers (Weaver 1958, Dunoyer de Segonzac 1970, Perry & Hower 1970). Thus the percentage of smectite in smectite–illite (or chlorite) mixed-layer clays and the presence and type of ordering serve as a maturation index. (2) The second is the transformation of poorly crystallized illite into well-crystallized mica (Maxwell & Hower 1967), which results in increased sharpness of the (001) X-ray diffraction peak at 10 Å. The sharpness of this peak was first used as an indicator of maturation by Weaver (1960, 1961). The width of the illite (001) peak at half height is used as a measure of illite crystallinity (Kübler 1967, 1968) and is one param-





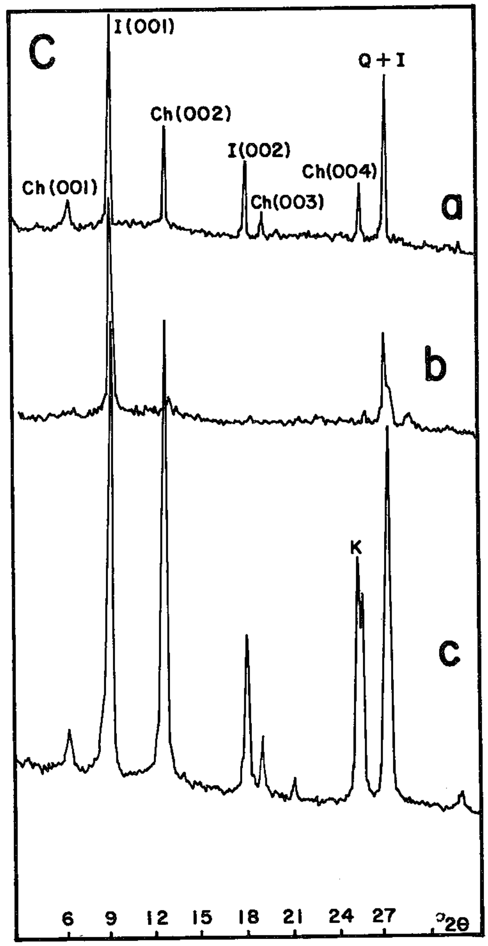


FIG. 4A. (a) Boundary between late diagenetic zone and anchizone (0.43° $\Delta 2\theta$, sample DL16-274) and (b) between anchizone and epimetamorphic zone (0.24° $\Delta 2\theta$, sample CR16–287) based on illite crystallinity (< 2 μm). Ch chlorite. I illite, Q quartz. B. Illite crystallinity as a function of grain size. Illite (001) peak is narrower (IC 0.48° $\Delta 2\theta$) in the coarser fraction (2–16 μm) (c), compared to the finer fractions (< 2 μm) (IC 0.65° $\Delta 2\theta$). Finer fractions (a) represent authigenic illite. The better crystallinity of the coarser fractions implies admixture of detrital illite or mica of either metamorphic or sedimentary origin. (b): fine fraction (< 2 μm) glycolated; Ca calcite. C. X-ray diffractograms of a sequence of three samples approaching the McGerrigle Mountains pluton in the Rivière-à-Claude section (section 12). Sample (a) shows the best crystallinity (0.13° $\Delta 2\theta$) in the study area. South of it (*e.g.*, samples b and c) IC gets increasingly poorer. Note that in sample (b) chlorite is absent and in sample (c), that kaolinite (K) is present. For explanation, see text.

eter employed to assess the degree of clay-mineral diagenesis. The higher the diagenetic grade, the better is the crystallinity, the narrower the peak and the lower the index of crystallinity.

The evolution of illite and illite–smectite mixed-layer minerals during burial diagenesis depends on factors such as temperature, chemical composition of the pore fluids and parent material. On the other hand, the value of the illite-crystallinity index measured by X-ray diffraction is affected by experimental conditions. To minimize the effects of the latter, crystallinity data are now usually reported as a difference in the 2θ angles corresponding to the midpoints on the flank of the diffraction peak ($\Delta 2\theta$ notation). However, the effect of varying the slit width, energy input, scanning speed, humidity and ion saturation can only be eliminated if experimental conditions are standardized by including the use of internal standards of known crystallinity (*e.g.*, Weber 1972). Particularly for lower grade rocks, with high proportions of smectite in the mixed layers, it is important to work under conditions of controlled humidity and ion saturation (*e.g.*, treatment with 0.5 N KCl solution or 1.0 N MgCl solution: Kisch 1980). For late diagenetic to low-grade metamorphic samples with a small or zero component of smectite, these precautions are less significant and were not observed in this study. In lower grade rocks, finer grain-size fractions (less than 2 μm) tend to show poorer illite crystallinity than coarser fractions (*e.g.*, 2–16 μm fraction) because the latter may contain well-crystallized detrital mica, whereas the former are usually enriched in poorly crystallized components from weathering or early diagenetic environments. Poor illite-crystallinity (IC) reflects high variability in d_{001}, which is the result of lattice tightening or loosening due to variations in layer charge, ion substitution or ion deficiencies. With increasing diagenetic and metamorphic grade, these differences tend to disappear as the finer fractions recrystallize progressively. This trend is clearly visible from a comparison of the less-than-2μm fraction and the 2–16μm fraction of samples from the late diagenetic stage and the anchimetamorphic stage in the study area (Fig. 4, Table 1).

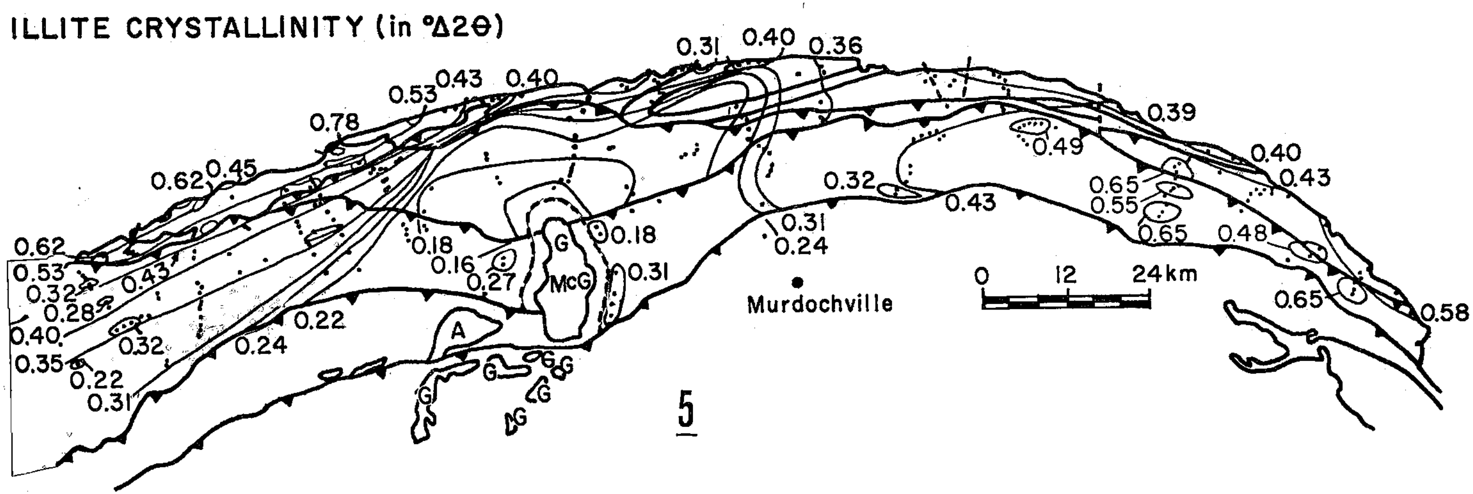
TABLE 1: ILLITE CRYSTALLINITY AS A FUNCTION OF GRAIN SIZE

Maturation Zone	Sample No.	Section No.	IC <2μm °Δ2θ	IC 2-16μm °Δ2θ	IC <2μm Glycolated °Δ2θ
Diagenetic Zone	DL 1-4	1	0.65	0.26	0.46
	DL 1-9	1	0.68	0.46	0.62
	DL 1-13	1	0.59	0.46	
	CL 5-65	5	0.46	0.20	
	CL 8-125	8	0.43	0.26	0.39
	CM14-226	14	0.49	0.25	
	TR20-341	20	0.65	0.46	
	TR20-343	20	0.48	0.33	
Anchizone	CL 5-69	5	0.34	0.26	
	CL 5-67	5	0.33	0.16	
	CL 7-113	7	0.36	0.20	
	DL 13-203	13	0.39	0.26	
	DL 13-273	13	0.17	0.17	
	DL 13-222	13	0.26	0.26	
Epimetamorphic Zone	DL 13-212	13	0.16	0.16	
	DL 13-219	13	0.16	0.16	

Organic matter maturation

The maturation scale established for coal rank, on the basis of vitrinite reflectance, is also applicable to kerogen maturation (*e.g.*, Stach *et al.* 1975). Vitrinite is the coal maceral derived from the carbohydrate-rich, woody tissue of higher plants; it contains considerable amounts of oxygen. For a given level of maturation, vitrinite has a relatively uniform chemical composition and, therefore, its optical characteristics (*i.e.*, reflectance) change in a predictable manner as a function of increasing thermal maturation. The limitations in the application of vitrinite reflectance as a maturation indicator have been discussed by Jones & Edison (1978) and Héroux *et al.* (1979). Progressive carbonization of kerogen with depth of burial (mainly as a function of temperature and heating time) is analogous to the gradual increase in the optical reflectance of vitrinite. The simplest indicator of kerogen maturation is its color in transmitted light. The opacity of kerogen increases proportionally with the degree of thermal aleration. However, above a vitrinite reflectance of about 2%, the color of kerogen is uniformly black.

In pre-Devonian sediments, reflectance is measured on asphaltic pyrobitumen owing to the lack of vitrinite in these deposits. Bituminous substances that decompose before melting are called pyrobitumens (Bell & Hunt 1963); low-oxygen (< 5% O_2) pyrobitumens are called asphaltic pyrobitumens. For a more detailed genetic classification of organic matter, see Rogers *et al.* (1974). Robert (1973) and Ammosov *et al.* (1975) have tried to establish an $\bar{R}_o$ scale for asphaltic pyrobitumen. They noted that reflectance values for pyrobitumen and vitrinite are similar with increasing temperature in the range of 1.0 to 2.0% $\bar{R}_o$ although reflectance values from pyrobitumen show a greater scatter than those from vitrinite of equal rank. Ammosov *et al.* (1975) did not use proper vitrinite but vitrinite-like substances in their comparison and, therefore, the calibration of the scale of pyrobitumen reflectance still



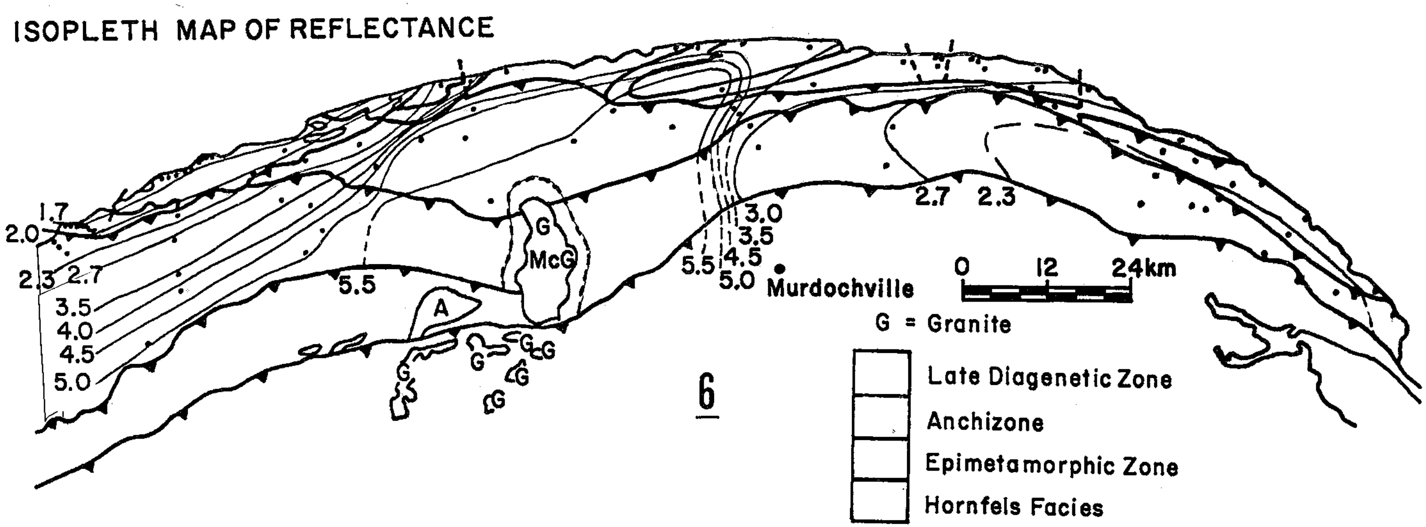


FIG. 5. Isopleth may of illite crystallinity (°$\Delta 2\theta$), Taconic belt, Gaspé Peninsula. A: Mt-Albert peridotite massif.

FIG. 6. Isopleth map of mean random pyrobitumen reflectance. Taconic belt, Gaspé Peninsular. Numbers are percentages of monochromatic light (wavelength 546 nm) reflected under oil.

awaits confirmation. Nevertheless, results based on pyrobitumen as a maturation indicator show coherent patterns, particularly in the late diagenetic and anchimetamorphic zones (Kisch 1980, Ogunyomi *et al.* 1980).

Terminology for Thermal Maturation Stages

Shales subjected to conditions less than true regional metamorphism react sluggishly and are sensitive to the chemical environment. Consequently, a sharp boundary does not exist between the realms of diagenesis and metamorphism. According to Winkler (1976), a temperature of approximately 200°C marks the boundary between diagenesis and very low-grade metamorphism (laumontite–prehnite–quartz facies and pumpellyite–prehnite–quartz facies). A temperature of 300 to 350°C defines the boundary between 'very low-grade metamorphism' and 'true regional metamorphism' (*i.e.*, the greenschist facies). This transition between diagenesis and epimetamorphism is called the anchizone (Harrassowitz 1927). For hydrocarbon generation this zone marks the end of dry gas generation (Kisch 1975, Frey *et al.* 1980, Kübler *et al.* 1979, Héroux *et al.* 1979). In this study, the boundary between diagenesis and the anchizone is placed at a reflectance value $\bar{R}_o$ of 2.7% and an illite-crystallinity value of 0.43° $\Delta 2\theta$; the boundary between the anchizone and the epimetamorphic zone is defined by a reflectance of $\bar{R}_o = 5.0\%$ and illite crystallinity of 0.24° $\Delta 2\theta$. We thus compromise between the boundaries proposed by Héroux *et al.* (1979), Kübler *et al.* (1979), Teichmüller *et al.* (1979), Kisch (1980) and Ogunyomi *et al.* (1980).

Results

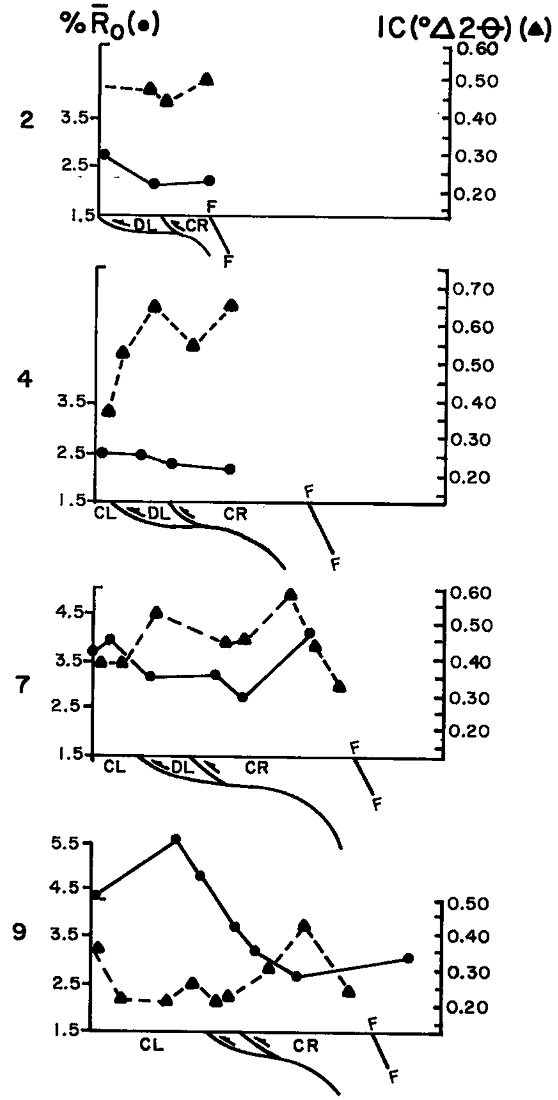
The thermal maturation pattern that emerged from this study for the Taconic belt of the Gaspé Peninsula is characterized by three configurations that are remarkably similar, both on the illite crystallinity and the reflectance maps (Figs. 5, 6). In the centre of the area, an epimetamorphic and higher-grade aureole 16 to 20 km wide surrounds the Devonian McGerrigle Mountains pluton and is followed outward by concentric shells of the anchizone and the late diagenetic zone. Towards the west, this central thermal dome gives way to a relatively simple pattern of a northward dipping "thermal slope". Maturation levels decrease more or less uniformly northwards with decreasing age of the sediments encountered in progressively deeper tectonic units. East of the thermal dome the configuration can be described as a "thermal trough", with the lowest maturation levels in a central elongate belt located in the Cambro-Ordovician Cap-des-Rosiers Group and the Middle Ordovician Deslandes Formation. It is bordered both to the north (in the late Middle Ordovician Cloridorme Formation) and the south (Cap-des-Rosiers Group) by more mature rocks. However, towards the east this trough-shaped configuration is less well defined.

Deviations from these broad regional trends are visible on the illite-crystallinity map (Fig. 5). In the epimetamorphic aureole of the McGerrigle Mountains pluton, anomalously poor illite-crystallinity is observed in a zone immediately east of the intrusion (IC = 0.31° $\Delta 2\theta$) and in a small area west of it (IC = 0.27° $\Delta 2\theta$). Oval or egg-shaped local anomalies of improved crystallinity occur in the diagenetic zone west of the pluton, where they are associated with green or red shales, or with the thrust plane separating the Cap-Chat Mélange and Tourelle Formation from the overlying Cap-des-Rosiers Group in the south.

Interpretation

Principal mechanisms of shale maturation

(1) *Contact metamorphism.* The central thermal dome, the most prominent feature on the thermal maturation maps of northern Gaspé Peninsula, is clearly related to the intrusion of the McGerrigle Mountains pluton. The width of the epimetamorphic aureole exceeds the exposed width of the intrusive body (8 km) by two to three times. This is most easily explained by a much larger extent of the intrusive body at shallow depth than is exposed at the surface (Fig. 7). Similar relations have been inferred from thermal maturation studies for the hypabyssal intrusion of the Bramsche massif in northwestern Germany (Stadler & Teichmüller 1971). Nadeau & Reynolds (1981) showed that the effect of intruding an igneous body in the Cretaceous Mancos Shale in the western United States was detectable over an area more than three times the width of the intrusive complex (2.5 km). This conclusion was based on the percentage of illite in illite/smectite mixed-layer clays. It is speculated that the northeastward bulging of the epizonal aureole reflects the subsurface trend of the intrusive body in that direction or, alternatively, an anisotropy in heat conductivity of the host rocks.



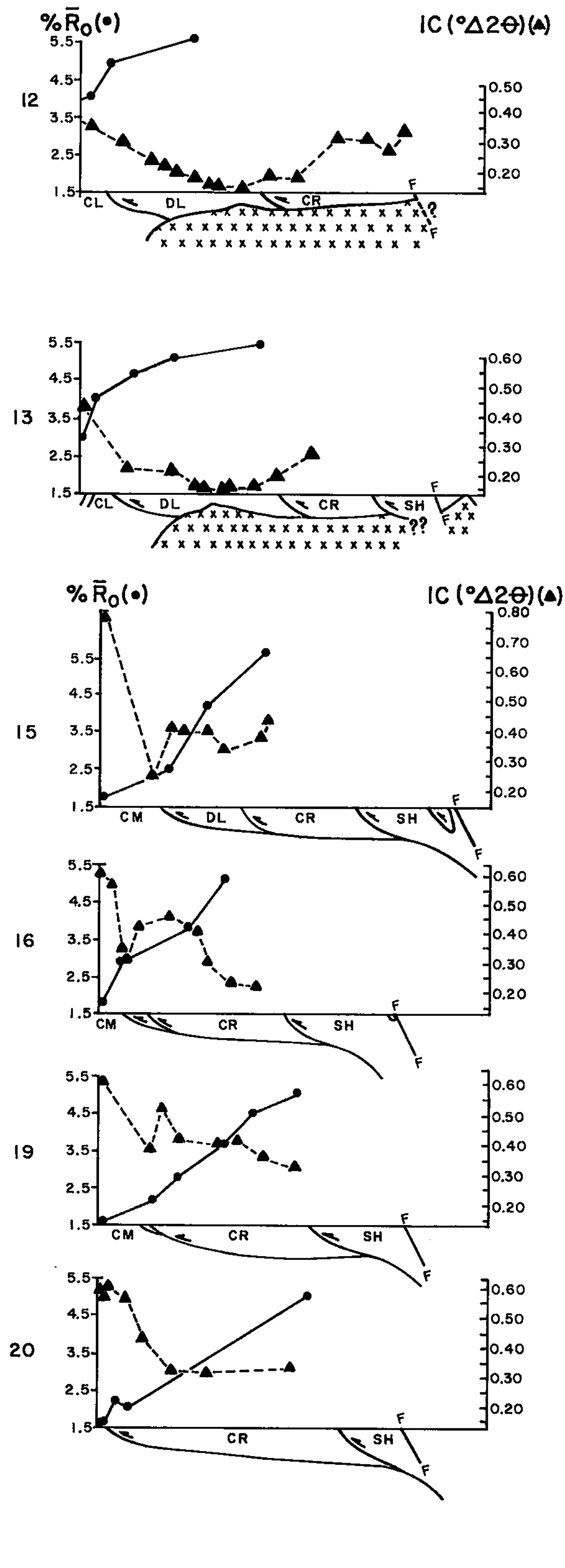


FIG. 7. Selected cross-sections of illite crystallinity and pyrobitumen reflectance plotted in N–S sections as a function of distance from the "thermal dome". Sections 2, 4, 7 and 9 are located east of the thermal dome; sections 12 and 13 traverse the central thermal dome; sections 15, 16, 19 and 20 are west of it. Each point in the sections represents the average of up to five samples. CL Cloridorme Formation, DL Deslandes Formation, TR Tourelle Formation, CM Cap-Chat Mélange, CR Cap-des-Rosiers Group, SH Shick Shock Group.

(2) *Transported burial diagenesis (preorogenic diagenesis)*. The contrasting maturation-pattern west and east of the central thermal dome

require different mechanisms of maturation. In the west, the decrease in maturation with increasing tectonic burial (and decreasing stratigraphic age) represents inverted diagenesis, which can only be explained if individual nappes acquired their thermal alteration before nappe emplacement, *i.e.*, most likely at the original site of deposition. This configuration is interpreted to reflect the results of burial diagenesis in rocks that have been transported more or less unchanged during and after nappe movement. That is to say, the effects of tectonic burial (due to emplacement and stacking of the nappes) did not supersede the effects of sedimentary burial. This interpretation is still valid, even if the tectonic contacts between adjacent thrust sheets or nappes are very steep or vertical because, in that case, there will be little or no tectonic burial. In areas of preserved burial-diagenesis (inverted or transported diagenesis), the observed levels of maturation may be used to estimate maximum temperatures (see below).

(3) *Synorogenic diagenesis and metamorphism.* In the late diagenetic zone and anchizone east of the thermal dome, such an explanation is not possible, because maturation levels increase northward with decreasing age across the nappe boundaries. Here, obviously, the thermal maturation induced by stratigraphic burial has been increased by later synorogenic heating related to tectonic burial or a general rising of the isotherms.

Estimate of maximum burial temperatures and burial depths in areas of transported diagenesis

Usage of the Karweil (1956) or Hood *et al.* (1975) nomograms to estimate burial temperatures from reflectance data requires knowledge of the effective heating time, *i.e.*, the time during which the sediment was within 15°C of the maximum temperature. Obviously, such estimates are meaningful only for those rocks that appear to have preserved their original diagenetic grade acquired during burial. Effective heating times can be estimated only very approximately because of the uncertainties in dating the (i) termination of sedimentation in the basin and (ii) the onset of tectonic transport.

Sedimentary burial of the Tourelle Formation probably reached its maximum at the end of the Arenigian or beginning of the Llanvirnian. The exposed top of the Tourelle Formation is about 475 Ma old (Fig. 2). The age of regional metamorphism in the area has been dated as 443 ± 18 and 438 ± 20 Ma (K–Ar determination on hornblende in amphibolite from Mounts Albert and Serpentine, respectively: Wanless *et al.* 1973). Muscovite from a brecciated granite, which is probably associated with the serpentine found in the western part of the Maquereau Group, yielded a K–Ar date of 442 ± 20 Ma. These dates on metamorphosed rocks in the Internal Domain demonstrate that dynamothermal metamorphism must have been completed in earliest Silurian time. From these data, the peak of regional metamorphism in the study area is estimated to be at 440 Ma and tectonic transport of the nonmetamorphosed rocks is assumed to have occurred within ± 10 Ma of this datum. This gives a possible time span of 35 Ma for the interval of maximum heating. As sedimentation continued beyond 475 Ma, the actual time available for the maximum heating should be less than 35 Ma. Also, effective heating time may be considerably shorter because the time of regional metamorphism cannot be dated exactly. From these data, a minimum heating time of 25 Ma may be derived (Table 2). However there is a high degree of incertainty obviously involved in this estimate. The paleotemperature of 170°C for the base of the Tourelle Formation, which is based on this heating time and a measured reflectance $\bar{R}_o$ of 1.5%, therefore, must be considered tentative. This applies equally to the burial-depth estimate of 5 to 6 km, which assumes a paleogeothermal gradient of 30 to 35°C/km (corresponding to the present average continental geothermal gradient). It may be possible to check estimates of his kind by paleotemperature and paleopressure determinations based on fluid-inclusion data (*e.g.*, Mullis 1979); this information is presently being acquired for the study area.

The present stratigraphic thickness of the Tourelle Formation has been estimated to be approximately 1 km (Hiscott 1977). If a 5-to-6-km burial is a realistic value for the base of the Tourelle Formation, then 4 to 5 km of younger rocks or other overlying tectonic units

TABLE 2. PALEOTEMPERATURES AND BURIAL DEPTH, TOURELLE FORMATION

Estimated Effective Heating Time in Ma	Assumed Paleo-Geothermal Gradient °C/km	Base of Tourelle Formation $\bar{R}_o$ 1.50%: Estimated Paleo-Temperature in °C (1)	(2)	Estimated Depth of Burial in km (1)	(2)
25	20	170	173	8.5	8.6
25	30	170	173	5.7	5.8
25	40	170	173	4.2	4.3
35	20	154	155	7.7	7.8
35	30	154	155	5.1	5.2
35	40	154	155	3.8	3.9

(1) Estimated using Karweil's (1956) nomogram.

(2) Estimated using Hood et al. (1975) nomogram.

must have been removed by denudation to expose the presently observed levels of maturation.

Illite-crystallinity anomalies

Anomalously low illite-crystallinity in the vicinity of the McGerrigle Mountains pluton is probably an effect of retrograde metamorphism caused by late-stage hydrothermal fluids involved in the circulation system of the intrusion. Similar anomalies have been observed around contact metamorphic aureoles in the Acadian belt of the Gaspé Peninsula (Duba & Williams-Jones 1981). In the argillic zone of porphyry-copper deposits, the occurrence of montmorillonite, besides kaolinite and sericite, is well known (*e.g.*, Jambor & Delabio 1978). The reduction of illite crystallinity is probably a related phenomenon. However, its precise relationship to the various concentric alteration zones of porphyry copper deposits seems not to have been studied yet.

Increased illite-crystallinity in red and green shales as compared to interbedded black and grey shales has been variously described in the literature (*e.g.*, Ogunyomi *et al.* 1980) and is attributed, in organic-matter-rich muds and shales, to the possible persistence of acidic pore fluids to greater burial depth, which may retard crystallinity improvement. Increased illite-crystallinity associated with fault zones may be explained by synkinematic recrystallization, if the temperatures during deformation were sufficiently high (Teichmüller *et al.* 1979).

Discussion

Thermal maturation levels in the Taconic belt of the Gaspé Peninsula show remarkably coherent patterns, both for illite crystallinity and pyrobitumen reflectance, attesting to the validity of the two parameters as maturation indicators. For the interpretation of these patterns, different mechanisms have been invoked for the areas west and east of the central thermal dome, *i.e.*, transported (inverted) preorogenic diagenesis and anchimetamorphism in the west and synorogenic alteration in the east. In general, preorogenic burial diagenesis is most likely to have been preserved in the most external parts of thrust belts. Towards the interior regions of mountain belts, the probability increases that original burial-diagenesis and metamorphism have been overprinted by higher-grade conditions during synorogenic heating. This is well documented in the Quebec City traverse of the Taconic belt (Ogunyomi *et al.* 1980). The curvature of the Taconic belt in the Gaspé Peninsula suggests that successively more internal parts of the orogen are exposed going from west to east. Therefore, the succession of a preorogenic maturation pattern by a synorogenic pattern towards the east is in agreement with the tectonic position of these specific areas within the orogen.

Maturation levels in the study area exceed the oil window. The potential for liquid hydrocarbons, therefore, is negligible. Since maturation levels decrease northward in the burial-diagenesis zone west of the thermal dome, it is possible that in the offshore area of the Gulf of St. Lawrence, maturation may still be favorable for the occurrence of liquid hydrocarbons. This is supported by the occurrence of organically mature to immature rocks on Anticosti Island (Petryk 1981) 60 to 80 km to the north.

Calibration of the reflectance measurements on asphaltic pyrobitumen in terms of maximum burial temperatures, which was attempted for a few samples from the preorogenic diagenetic zone, is tentative at best. More reliable paleotemperatures may be obtained from water-rich, two-phase fluid inclusions following the method of Mullis (1979). Fluid inclusions rich in methane also provide the possibility of direct paleopressure determinations required to establish paleogeothermal gradients. These fluid-inclusion studies are presently underway.

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