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G. Macauley, M.G. Fowler, F. Goodarzi,
L.R. Snowdon, and L.D. Stasiuk

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ORDOVICIAN OIL SHALE—SOURCE ROCK SEDIMENTS IN THE CENTRAL AND EASTERN CANADA MAINLAND AND EASTERN ARCTIC AREAS, AND THEIR SIGNIFICANCE FOR FRONTIER EXPLORATION

Abstract

Organic geochemistry (including Rock-Eval pyrolysis, total organic carbon analyses, and chromatography of the saturate extract fractions) and optical microscopy data (including maceral identification, reflectance and fluorescence determinations) are examined and the stratigraphic relationships of eight organic-rich deposits are reviewed. Regional distribution of the organic-rich zones, kerogen typing, thermal maturation conclusions and petroleum product characterizations are analyzed for their significance to adjacent frontier exploration areas.

Type I kerogens, dominated by *Gloeocapsomorpha*, are described from Upper Ordovician Yoeman beds of the Williston Basin and from the Lower Ordovician Green Point Group in western Newfoundland. All other units contain Type II amorphous kerogen. Deposits in the Collingwood Member in southern Ontario and the Table Head and Humber Arm groups in western Newfoundland produce similar bitumen extracts, whereas, although geochemically and petrographically similar to the above, organic-rich beds on Southampton, Baffin and Akpatok islands in the Arctic produce bitumens that are characteristic of a hypersaline depositional environment.

Although all the above units represent excellent potential source rocks where buried to depths sufficient to generate hydrocarbons in the frontier areas, geographic distribution, limited by non-deposition or by their absence in areas of later sea-floor spreading, may be a negative factor.

Résumé

Des données de géochimie organique (y compris par pyrolyse Rock-Eval, par analyses du carbone organique total et par chromatographie des fractions d'extraits de matériaux saturés) et de microscopie optique (y compris l'identification des macéraux, la détermination de la réflectance et de la fluorescence) sont analysées, et les liens stratigraphiques de huit gisements à haute teneur en matières organiques sont passés en revue. La répartition régionale des zones à haute teneur en matieres organiques, la catégorisation des kérogènes, l'établissement de la maturation thermique et la classification des produits de pétrole sont étudiés en fonction de leur importance par rapport aux zones d'exploration pionnières voisines.

Les kérogènes de type I, en grande partie composés de *Gloeocapsomorpha*, des couches de Yoeman de L'Ordovicien supérieur (bassin de Williston) et du groupe de Green Point de L'Ordovicien inférieur (ouest de Terre-Neuve) sont décrits. Toutes les autres unités contiennent du kérogène amorphe de type II. Les gisements situés dans le membre de Collingwood (sud de l'Ontario) et dans les groupes de Table Head et de Humber Arm (ouest de Terre-Neuve) produisent des extraits de bitume semblables tandis que, même s'ils sont géochimiquement et pétrographiquement semblables aux précédents, les couches à haute teneur en matières organiques observées dans le î les arctiques de Southampton, Baffin et Akpatok produisent des bitumes caractéristiques d'un milieur de sédimentation sursalée.

Même si toutes les unités susmentionnées représentent d'excellentes roches mères possibles, là où eleles se trouvent enfouies à des profondeurs suffisantes pour la formation d'hydrocarbures dans les zones pionnières, leur répartition géographique, limitée par leur absence dans les zones d'expansion oceanique ultérieures, peut constituer un facteur négatif.

Summary

Organic geochemical analysis using a Rock-Eval pyrolysis apparatus provided data for the classification and maturation of eight organic-rich Ordovician deposits. Samples were selected initially to examine the potential of these strata as oil shale deposits, but analysis was extended to determine their significance as petroleum source rocks because of their proximity to offshore frontier areas. All were investigated by organic petrology studies including reflectance, fluorescence, and maceral identifications, and by chromatographic analysis of the saturate extract fractions. X-ray diffraction analysis was utilized to identify the inorganic mineral components.

All kerogens are recognized to be marine in origin and are devoid of any humic component, as is expected from sediments of Ordovician age. Most of these organic-rich deposits are geochemical Type II, typified by amorphous matrix bituminite kerogen. A Type I kerogen, characterized by the alga *Gloeocapsomorpha*, and an admixed Type I-II deposit, are also recognized. The majority of the deposits are thermally immature to moderately mature (in the sense of petroleum generation), although one occurrence of overmaturity is recorded.

Immature Type I kerogen is present in the Upper Ordovician Yoeman kukersites in the Williston Basin, but thermal immaturity precludes these as significant source beds over much of the southern Saskatchewan part of the basin. Admixed *Gloeocapsomorpha* and matrix bituminite characterize the organics of the Lower Ordovician Green Point Group in western Newfoundland. Although immature to only marginally mature in surface exposures, these would be prime source beds where buried deeply enough to generate hydrocarbons. Petrographically similar, but overmature, kerogens are recognized in Lower Ordovician beds on the Grand Banks.

Upper Ordovician Collingwood beds contain Type II amorphous kerogen, which increases eastward from marginally mature on the islands of Lake Huron to mature in the Whitby area and overmature near Ottawa. Equivalent beds in the St. Lawrence Lowland and the Anticosti Island area are highly mature to overmature. The areas of overmaturity can in part be related to igneous activity. A local irregularity in the maturation pattern along the Lake Huron – Collingwood outcrop trend can be correlated with regional tectonic features. Collingwood oil shales have sourced Cambrian – Ordovician petroleum accumulations in southern Ontario. The oils are chemically distinct from some in the Michigan Basin and from those of the Williston Basin kukersites.

Only immature amorphous Type II kerogens are recognized in deposits of the eastern Arctic Islands (Southampton, Baffin, Akpatok). Although these kerogens are indicated to be identical, by Rock-Eval geochemistry and organic petrography, to those of the Collingwood oil shales, biomarkers in the extracted bitumen fraction from these northern units indicate a hypersaline depositional environment even though evaporitic deposits are not known within the Ordovician section in these northern areas. This indication of hypersalinity is different from that for the Collingwood but similar to that of the source rocks of the Silurian oils from the Michigan Basin. The Boas oil shale of Southampton Island is a time equivalent of the Collingwood beds but the exact stratigraphic positions of the organic intervals on Baffin and Akpatok islands are less well defined. If present and buried to sufficient depth, these strata would constitute excellent source rocks in the northern offshore frontiers; however, the areal distributions of these organic-rich strata are in some doubt. There is as yet no evidence of Boas beds under Hudson Bay. All units may be absent from Foxe Basin, Baffin Bay, Davis Strait and possibly the Labrador Sea in areas of sea-floor spreading subsequent to their deposition.

Marginal to moderately mature Type II amorphous kerogens dominate in the Lower Ordovician Humber Arm and Middle Ordovician Table Head groups of western Newfoundland and have probably sourced the oil shows of that area. Suspected *Gloeocapsomorpha* remnants may be significant to the understanding of marine Type I/II relationships. Regional tectonic interpretations indicate that overmature Macastey beds are to be expected in the offshore Anticosti Basin in the northern part of the Gulf of St. Lawrence.

Sommaire

L'analyse géochimique organique par pyrolyse Rock-Eval a permis de recueillir des données pour la classification et l'établissement de la maturation de huit gisements ordoviciens à haute teneur en matières organiques. On a d'abord choisi des échantillons afin de déterminer la possibilité de trouver dans ces couches du schiste bitumineux; la portée de l'analyse a ensuite été accrue afin de déterminer dans quelle mesure ces couches peuvent constituer des roches mères de pétrole en raison de leur proximité à des zones pionnières extracôtières. Elles ont toutes fait l'objet d'analyses pétrologiques organiques (réflectance, fluorescence et identification des macéraux) et d'analyses chromatographiques des fractions d'extraits de matériaux saturés. On a en outre eu recours à l'analyses par diffraction de rayons X pour identifier les composantes minérales inorganiques.

Tous les kérogènes sont d'origine marine et dépourvus de toute composante humique, comme il était à prévoir de sédiments d'âge ordovicien. La plupart de ces gisements à haute teneur en matières organiques sont de type II, caractérisés par un kérogène bituminite à matrice amorphe. On a en outre relevé la présence d'un kérogène de type I, caractérisé par l'algue *Gloeocapsomorpha* et un gisement ou les types I et II sont mélangés. La majorité de ces gisements sont thermiquement immatures à modérément matures (relativement à la formation du pétrole), mais on a relevé la présence d'un gisement surmature.

Du kérogène immature de type I se trouve dans les kukersites Yoeman de l'Ordovicien supérieur dans le bassin de Williston, mais leur immaturité thermique les exclut comme couches mères importantes dans la grande partie du sud de la Saskatchewan faisant partie du bassin. Les matières organiques du groupe de Green Point de l'Ordovicien inférieur dans l'est de Terre-Neuve sont caractérisées par la présence combinée de *Gloeocapsomorpha* et de bituminite à matrice. Même si elles sont immatures à marginalement matures dans les affleurements, ces roches constitueraient des roches mères importantes là où elles ont été enfouies suffisamment profondément pour produire des hydrocarbures. Pétrographiquement semblables, mais surmatures, des kérogènes occupent des couches de l'Ordovicien inférieur dans les Grands Bancs.

Les couches de Collingwood de l'Ordovicien supérieur contiennent du kérogène amorphe de type II qui passe vers l'est de marginalement mature dans les îles du lac Huron à mature dans le région de Whitby et surmature près d'Ottawa. Des couches équivalentes dans les basses terres du Saint-Laurent et l'île d'Anticosti sont très matures à surmatures. Les zones de surmaturité peuvent en partie être liées a une activite ignée. Une irrégularité locale dans la configuration de maturation le long de la direction de l'affleurement s'étendant du lac Huron à Collingwood peut être corrélée à des formes tectoniques régionales. Les schistes bitumineux de Collingwood sont les roches mères d'accumulations de pétrole cambrien et ordovicien dans le sud de l'Ontario. Ces pétroles sont chimiquement différents de certains pétroles que l'on retrouve dans le bassin de Michigan et de ceux que renferment les kukersites du bassin de Williston.

Dans les gisements de l'est des iles arctiques (Southampton, Baffin, Akpatok), on n'a relevé que la présence de kérogènes amorphes et immatures de type II. Même si ces kérogènes sont identiques ainsi qu'établi par géochimie Rock-Eval et pétrographie organique, à ceux des schistes bitumineux de Collingwood, des biomarqueurs dans la fraction du bitume extrait des ces unités septentrionales indiquent que le milieu de sédimentation était sursalé même si aucun dépôt d'evaporites n'a été relevé dans la section ordovicienne de ces zones septentrionales. Par cette sursalinité, ces kérogènes diffèrent de ceux de Collingwood mais ils sont semblabes à ceus des roches mères des pétroles siluriens du bassin du Michigan. Le schiste bitumineux de Boas dans l'île de Southampton est chronologiquement équivalent aux couches de Collingwood mais les positions stratigraphiques des intervalles organiques dans les îles de Baffin et d'Akpatok sont moins bien définies. Si elles étaient présentes et enfouies à une profondeur suffisante, ces couches pourraient constituer d'excellentes roches mères dans les zones pionnières extracôtières du nord; cependant, la répartition de ces couches à haute teneur en matières organiques n'a pas été établie avec certitude. Aucun indice n'a encore été recueilli en ce qui concerne la présence des couches de Boas au-dessous de la baie d'Hudson. Toutes les unités pourraient être absentes du bassin de Fox, de la baie de Baffin, du détroit de Davis et peut-être de la mer du Labrador, dans des zones où le fond océanique a pu subir une expansion après leur mise en place.

Des kérogènes amorphes de type II de marginalement matures à modérément matures occupent la grande partie des groupes de Humber Arm de l'Ordovicien inférieur et de Table Head de l'Ordovicien moyen dans l'ouest de Terre-Neuve. Ils sont probablement à l'origine des indices de pétrole observés dans cette zone. L'analyses de restes présumés de *Gloeocapsomorpha* pourrait contribuer de façon importante à la compréhension des liens marins à établir entre les kérogènes de type I et II. D'après des interpretation de la tectonique régionale, les couches surmatures de Macastey devraient être présentes dans le bassin extracôtier d'Anticosti, dans le partie nord du golfe du Saint-Laurent.

INTRODUCTION

Lower Paleozoic strata are potential targets for petroleum accumulations in many of the frontier exploration areas of the Canadian Arctic and the eastern offshore. Three principal conditions must be satisfied for the recognition of exploration potential. There must be a source (quality, quantity and maturation of kerogen) for the hydrocarbons, and reservoir beds (porous zones) must be present in a geological setting (cap rock, migration path, timing, preservation) conducive to hydrocarbon entrapment.

This report is basically a geological-geochemical review which deals with Ordovician organic-rich rocks as potential source beds for the offshore areas of Hudson Bay, Foxe Basin, Baffin Bay and Davis Strait, offshore Newfoundland, and the Gulf of St. Lawrence. Details are included from the petroleum productive areas of southern Ontario and the Williston Basin of southeastern Saskatchewan, where Ordovician rocks have been established as source beds. Except for core samples in southern Ontario and the Williston Basin, data are primarily from sampled surface exposures where the beds are thermally immature. Optimum knowledge of kerogen character can be ascertained from the study of immature deposits. Projections can then be made concerning the quality and quantity of generated hydrocarbons where these sediments have undoubtedly been variably matured with increasing burial in the offshore areas. This report presents a geological comparison of the deposits which includes an initial, but comprehensive, geochemical investigation that recognizes possible source beds, the classification of their kerogen component, and the character of generated oils.

Background for this paper is derived mainly from Geological Survey of Canada Open File Reports on the organic-rich beds (in part oil shales) (Fig. 1) in southern Ontario (Macauley, 1987a; Macauley and Snowdon, 1984), on Southampton Island (Macauley, 1986), on Baffin and Akpatok islands (Macauley, 1987b), in Newfoundland (Macauley, 1987c), and in the Williston Basin (Osadetz et al., 1989). Interpretive concepts for kerogen classification and maturation have been outlined in Macauley et al. (1985). For the investigations published in the series of Open File Reports, Rock-Eval pyrolysis was the principal investigative tool, and data from many hundreds of pyrolyses are included therein. Only the interpretations and conclusions are discussed here. The reader is referred to these earlier reports for specific analytical results. The Open File studies contain brief comments on the organic petrology of the kerogens and on hydrocarbon characterization by gas chromatography of the solvent extract fraction. Results from both types of analysis are presented more extensively in this report.

Many other publications, in which the stratigraphic framework of these deposits has been described, are more fully referenced in the above Open File Reports than herein. Although possible time correlations are reviewed, and some regional depositional concepts are mentioned, no attempt is made in this study to substantiate the regional depositional-tectonic history of the basins and arches that controlled the deposition of these sediments.

OIL SHALES AND SOURCE ROCKS

Oil was retorted sporadically (the wood frame buildings ignited easily) from the organic-rich beds of the Collingwood Member, Lindsay Formation, in southern Ontario (Fig. 1, location A) from 1859 through 1861, but was then displaced by the less expensive conventional oil production at Oil Springs in the Petrolia area. Because of this early economic interest, and a location close to the Ontario industrial heartland, the Collingwood Member is the most completely studied of Canada's known Ordovician oil shale deposits. Although not in itself a source for frontier petroleum accumulations, the Collingwood oil shale is a known source for Ontario conventional oil deposits (Powell et al., 1984) and has undergone various levels of thermal maturation (Macauley et al., 1985; Macauley, 1987a), thus providing a comprehensive background to assess the frontier area oil shale occurrences.

Nelson and Johnson (1966) first described in detail the occurrence and characteristics of oil shale beds on Southampton Island (Fig. 1, location B): these were later defined as the Boas oil shale by Heywood and Sanford (1976). Nelson and Johnson (1976) published numerous field Fischer assay-type analyses, but more specific kerogen characterization was not available until Macauley (1986) sampled the Boas beds to evaluate their economic potential in a local energy-poor area.

Workum et al. (1976) described unnamed, organic-rich Ordovician beds on Akpatok Island (Fig. 1, location C) in the northern part of Ungava Bay. On the basis of this reported occurrence and the known oil shales on Southampton Island, Macauley (1987b), along with N.J. McMillan of the Geological Survey of Canada, traversed southern Baffin Island and encountered several sections of previously unreported and as yet unnamed organic-rich beds (Fig. 1, location D).

Oil shows have been recorded in Ordovician sandstones in western Newfoundland (Fleming, 1970), although the source for these shows has not been established. Macauley (1987c) encountered organic-rich beds in the Lower

Figure 1. Principal Ordovician oil shale localities of the central and eastern Canadian mainland and Arctic areas, with significant regional tectonic elements.

Ordovician Green Point Group Fig. 1, location E). Possible source beds were also described by Macauley (op. cit.) in younger Ordovician Table Head graptolitic beds (Fig. 1, location E).

Thin kukersite layers have been described in the Upper Ordovician Yeoman Formation, initially defined as an upper member of the Red River Formation, in southeastern Saskatchewan (Fig. 1, location F). Although not located within the initial study area of this paper, discussion is here included because of the similar stratigraphic position of these layers to the other organic-rich intervals, the significance of the Red River Formation in early geological studies across North America, and in order to compare the Yeoman deposit with the others on the basis of geochemistry.

STRATIGRAPHY

Some authors (Barnes, 1973; Heywood and Sanford, 1976; Workum et al., 1976) have unequivocally correlated the Collingwood, Boas and Akpatok Island oil shale intervals. Others (Nelson, 1981; Nelson and Johnson, 1966, 1976; Macauley, 1986, 1987b) have been less inclined to state a definite time equivalence of these units although good cause can be shown to do so. Many of the earlier correlations, including those involving Nelson, were based on macropaleontological studies. On reviewing these data, Macauley (1986, 1987b) noted extreme difficulties inherent in correlating on the basis of macrofauna through Middle–Upper Ordovician sequences in North America. Much of the work by Barnes involved conodont determinations, which, in conjunction with graptolite studies, may be the key to time correlations.

The Green River Group shales and the graptolitic limestones of the Table Head Group in western Newfoundland are both definitely older than any of the above deposits.

Collingwood Member — southern Ontario

Exposures of the Collingwood Member occur on the shores of Manitoulin Island, along the shoreline of Georgian Bay near Collingwood, and in the area bordering Lake Ontario to the east of Whitby (Fig. 2). They have been removed to the north by erosion. The most detailed information on the beds has been acquired from numerous coreholes, most of which were part of an oil shale assessment program carried out by the Ontario Geological Survey (Johnson et al., 1983, 1985).

Collingwood beds form the upper member of the Lindsay Formation (Russell and Telford, 1983). Impure organic-rich Collingwood carbonate overlies a thick pure carbonate sequence of the Lindsay Formation and is in turn overlain by organic-poor shales of the Blue Mountain Formation. The Collingwood is included within the Lindsay Formation because of their common carbonate mineralogy and also because thin oil shale beds and/or lenses occur within a dominant carbonate section which is defined as a lower part of the Collingwood Member. Organic-rich beds are also present locally in the Whitby area as the Rouge River Member (Fig. 2) within the overlying Blue Mountain shales (Russell and Telford, op. cit.).

The Collingwood/Lindsay carbonate contact has been described and discussed in some detail by Churcher (1985) who had difficulty reconciling apparently conformable, gradational boundaries with obviously eroded uppermost carbonate surfaces at other nearby localities. Collingwood beds pinch out southward (Fig. 2), occurring as sporadic outliers along the southern distributional limit (Churcher, 1985). Detrital zones are part of the normal depositional process in all shallow water sediments and also in some deeper water deposits. Nowhere is deposition always continuous; each break may represent only a local disturbance with the entire sedimentary record represented over a broader area. According to Barnes (1985), "there is no conodont faunal evidence . . . for a disconformity between the Lindsay carbonates and the Collingwood shales". Deposition is considered to have continued uninterrupted from the Lindsay carbonate through the Collingwood Member.

Similarly, the Collingwood/Blue Mountain contact can also be locally gradational, locally sharp but conformable, and locally erosional (Harris, 1984). Because of the disappearance of several conodont species at the base of the Blue Mountain Formation, Barnes (1985) has suggested a possible disconformity between the units, and also suggested that the low diversity of North Atlantic fauna in the lower Blue Mountain beds indicates that this unit is the interval of maximum deepening. Because of the observed gradational and conformable contacts, and the indicated deeper water conditions, any loss of geological record at the Collingwood/Blue Mountain boundary must be attributed to periods and/or local areas of nondeposition rather than to uplift and erosion.

Some degree of depositional continuity across the Collingwood/Blue Mountain boundary can be interpreted from the presence of thin organic-rich beds in the Rouge River Member of the Blue Mountain Formation in the Whitby area (Fig. 2). The organic interbeds thin and disappear to the west.

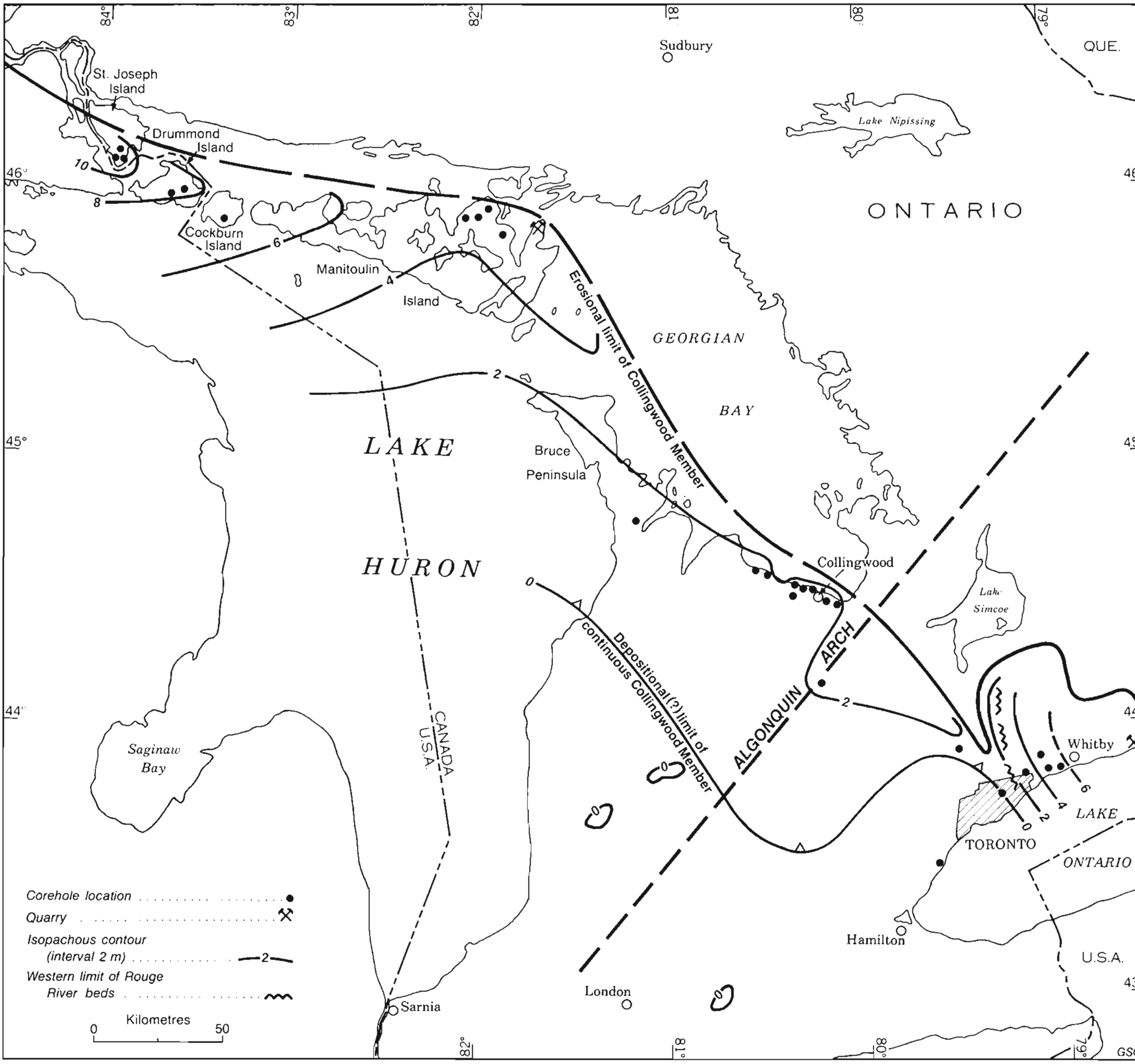


Figure 2. Thickness distribution of Collingwood Member oil shale beds, southern Ontario, showing control corehole locations. (Depositional limit generalized from Churcher, 1985.)

Lithology

Collingwood oil shales (Macauley et al., 1985) are characteristically black, organic-rich, laminated and fissile, containing a rich invertebrate fossil fauna characterized by abundant trilobites concentrated in bioclastic beds. They have been variously described as shale, limestone and marl. Calcite is the principal mineral constituent (50% ±), followed by quartz (35% ±) and clays (15% ±), and only minor feldspar (Snowdon, 1984). Within the clays, illite predominates over chlorite. Replacement of calcite by dolomite is sporadic, but is more common to the west on the islands of Lake Huron. Total organic carbon (TOC) content may exceed 10 per cent, but averages in the range of 5 to 6 per cent (Macauley, 1987a). These beds are lithologically impure limestones to lime marlstones (Russell and Telford, 1983), in part grading to dolomitic marlstone or impure dolostone. "Shale" can be used only in the sense of fissility, not in any way to indicate a dominance of the clay mineral component.

Distribution

Although by definition the Collingwood Member comprises all organic-rich intervals to the base of the lowest organic-rich bed, and thus includes considerable organic-poor carbonate, the unit as isopached herein (Fig. 2) is restricted to the upper continuous organic-rich section. On the basis of potential oil shale development, the percentage of oil shale within the lower dominant carbonate section is economically unattractive (Macauley, 1987a); however, these lower beds would certainly have been significant as source rocks. In this aspect, the isopachous contours of Churcher (1985) reflect the thickness of the total Collingwood Member.

The thinnest sections (<2 m) are present in the Collingwood area, close to the Algonquin Arch, with thickening to both the northwest and southeast. Maximum thickness (almost 11 m) is encountered on St. Joseph Island. Values represent complete sections, although many are located near quarries (Fig. 2) and the drift covered northern erosional limit of the unit. Subsurface well data (Churcher, 1985) define a southerly nondepositional (or erosional?) limit.

Black organic shales of the stratigraphically equivalent Billings Formation are preserved locally near Ottawa (Fig. 3) in a partly fault controlled feature (Baer et al., 1971). Billings shales overlie interbedded limestone and shale of the Eastview Member of the Lindsay Formation (Williams, in progress; Williams et al., 1984). The Eastview section has been correlated to the *Mesotrypa* beds of the Collingwood area (Parks, 1928), which appear to represent the lower interbedded limestone/organic shale interval of the Collingwood Member as defined by Russell and Telford (1983), but which Williams (op. cit.) has now correlated with the Collingwood Member while equating Billings beds with the Blue Mountain Formation. Because of the structural complexities in the Ottawa area, precise thickness measurements are difficult.

Equivalent strata are also present in the Utica, Lachine and Lotbinière formations of the St. Lawrence Lowland, the Mictaw Group on Gaspé Peninsula, the Macasty Formation on Manitoulin Island and as unnamed beds at Lac St. Jean (Fig. 3). A sequence of Ordovician beds at Lake Timiskaming along the Ontario-Quebec border contains no organic-rich strata. Sinclair (1965) concluded that, although time equivalent beds were present, the Collingwood was not represented in that area.

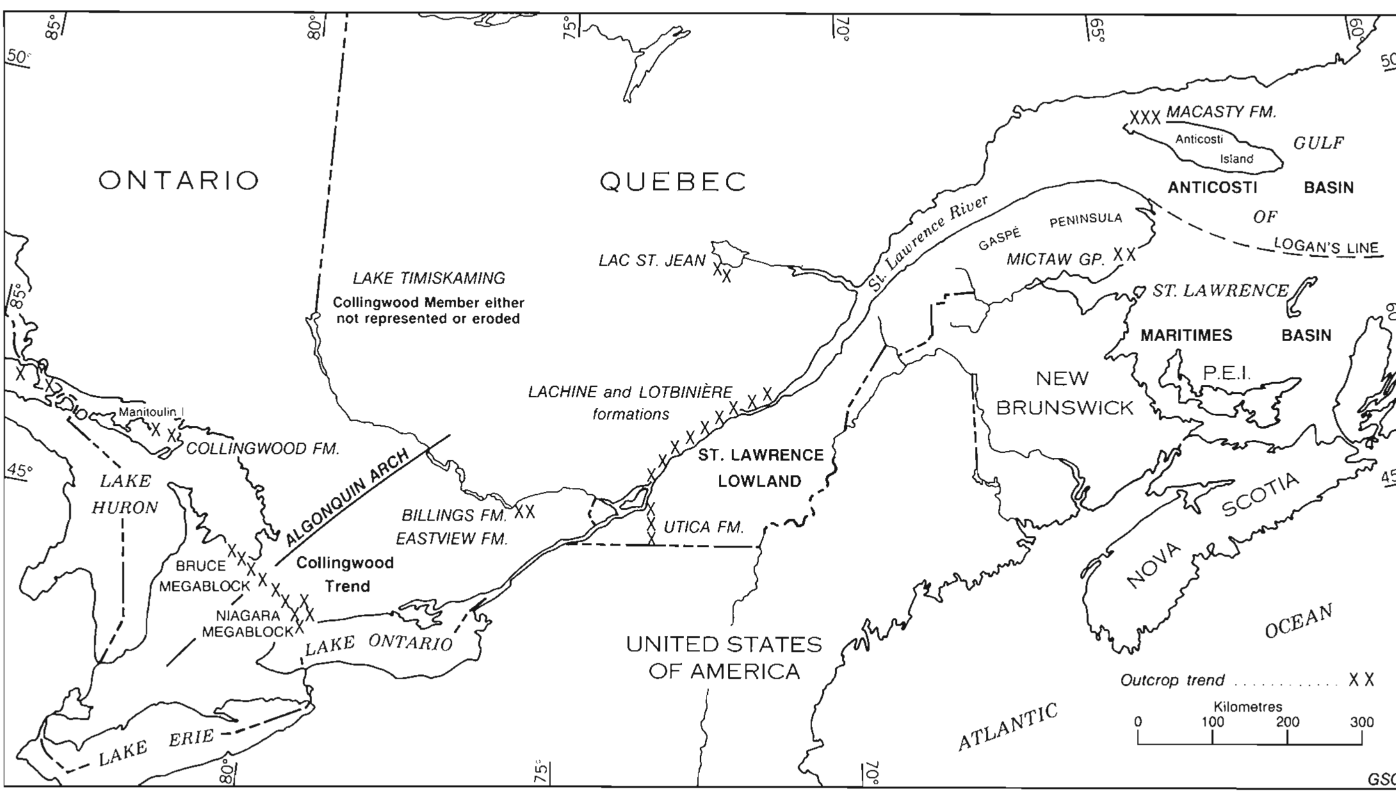


Figure 3. Distribution of organic beds in Ontario and Quebec considered correlative to the Collingwood Member. (After Macauley, 1987a.)

Age

Based on macropaleontological studies and correlation of the organic beds of southern Ontario to the Utica Formation of New York, early writers (Logan, 1863; Raymond, 1912; Foerste, 1924; Parks, 1928; Wilson, 1946) generally placed the Collingwood Member as the lowermost unit within the Upper Ordovician.

Much more definitive age dating is now available through detailed conodont determinations, for which background references and detail can be reviewed in Barnes (1985): only Barnes' general conclusions are summarized here. The evolution of *Amorphognathus* from *A. superbus* through *A.* sp. cf. *A. superbus* to *A. ordovicicus* is the key to the increase in precision, and is supplemented by recognized changes in the genus *Phragmodes*. Barnes (op. cit.), following Sweet et al. (1971), dated the Lindsay carbonates as Edenian and the lower Blue Mountain shales as early Maysvillian (early Ashgill). Collingwood beds occur near the Eden–Maysville time boundary.

Sinclair (1965) recognized the youngest Ordovician strata at Lake Timiskaming as Edenian. At that time, the Collingwood was generally placed at the Middle–Upper Ordovician boundary. On the basis of Barnes' (1985) placement of Collingwood deposition at the end of the Edenian, equivalent strata were either never deposited here or were eroded before deposition of Silurian beds.

Deposition

The Collingwood beds are typical of marine, widespread, thin, shallow water (possibly at, or close to, wave base), organic-rich deposits, commonly carbonates, that follow periods of widespread carbonate sedimentation and which are succeeded by non-organic clay shales. Numerous examples of such sequences are known in the Devonian of Canada, including the Middle Devonian Marcellus Formation of southern Ontario, the numerous dark shales included within the "all inclusive" Horn River Formation of the Northwest Territories (Williams, 1983), and the Canol Formation related to the Kee Scarp reefs of the Northwest Territories (Williams, op. cit.).

Many of these Devonian organic beds were deposited within starved basins (Williams, 1983) and consequently may represent long periods of time. Williams (pers. comm., 1986) considers that thin intervals representing long periods of time were more the norm in geological history than thick sections produced by rapid sedimentation over short time periods. Without providing background detail, the observation is made here that these Ordovician organic shales are often assigned wide age ranges; fossil zones are designated to be missing; and periods of uplift, erosion and unconformities are assigned that cannot be substantiated by the lithological sequence encountered. Extremely low rates of sedimentation adequately explain these paleontological-lithological enigmas without recourse to major tectonic events and/or periods of erosion. Such conditions may have been part of the depositional history of the Collingwood Member.

The combined section of Lindsay carbonate, Collingwood organic-rich limestone, and uppermost Blue Mountain non-organic shale is considered to be a complete and normal depositional sequence, uninterrupted by tectonism, uplift or erosion on any significant scale. The interbedded carbonate-organic limestone sequences in the lower part of the Collingwood Member and in the Eastview Member of the Ottawa area represent an initial retreat of carbonate sedimentation, whereas the interbedded organic beds within the overlying Rouge River Member may well reflect the proximity of a younger area of carbonate bank that was subsequently removed.

Thinning over the Algonquin Arch indicates a minor tectonic influence on the depositional pattern. Sanford et al. (1985) have demonstrated the effect of basement controlled fault blocks on the Paleozoic sequence in southern Ontario and the importance of these features to the accumulation of hydrocarbons within the Paleozoic section; however, there is not yet any particular evidence to indicate that their mapped structural features greatly influenced Collingwood sedimentation.

Boas oil shale — Southampton Island

Nelson and Johnson (1966) mapped the occurrence of Ordovician oil shale beds on Southampton Island on the basis of float samples and a single outcrop location at Sixteen Mile Brook (Fig. 4). Heywood and Sanford (1976) defined the Boas oil shale from an outcrop on the Boas River. Macauley (1986) concurred with the distributional pattern mapped by Nelson and Johnson and with the nomenclature proposed by Heywood and Sanford.

Nomenclature for the Ordovician of Southampton Island was brought northward from the defined sections at the south end of Hudson Bay by both Nelson and Johnson (1966) and Heywood and Sanford (1976). The former believed that the oil shale is at the approximate Ordovician–Silurian boundary, whereas the latter placed the oil shales at the approximate Middle–Upper Ordovician boundary, essentially coeval with the Collingwood Member in southern Ontario. Considerable confusion has existed over the exact position of these organic beds, or whether one or more oil shale intervals might be present, and over the use of the Bad

Cache Rapids and Churchill River groups and Red Head Rapids Formation on Southampton Island. These problems were outlined by Macauley (1986) and although the answers were not essential to his geochemical evaluation of the oil shale interval(s), he did conclude that a single oil shale unit is present on Southampton Island.

Lithology

Two distinct organic lithotypes are recognized within the Boas oil shale. The upper unit is a dark brownish black to dark brown, finely laminated, fissile, very organic-rich (organic carbon ranging from 10-20%) limestone. The lower beds are light to medium brown, aphanitic, poorly laminated, hard, organic (approximately 2-6% organic carbon) limestone which is interbedded with and overlies similar but essentially non-organic, light yellow-brown limestone.

X-ray diffraction analyses (Macauley, 1986) reveal that the organic beds are limestones, variably dolomitic (2-14%) and with a significant quartz content (20-35%). The quartz is of micro size as silt and sand grains are not detectable to the naked eye. Whether the quartz is detrital or of authigenic origin was not determined; however, terrestrial detritus appears to be minimal as both clay minerals and feldspar are virtually absent.

Distribution

Interpreting from Macauley (1986), only the lower lithotype is present at the type section. The upper high grade beds are extremely thin, less than 30 cm where exposed at Sixteen Mile Brook. Identification of a thin detrital zone, about 5 cm thick, from fragments in the surface float, confirms that the laminated beds are present at Gore Point, whereas they appear to have been removed at the surface in the Boas River area.

Nelson and Johnson (1966) considered that some 16 to 17 m of the lower interval, comprising the interbedded organic and organic-poor limestones, are present at Sixteen Mile Brook below the laminated bed, and that as much as 50 per cent of the interval could be the organic-rich section on the evidence of float distribution. They reached a similar conclusion for the Gore Point section. Four metres of dominantly yellow-brown, thin to medium bedded, hard, organic-poor limestone underlying the laminated shales at the Sixteen Mile Brook outcrop contain only scattered low-organic interbeds (Macauley, 1986). Macauley (op. cit.) considered that the thickness of section containing low organic limestone at Gore Point could be a few metres at most, somewhat thinner than previously projected. At Boas River, Macauley (op. cit.) described slightly over 2 m of low-organic limestone overlying less than 2 m of organic-poor yellow-brown limestone. The lower contact of the organic beds is transitional from the underlying organic-poor carbonate. In all three areas, the yellow-brown limestones directly overlie Precambrian rocks.

The oil shale exposures follow the Precambrian – Paleozoic contact closely with only thin intervening barren beds. In several areas, mapped by both Heywood and Sanford (1976) and Nelson and Johnson (1976), Boas beds are absent as the result of nondeposition against Precambrian topographic highs.

The upper contact with apparent brown to grey, in part "reefy", carbonate is sharp and apparently conformable at the Sixteen Mile Brook outcrop. Scree covers the entire slope at Gore Point and the distribution is interpreted from the essentially in-place talus. The uniformity of the band of organic-rich laminate detritus may indicate conformity for both the upper and lower contacts of the bed.

Age

Barnes (1973) placed the "petroliferous" limestone of the Boas River section in conodont Fauna 12 of Sweet et al. (1971) based on the presence of *Amorphognathus ordovicicus* and other diagnostic conodonts for that interval, thus placing those beds in the Edenian – Maysvillian and confirming a time correlation with the Collingwood oil shales. Barnes (op. cit.) also indicated that the strata assigned to the Bad Cache Rapids Group on Southampton Island equate faunally with the uppermost Ordovician Farr Formation at Lake Timiskaming, Ontario, placing both in the Edenian, confirming the possible nondeposition or erosion of Collingwood-Boas equivalents in the Timiskaming outlier.

Uyeno (pers. comm., 1987) independently confirmed that the Boas section beds are within the *A. ordovicicus* Zone. Uyeno also reported that no conodonts were recovered from a sample of the laminated beds from Sixteen Mile Brook.

From his dating of overlying organic-poor carbonates and the underlying Boas low-organic limestones, Barnes (1973) suggested a hiatus of Maysvillian age in the depositional sequence on Southampton Island. This hiatus would of necessity occur bounding or within the interval of the laminated shales. Barnes (op. cit.) dated the overlying Churchill River Group and Red Head Rapids Formation as late[1] Maysvillian to Richmondian, probably Richmondian.

[1]late and early are used informally in this report.

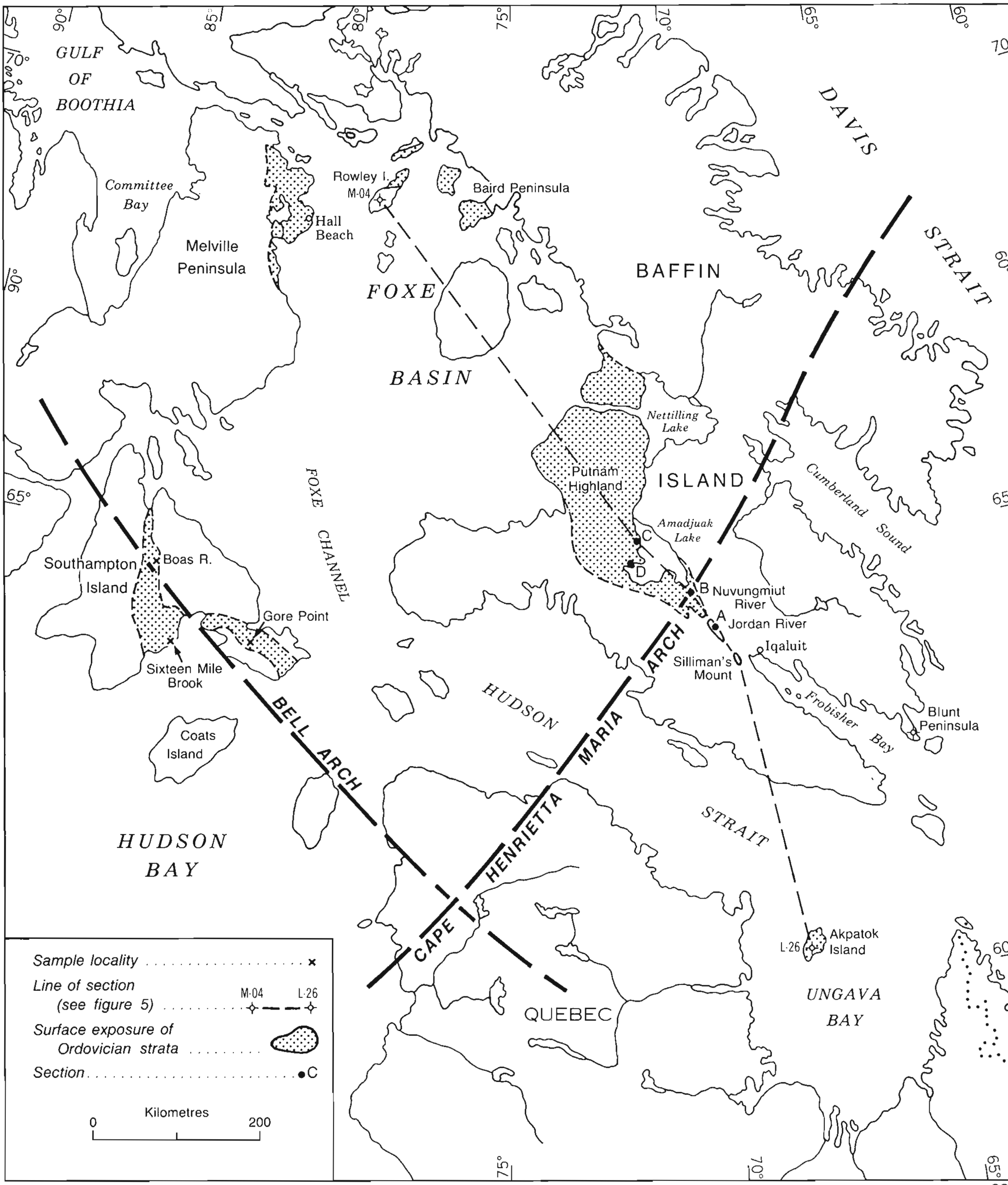


Figure 4. Distribution of Ordovician strata on Melville Peninsula and Southampton, Baffin and Akpatok islands, showing sample localities of organic-rich beds. (After Macauley, 1987b.)

Deposition

Although the Boas oil shales are in many ways characteristic of the thin, widespread organic intervals that follow widespread carbonate sequences, there was no influx of the overlying terrigenous clastic detritus common to the other examples, such as the Collingwood Member. There are virtually no clays and the quartz appears to be authigenic. Deposition within a starved basin can be readily envisioned.

Barnes' faunal hiatus within the Maysvillian may well be represented by the thin laminated organic-rich beds that failed to yield conodonts and thus are not dated specifically. Because the upper contact appears conformable, slow deposition over a long time period is a preferred explanation, rather than invoking tectonic activity and/or a period of erosion. In order for deposition of apparent shallow-water carbonates to resume at the end of the hiatus, the organic-rich beds are presumed to have been deposited in relatively shallow water, probably not much below effective wave base.

Unnamed organic beds — Baffin Island

A sequence of Lower to Middle Ordovician carbonate rocks in the southern part of Baffin Island (Fig. 4) has been known since the early paleontological reports describing the macrofauna of the Putnam Highland, by Gould et al. (1928), and of Silliman's Fossil Mount near the settlement of Iqualuit, by Roy (1941). Miller et al. (1954) contributed additional macrofaunal detail. In a geological reconnaissance of the southern part of the island Blackadar (1967) further assessed the macropaleontology of the area. This prime interest in paleontology resulted from the difficulties in defining the stratigraphic positions of many sections within the Middle to Upper Ordovician sequences of North America; consequently, these accounts reported only briefly on the lithologies encountered and recorded the sections as undivided Ordovician. Neither oil shales nor organic-rich (bituminous) beds were reported to be present with any precision. Roy (op. cit.) did note the presence of black limestones and limy shales in Foxe Land (probably Putnam Highland) and on Blunt Peninsula (Fig. 4). He correlated these strata with the Collingwood oil shales of southern Ontario. In a Geological Survey of Canada Open File Report, Macauley (1987b) described a threefold lithological sequence for the area and the presence of two organic-rich intervals at three obscure exposures. The section is presented in considerable detail here because the original work was unpublished.

On southern Baffin Island, a threefold stratigraphic subdivision, dominantly carbonate, is based firstly on colour and bedding characteristics, and secondly on the presence of a "shaly" bed within the middle unit. The section is described from top to base, commensurate with subsurface procedures, as further clarification will result only from drilling and/or coring. Good surface sampling is extremely difficult as Ordovician beds are almost everywhere covered by surficial muds.

Upper unit

Ordovician rocks are preserved in hills, or "mounts", capped and preserved by a distinct orange coloured limestone, which weathers to an equally distinct orange-yellow, soft, surficial mud. These beds, generally less than 15 m thick, are knobby, with small, lighter coloured, cryptocrystalline nodules ranging from 2 to 5 cm in diameter. The matrix is a slightly darker, finely crystalline limestone. Because of the extreme weathering effects, exposures are few and the contact with the underlying unit could not be directly examined in surface beds.

Middle unit

The medial unit is composed of light to medium grey, cryptocrystalline limestone which occurs as flat, elongate nodules, 2 to 5 cm 'thick', and generally greater than 10 cm in length, within a matrix of slightly darker, finely crystalline limestone. This rock type weathers to a distinct, light grey, soft, surficial mud. Both the colour and the bedding characteristics distinctly separate this from the upper unit. The difference in colour of the surface muds readily differentiates the two units when viewed from the air. Admixing of the surface muds, especially near the contact, obscures this feature when on the ground.

Blue-grey limestone, containing abundant carbonate nodules 2 to 3 cm in diameter, is distinctive as interbeds within the middle carbonate sequence. A widespread, distinctive, blue-grey bed, 1 to 2 m thick, which occurs approximately 8 m below the top of the grey interval, forms a prominent regional marker. Blue-grey beds are more prominent on the shores of Amadjuak Lake (Figs. 4, 5) where the section consists of alternating grey limestone and blue-grey zones, similar to that reported by Gould et al. (1928) on Putnam Highland. Although these beds are described in the literature as blue-grey "shale," they are limestones, in part dolomitic and commonly with a minor quartz content. Clay minerals are virtually absent. The colour and softness have been key factors in characterizing the rock as shale, although mudstone would have been a more accurate term.

Thickness of the middle unit varies from 100 to 125 m in the Silliman's Fossil Mount and Amadjuak Lake areas to a possible 190 m on Putnam Highland, where the shalier beds are more dominant.

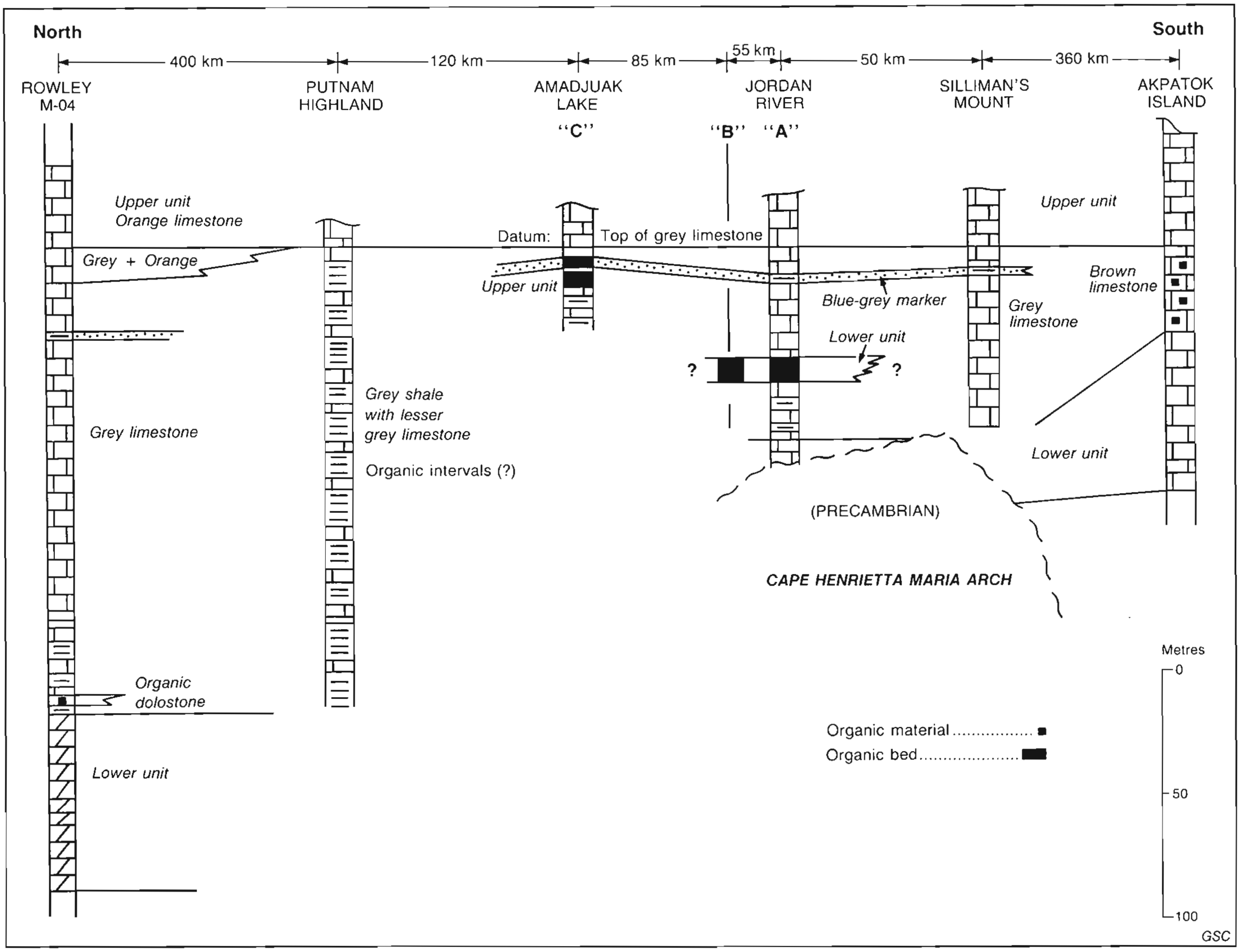


Figure 5. *Diagrammatic north-south, Ordovician, lithostratigraphic correlation section, through Rowley, Baffin and Akpatok islands. Location of section is shown on Figure 4. (After Macauley, 1987b.)*

Organic-rich beds are present within this middle unit at three locations (Fig. 4). At locations A (Jordan River) and B (Nuvungmiut River), oil shale is present in the lower part of the grey interval, whereas at Amadjuak Lake (location C), the organic beds are possibly equivalent to, and directly below, the regional blue-grey marker bed (Fig. 5).

Lower unit

A basal unit, probably less than 10 m in thickness, is composed of medium bedded (5-15 cm), light grey to grey-brown, resistant limestone, which weathers grey and forms ledges. Where observed, the limestones appear to be non-argillaceous and devoid of shaly interbeds. The basal unit rests unconformably on the Precambrian.

Lithology

The lower of the two organic intervals, located near the Jordan and Nuvungmiut rivers (Fig. 4; locations B, C), consists of dark brown, thinly laminated, 'papery' beds, overlying medium to dark brown, bedded (1-5 cm), somewhat more resistant oil shale. All the organic-rich beds are primarily limestone, with lesser, variable, dolomite content, and minor clay minerals (chlorite and illite) and feldspars (mostly plagioclase). Quartz content ranges from 20 to 40 per cent, but no grains as large as silt or sand size can be detected.

Clay minerals (mostly chlorite and illite), abundant quartz, and a variable calcite-dolomite content define the younger organic shales (location C) as argillaceous dolomitic limestone to calcareous dolomitic shale. The term mudstone may be more appropriate as induration did not reach the point at which fissility develops. Samples are distinctly brown when wet, but dry to a grey tone. From a distance, the organic beds appear black, but, on closer inspection, have a distinct greenish tinge on the weathered outcrop surface, possibly from the chlorite content. Minor chlorite may also be the reason for the bluish tinge of the blue-grey beds.

Distribution

Because of the extreme weathering in this Arctic area, and the generation of a fine, lime-flour mud which overlies most of the Ordovician beds, good exposures are relatively few; consequently, the areal distribution of the organic beds is difficult to map.

At Section A on the Jordan River (locations R and S of Blackadar, 1967), oil shales occur 30 to 35 m below the regional blue-grey marker bed and are exposed in a small gully that has cut sufficiently deeply into the surficial mud to expose the bedrock. Laminated 'papery' beds are interpreted from the distribution of their debris in the talus, as forming an approximately 5 m thick interval, although they are not sufficiently resistant to outcrop. Underlying, thicker bedded oil shales are exposed over a 7 to 9 m interval for a total estimated organic-rich section of 12 to 14 m. A distinct brownish coloured band indicates the top of the oil shale when seen from the air. Below the oil shale, an estimated 15 to 20 m of section is overlain by grey mud which contains grey limestone, shale, minor orange carbonate and Precambrian float. Grey weathering, ledge-forming carbonate of the lower unit is exposed along the Jordan River at the base of the hill.

Oil shale float, occurring as distinct 'florets' of 'papery' chips brought to the surface by frost heave, was encountered along a low slope on a hillside near the Nuvungmiut River at location B (locations M and N of Blackadar, 1967; see Macauley, 1987b for greater detail). No bedrock oil shale was noted as the gully examined was very shallow and on a gentle slope. Because the thicker bedded oil shales exposed at Jordan River are much more resistant to erosion than the 'papery' beds, the lower strata would probably not be recognized either as detritus or outcrop at this location. Very specific topographic conditions of slope and gully erosion are required to expose the oil shales in the Ordovician beds of southern Baffin Island.

Because Silliman's Fossil Mount (Fig. 4) has been so often the basis of paleontological papers, Macauley (1987b) carefully scrutinized that section for organic beds. None was encountered even though the surficial muds were examined closely for frost heaved oil shale 'florets'. Orange-coloured limestone caps the mount. The blue-grey marker bed (possibly bed B of Roy, 1941) is distinctive near the top of the grey section. Sufficient section below the marker zone remains concealed so that the organic beds of the Jordan River could be present (Fig. 5) but completely covered by the surface muds. Alternatively, the organic zone could be absent as the result of a facies change. The base of Silliman's Fossil Mount is almost at the Precambrian–Ordovician contact, and there is no evidence of the lower, ledge-forming limestone at the base of the sedimentary section.

Only a thin Ordovician section is present at the northwest end of Amadjuak Lake (Fig. 4, location C). There is an insufficient interval here below the blue-grey marker to expose beds equivalent to the Jordan River section.

At the Amadjuak Lake section, orange carbonate overlies approximately 8 m of middle grey zone beds which downward comprise 3 m of grey talus covered interval; 4 m of brown talus, which appears to be in place and consists of low grade organic rock; and a 0.4 m thick limestone bed overlying 7 m of brown oil shale. Below the oil shale are 0.2 m of blue-grey lime mudstone; 1 m of light brown, aphanatic limestone; 1.3 m of blue-grey lime mudstone; 0.7 m of grey nodular limestone; and 0.2 m of blue-grey lime mudstone, of unknown total thickness, at the base.

At location D on Amadjuak Lake, a similar section was visited by Macauley (1987b) and found to contain only blue-grey beds interbedded with limestone: none of the beds is organic-rich. Greater detail of this particular sequence will undoubtedly be gained by additional study of the Putnam Highland sections.

Whether or not sufficient section is present between the outcrops at Amadjuak Lake and Precambrian rocks to the east to contain the lower organic beds can only be conjectural. There is a distinct possibility that the lower ledge-forming limestone and the older of the organic-rich units are locally missing as the result of nondeposition against Precambrian topographic highs, similar to areas of nondeposition of the Boas oil shale on Southampton Island.

At the Aquitaine et al. M-04 corehole on Rowley Island, to the northeast of the Baffin Island Ordovician sections (Fig. 4), the upper orange/middle grey zonation is distinct (Macauley, 1987b). An interval of interbedded orange and grey strata indicates continuous, transitional facies deposition across the boundary. The blue-grey marker bed is well developed. Not only do the middle and lower units thicken, there is also a considerable underlying section of older Ordovician beds in the Rowley corehole. Both this corehole and the thicker Putnam Highland sections reflect Foxe Basin deposition flanking the thinner sections of the mid-continental Cape Henrietta Maria Arch (Figs. 1, 5; Sanford et al., 1985).

Age

Unfortunately, most of the early macrofaunal collections made at Silliman's Fossil Mount and on Putnam Highland (Gould et al., 1928; Roy, 1941; Miller et al., 1954) were made on the assumption that a single stratigraphic interval was present and probably covered a restricted time span. Considerable confusion resulted as different authors variously assigned the beds to the Middle or to the Upper Ordovician. Many excellently preserved specimens are available as float within the surficial mud deposits. Although not attempted by the early collectors, most of these fossils can be assigned to the orange or grey units both by their own colour and that of the adhering lime mud.

Blackadar (1967) collected at more widespread locations but did not provide lithological descriptions of the enclosing rock or of adjacent float detritus. Interpreting from his work, the lower ledge-forming limestone can be assigned to a late Wilderness stage. Most of his Middle Ordovician Barneveld stage localities appear to be within the middle grey unit, whereas his post-Barneveld(?) collections may relate to the uppermost grey beds, especially those sections at the north end of Amadjuak Lake. No specific age for the orange beds can be interpreted from his report.

Nowlan (1987) identified conodonts from three sample localities: the organic beds (GSC locality C-151099) and the blue-grey marker interval (locality C-151098) at the north end of Amadjuak Lake, and the organic-rich beds at Jordan River (locality C-151097).

At Amadjuak Lake a diverse conodont assemblage, comprising thirteen species in over 400 moderately well preserved specimens, indicates a Late Ordovician (late Edenian – early Maysvillian) age for the blue-grey marker unit, compatible with the post-Barneveld(?) determinations of Blackadar (1967). The equivalent, or certainly near equivalent, organic shale of Black Beach (Fig. 5) is dated by Nowlan (1987) as probable mid-Trentonian to early Maysvillian, based on a less diverse assemblage (6 species, 27 specimens). Specimens of the diagnostic *Amorphognathus* are present in the organic shale but could not be identified as to species. Because of the interrelationship of the two rock types in the outcrops, the organic beds must also be considered as Late Ordovician deposits.

At Jordan River, five conodont species in 135 also moderately well preserved specimens, indicate a possible age range from Middle to early Late Ordovician (Trentonian to early Maysvillian); however, Nowlan (1987) stressed that a later Maysvillian to Gamachian age could not be ruled out. Based on its position in the sections (Fig. 5), this zone must be older than the Amadjuak Lake intervals and is probably Trentonian (Barneveld) as reported by Blackadar (1967).

Although the evidence presented is some indication that the upper organic beds are time equivalents of the Boas organic beds on Southampton Island and the Collingwood Member of southern Ontario, thus representing a widespread geological event, Nowlan (1987) has cautioned that "with Late Ordovician dark limestone/black shale units . . . there is considerable variability in age with some in the Edenian and some as young as late Maysvillian or Richmondian. Each occurrence probably has to be taken on its own merits and assumptions of time equivalence are risky".

Deposition

At present, all that is known of the Baffin Island organic-rich beds are that they are of marine origin. Their regional distribution and relationship with other organic-poor strata are too poorly known to allow the interpretation of their depositional histories from only the lithological characteristics.

Unnamed carbonate — Akpatok Island

Brown 'bituminous' limestones have been described by Workum et al. (1976) from upper Middle to lower Upper Ordovician beds on Akpatok Island (Fig. 4), located at the northern limits of Ungava Bay, some 400 km south-southeast of the Ordovician beds on Baffin Island, and some 800 km east-southeast of the oil shales on Southampton Island. Workum et al. (op. cit.) indicated a correlation between these beds and the Collingwood and Boas oil shales of Ontario and Southampton Island respectively, based on the presence on Akpatok Island of a *Leptobolus-Triarthrus-Pseudogygites-Geisonoceros* fauna in a brown, bituminous, argillaceous limestone some 4.6 to 9.1 m above high sea level in their Section II, and their interpretation that this assemblage is characteristic of the late Edenian. The characteristic conodont *Amorphognathus ordovicicus* was not listed even though Barnes (1973, 1985) was involved in this study and had recognized that species to be significant to the Collingwood – Boas correlations.

Ordovician geology on Akpatok Island is known from a combination of exposures in the massive cliffs that form the eastern shoreline of the island in particular, and a single borehole, Premium Homestead Akpatok L-26. The 'bituminous' carbonates were not cored at the L-26 location; consequently, their geology is known best from surface exposures.

Lithology and distribution

The island is capped by more than 50 m of orange-brown limestone, much more massive and less nodular than the upper orange coloured unit on Baffin Island, but clearly a related lithology (Fig. 5). An underlying middle unit, somewhat less massive and much less resistant to erosion, and approximately 35 m thick, contains light brown to minor medium brown, cryptocrystalline, in part poorly organic limestone, comparable in character to the lower beds of the Boas organic-rich interval on Southampton Island. The 'bituminous' bed of Workum et al. (1976) is within this interval, but does not appear to contain any organic-rich, laminated oil shale. Macauley (1987b) thoroughly searched the surface detritus for the laminated lithology. A basal unit of massive bedded, ledge-forming carbonate is exposed at low tide. The lithological similarity of these intertidal beds to the lower unit of Baffin Island is readily apparent, although their thickness, approximately 60 m from the borehole data, is greater than that of the Baffin Island unit (Fig. 5). They overlie roughly 310 m of grey-green and white shales and sandstones assigned by Workum et al. (op. cit.) to the Lower to early Middle Ordovician.

Akpatok Island is a remnant Ordovician outlier in Ungava Bay — only Precambrian rocks are present in the adjacent mainland areas of Quebec. The areal distributions of the upper orange beds and of the lower ledge-forming limestones can be projected northward to Baffin and Rowley islands (Figs. 4, 5). The geographic relationships of the middle section are less definite because of the facies changes indicated above. Whether the indicated thinning on Akpatok Island is depositional or in part relates to facies change at either the top or the base is presently indeterminate.

Age

Workum et al. (1976) reviewed all earlier paleontological publications and added numerous new faunal identifications. The most significant interval studied by these workers is the 4.5 m of brown 'bituminous' limestone of their *Leptobolus-Triarthrus-Pseudogygites-Geisonoceros* faunal zone, which occurs 4.6 to 9.1 m above high sea level and which they dated as late Edenian and correlated with both the Collingwood and Boas oil shales. They identified a post-Edenian fauna in the interval from 27 to 152 m above mean sea level in Section II. Earlier studies had identified the upper beds of the section as Richmondian. *Panderodus staufferi*, from an interval 23 to 30 m above mean sea level in Section I, slightly above the 'bituminous' interval, was assigned to conodont Fauna 12. In the L-26 corehole, Fauna 2 (Whiterockian) occurs 264 to 298 m below sea level. Workum et al. (op. cit.) concluded that the organic-rich strata on Akpatok Island are younger than those at Silliman's Fossil Mount on Baffin Island.

Although an exact correlation of these faunal intervals with the threefold section described herein is difficult, because of the different colour descriptions of the various authors, the upper orange-brown beds are most likely within the Upper Ordovician Richmond Stage. The lower ledge-forming beds appear to equate lithologically with the uppermost Ship Point beds described by Trettin (1975) as containing conodont Fauna 3 belonging to the Wilderness Stage. This age is compatible with the lower, conodont Fauna 2 determination of Workum et al. (1976) for this interval of the Akpatok Island section.

Nowlan (1987) identified conodonts from two samples from the middle unit of brown, poorly organic limestone on Akpatok Island. Float near the top of the unit, of necessity close to the boundary with the overlying orange weathering unit, yielded five conodont species from 139 specimens (GSC locality C-147500). A small (< 1 m thick) outcrop toward the base of the middle unit yielded nine species from 261 specimens (locality C-147499). All specimens are moderately well preserved. The assemblages are dominated by prolific simple cone taxa, which are biostratigraphically poorly diagnostic. The faunas identified from both collections are consistent with an age range of latest Middle to Late Ordovician (Shermanian to Gammachian).

No definite paleontological correlations can be made between the Baffin and Akpatok Island sections; however, a possible stratigraphic equivalence, comparable to the proposed lithological correlation (Fig. 5), can be reasonably surmised. There is no additional evidence to confirm or reject the proposed correlation, by Workum et al. (1976), of an organic-rich interval on Akpatok Island with both the Collingwood and Boas beds.

Deposition

The poorly organic, brown limestone beds encountered on Akpatok Island are marine, but little can be determined from the limited lithological and distributional data as to the depositional history, which must be defined by lithology alone. The rate of deposition must have been slow for this relatively thin interval to encompass such a significant time span.

Table Head Group — western Newfoundland

Various publications, including both local mapping reports and regional geological studies, have described the occurrence of oils seeps in western Newfoundland. These are well summarized in Fleming (1970) and Sheppard and Hawkins (1981). Hydrocarbon shows, in the forms of bitumens and petroleum, occur most commonly in the sandstones of the Ordovician Green Point and Humber Arm groups (Fleming, op. cit.). Black shales of the Middle(?) Ordovician Table Head Group and 'bituminous' beds of the Lower Ordovician Green Point Group were presumed to be the most probable source of these hydrocarbon shows. Beds of the Table Head Formation were considered to be of particular interest because of their possible time equivalence to the other organic-rich beds of this report.

The Cambro-Ordovician geology of western Newfoundland is complex in that an autochthonous carbonate sequence is overlain by a thick allochthonous clastic succession of equivalent and older strata, which was transported westward in a series of thrust sheets during the Late Ordovician Taconic Orogeny (Sheppard and Hawkins, 1981). Several of the carbonate sequences are lithologically similar and many of the terrigenous clastic beds contain few fossils so that age determinations are inconclusive. Limestones and uppermost shaly beds of the Table Head Group are among the youngest Ordovician rocks preserved in western Newfoundland within the autochthonous sequence.

Lithology and distribution

The Table Head Group outcrops continuously in the vicinity of Table Point (Fig. 6). The uppermost beds are exposed near the settlement of Bellburns. Although often described as black shale because of the recessive weathering characteristics and shaly bedding, the upper unit consists of a series of dark grey to black, shaly limestones that are not true shales. The colour is black when wet, but invariably dries to medium to dark grey. Nodules of black carbonate, approximately 2 cm in diameter on average, are enclosed in a dark grey, slightly siliceous, slightly dolomitic limestone. Their soft recessive character contrasts sharply with the massive cliffs of underlying resistant Table Head carbonates. Macauley (1987c) noted that, except for the mud matrix, these upper beds much resembled the knobby limestones characteristic of the lower Table Head as mapped in the East Bay area (Fig. 7).

In Piccadilly Quarry (Fig. 7), approximately 10 m of laminated, light to medium grey-brown, graptolitic carbonate, containing both calcite and dolomite, overlies typical, coarse nodular, lower Table Head limestone. Similar beds, slightly less laminated, were also sampled by Macauley (1987c) on the south side, and toward the west end, of East Bay. Only traces of clay are present, but the samples contain an average 25 per cent quartz, which must occur as particles smaller than silt size. Klappa et al. (1980) defined the Black Cove Formation as comprising black graptolitic shales outcropping along the eastern shoreline of East Bay (Fig. 7). There seems little doubt that the graptolitic beds of the Piccadilly Quarry correlate with the beds defined as Black Cove Formation.

Age

Finney and Skevington (1979) studied the graptolites from the Piccadilly Quarry and assigned them to the *Diplograptus decoratus* Zone of early Middle Ordovician age. They also indicated that this fauna had been reported from the Black Cove area, where the Black Cove Formation was subsequently defined, and also from the outcrops of Table Head Group at Table Point.

Green Point Group — western Newfoundland

Rocks of the Green Point Group consist of thinly bedded, black, grey, green, and red argillites (shales), limestones and limestone conglomerates at the type section at Green Point (Fig. 7). Corkin (1965) described some of the shales as 'bituminous' and reported the presence of sandstone beds. Green Point shales, forming part of the allochthonous sequence, are by far the most interesting rocks in terms of organic content (Macauley, 1987c).

Lithology and distribution

At Green Point, approximately 50 m of very finely laminated, calcareous, dolomitic shale, variably very dark grey and green, are exposed in vertical beds for which top and base are indeterminate. Laminae to thin beds (<2 cm) of very fine grained sandstone and some carbonate beds up to 5 cm thick are interspersed within the shales. A conglomerate bounds the shales at one end. On Port au Port Peninsula, poorly laminated, dark grey, dolomitic shale occurs as a thin bed within a sandstone sequence (with minor conglomerate) in a small roadside outcrop (Macauley, 1987c). The lithological comparability of the black shales in the two areas is obvious. Mineralogically, both are dominated by quartz, with a variety of accessory clay minerals, feldspars, and both calcite and dolomite. These beds are true shales rather than carbonates. The shales are distinctly organic, reacting positively in a flame by igniting but not burning freely.

Age

A Lower Ordovician age has been assigned to these beds on the basis of the graptolites *Dictyonema flabelliforme* and *Staurograptus dichtomus* (Fleming, 1970).

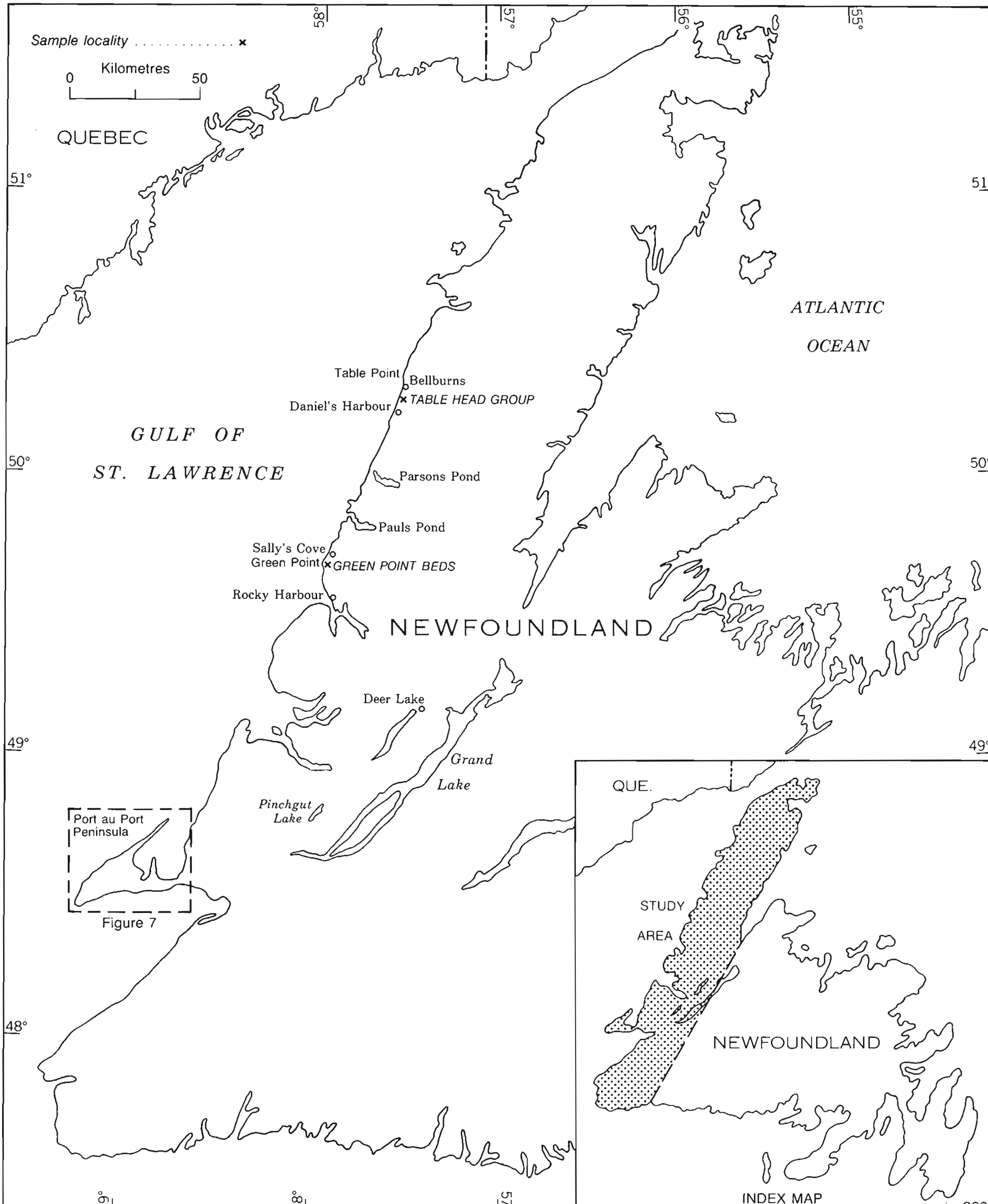


Figure 6. *Sample location map, Table Head and Green Point groups, western Newfoundland.*

Humber Arm Group — western Newfoundland

Three samples were collected along the shores of West Bay from the darkest coloured shale beds in a sequence of contorted Humber Arm clastics. In composition, all these shales are dominated by quartz, with lesser calcite, dolomite and a variety of clay minerals. The shales are part of the allochthonous clastic terrane that was thrust westward over the carbonate sequence. They are possibly older than the Table Head Formation and could be approximate equivalents of the Green Point Group.

Yeoman Formation — southeastern Saskatchewan

Long before the recognition of oil shales and source beds, both age determinations and correlations of the Arctic Ordovician sequences and the Red River Formation in Manitoba were subject to geological investigation, especially the dating and relationships of Middle versus Upper Ordovician strata (Gould et al., 1928; Roy, 1941; Miller et al., 1954; Workum et al., 1976; and many others). Based on surface exposures in Manitoba, the Red River Formation was defined as a carbonate unit, subdivided into three informal

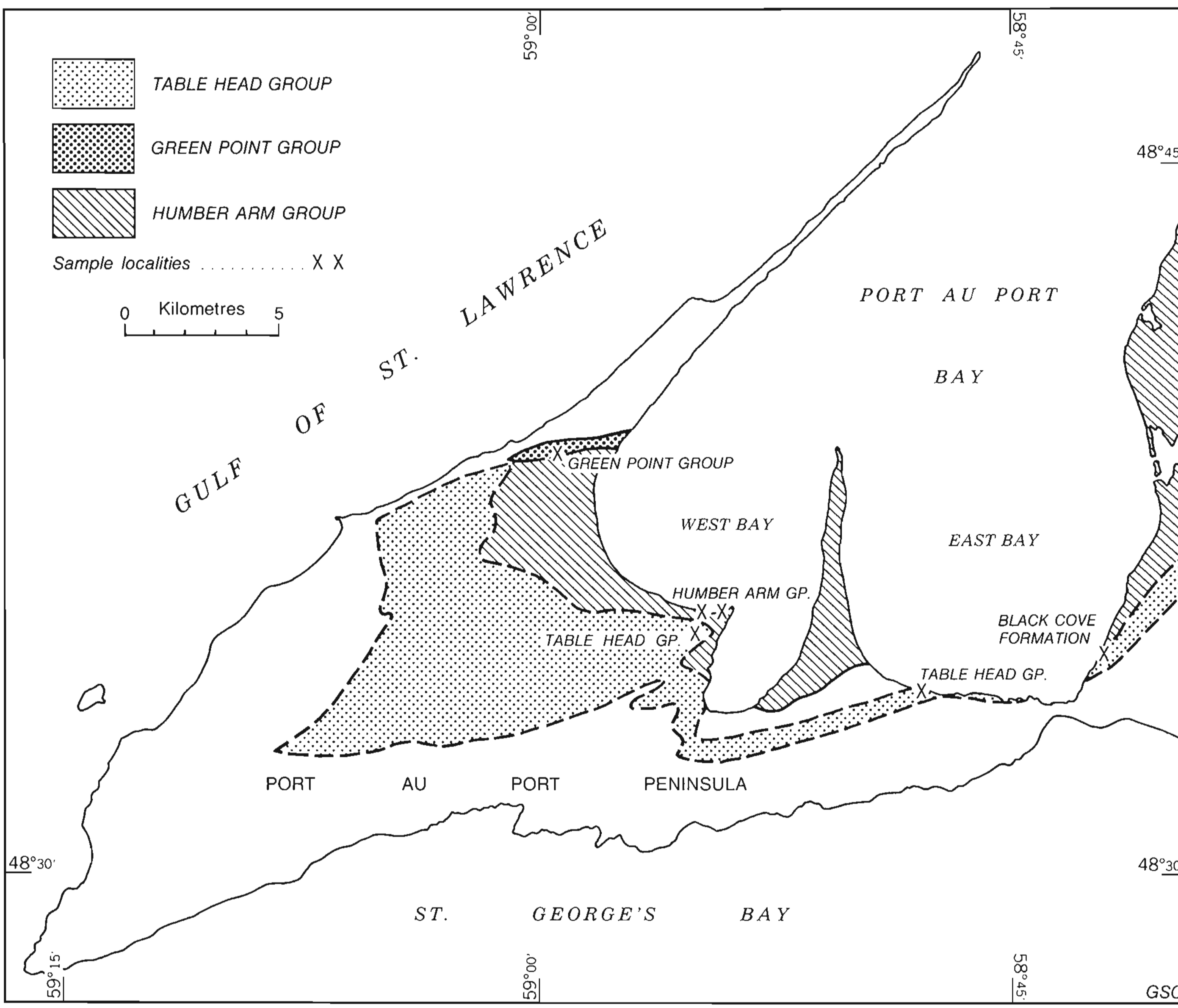


Figure 7. Sample location map, Table Head Group graptolitic limestone, Green Point and Humber Arm groups, Port au Port Peninsula, western Newfoundland. (After Macauley, 1987c.)

members on the basis of mottling, and differentiated from the overlying Stony Mountain Formation by shale content and reddish colouring of the latter. The underlying Winnipeg Formation is a terrigenous clastic sandstone – shale interval.

As drilling progressed in Williston Basin, evaporites were recognized in the upper Red River section, leading to the definition of the lower, Yeoman, carbonate and upper, carbonate-evaporite Herald beds. Present nomenclature (Kendall, 1976; Kohm and Louden, 1978) includes the entire carbonate-bearing section as the Bighorn Group, including, in descending order, the Stony Mountain, Herald and Yeoman formations. These overlie the Winnipeg Formation, which rests with erosional unconformity on Cambrian beds centrally within the basin, and on Precambrian rocks on its periphery. Many workers in the petroleum industry continue to use the Red River as a Formation with Herald and Yeoman beds as part of that formation, even though these units have been further subdivided.

The Yeoman Formation has a thin lower Unit "A" containing argillaceous carbonates that are transitional upward from the Winnipeg shale to typical mottled dolomitic limestones and/or dolostones of Unit "B". Although containing similar carbonates to those of Unit "B", Unit "C" is characterized by the presence of kukersite (locally termed 'kerogenite'; Stoakes et al., 1987). The uppermost unit, Unit "D", is a thin interval, transitional from the mottled Yeoman beds to dolostone muds of the younger Herald Formation. Stoakes et al. (op. cit.) have presented a more comprehensive review of the stratigraphy.

Genik (1954) divided the Winnipeg Formation into lower, Black Island sandstone, and upper, Icebox shale members. Although other authors have locally further subdivided the Winnipeg Formation, proposed new but equivalent names, and raised the unit to group status, Genik's nomenclature is still commonly used. Osadetz and Snowdon (1986) reported a significant (for source rock) upward increase in organic carbon within the Icebox Member.

Lithology and distribution

As described by Stoakes et al. (1987), kukersite beds are black to reddish, thinly laminated, occasionally crinoidal, organic-rich carbonates which are present as beds varying from a few centimetres to almost half a metre in thickness. Bioturbation has irregularly reduced the organic content and lightened the colour of the sediment. The laminites commonly overlie a cemented hardground surface with organic-rich sediment extending downward into surface breaks. The upper contact is commonly poorly defined with the laminites grading into the overlying, bioturbated, organic-poor carbonate. Individual laminite beds are laterally discontinuous and non-correlative, but as a group characterize the areally widespread, 15 m thick Unit "C" of the Yeoman Formation.

Age

Although there has been considerable debate concerning the age of the Red River Formation, deposition of these carbonates is now generally considered to encompass a broad time period through the Trenton (Barneveld), Eden and Maysville stages and terminating in the Richmondian (see Foster, 1972). Within this time frame, the kukersites may have been deposited during the late Edenian to early Maysvillian. There has always been general agreement that the age of the overlying Stony Mountain beds is Richmondian. The underlying beds of the Winnipeg Formation appear to be diachronous to some extent within the Black River–Trenton (Wilderness – Barneveld). Whether or not depositional continuity ever existed between the Williston Basin and the northerly Arctic Islands is debatable and exact time equivalents may be difficult to define; however, there is certainly an indication of widespread events in the probable coeval deposition of organic-rich strata.

Deposition

Although much more restricted in both areal extent and thickness, Yeoman kukersite layers are similar to the Collingwood and Boas beds as accumulations of organic detritus following the drowning of a carbonate-producing environment. The formation of Yeoman kukersite can be attributed to drowning in irregular lows.

The organic content in the Icebox Member of the Winnipeg Formation shows an interesting variation from the norm for organic-rich deposits. The organic-poor terrigenous shale in the lower part shows an upwardly increasing organic content into a carbonate sequence; a distinct reversal of the final-phase relationship usually observed of widespread organic-rich beds following the cessation of carbonate deposition. There is insufficient kerogen in the Icebox Member to consider the beds as organic-rich; however, organic carbon content is sufficient to provide a significant source potential. The probably diachronous nature of the Winnipeg – Red River contact may reflect accumulation of organic materials derived from laterally deposited carbonates.

ORGANIC PETROGRAPHY

On completion of the Rock-Eval pyrolyses, specific samples were chosen for investigation of their organic matter by optical analysis, to provide greater detail of the kerogens so that the geochemical data might be better interpreted. For optical analysis, polished specimens were prepared according to the recommendations of Mackowsky (1982). The polished sections were then examined using reflected white light and fluorescent light microscopy. Plate 1 illustrates typical petrographic characteristics of the various deposits under fluorescent light microscopy.

Random reflectance measurements in oil (n = 1.518 at 24°C) were made using a Zeiss MPM II reflected light microscope fitted with white (halogen) and fluorescent HBO light sources. Spectral intensities were measured in the range of 410 to 700 nm and fluorescence curves generated using a Zonax microcomputer equipped with a plotter. The fluorescence spectra were obtained using an ultraviolet (365 nm) excitation filter and a 420 nm barrier filter. This allowed the determination of fluorescence spectra for hydrogen-rich components with λmax (wavelength of maximum intensity) 420 nm. The fluorescence properties determined include λmax and the Red/Green Quotient (Q).

Only a synopsis of the petrological data is included here. Much more comprehensive reviews will be available in papers concerned primarily with the organic petrology of each organic unit.

Collingwood Member — southern Ontario

Only samples from the Collingwood area have been studied petrographically to date. The greater part of the kerogen is amorphous sapropelic material (Plate 1b). Marine flora (tasmanales) and fauna (chitinozoa), bituminite (Types I and II), matrix bituminite, non-fluorescing bituminite Type III, and bitumen are also present. Different generations of bitumen were detected. Non-fluorescing material may comprise as much as 20 per cent of the organic matter.

Fluorescence intensities (λmax 450-510 nm), Red/Green Quotients (Q 0.28-0.44) and reflectances of the bitumen and chitinozoa all indicate an immature to marginal/low thermal maturation relative to petroleum generation.

Samples have not been studied from the islands of Lake Huron, from the Whitby area, or from the Billings-Eastview section of the Ottawa area.

Boas oil shale — Southampton Island

Three samples representing high, medium and low yield beds were examined (Macauley, 1986). In the two 'better-yield' samples, the organic matter is almost entirely matrix bituminite with negative fluorescence intensity alteration. Only a very little liptinite is preserved. Some grey, rounded, non-fluorescing bodies (Type III kerogen ?) are present and these have low reflectance values (0.33-0.48). Only bitumen-stained carbonate could be recognized in the low yield sample.

Fluorescence intensities (λmax) range from 477 to 500 nm and Q values from 0.53 to 0.59 for the sapropelic kerogen. Bitumen reflectances range from 0.15 to 0.24. These values are all indicative of the thermal immaturity of this marine sapropelic deposit.

Unnamed organic beds — Baffin Island

Samples locales are the same as those previously described and illustrated on Figure 4. The laminated and massive lithologies of the lowermost mapped oil shale bed were sampled at Jordan River (location A) and Nuvungmiut River (location B). The upper organic unit (Fig. 6) was sampled at Amadjuak Lake (location C).

Kerogen content directly reflects the different lithotypes. The laminated beds contain fluorescent marine flora (acritarchs and tasmanite algae), matrix bituminite, non-fluorescent marine fauna (chitinozoa and graptolites) (Plate 1f) and bitumen. Up to 15 per cent of the organic matter may be non-fluorescing. The more massive beds show a less diversified organic content dominated by matrix bituminite and a fluorescent marine fauna (acritarchs and tasmanales). Acritarchs were also noted within the organic-poor blue-grey beds. These unnamed organic beds are marine deposits in which the greater part of the kerogen is amorphous sapropelic material.

Maturities were determined from fluorescence intensities (λmax ≈ 500 nm), Red/Green Quotients (0.43-0.52) and from the reflectance values of bitumen, chitinozoa and graptolites. All indicate an immature thermal maturation relative to petroleum generation.

A further excellent opportunity is provided here to compare maturation parameters based on bitumen, chitinozoa and graptolite reflectances with the fluorescence properties of acritarchs (Goodarzi, 1984, 1985; Goodarzi and Norford, 1985; Goodarzi et al., 1987). Within a single sample, the reflectance values increase from bitumen (0.17-0.22) through graptolites (0.54-0.60) to chitinozoa (0.71-0.80).

Graptolite reflectances are generally lower than those of the chitinozoa, which contrasts with the earlier results of Goodarzi and Norford (1985) wherein graptolite reflectances were higher than those of the chitinozoa. The Baffin Island kerogens are immature and hydrogen rich, whereas those of the prior study were mature to overmature and in a normal to hydrogen-poor environment. Reflectances of non-fluorescent vitrinite kerogens are often suppressed in hydrogen-rich matrices (Hutton and Cook, 1980). Similar conditions may have selectively or disproportionately suppressed the graptolite reflectances relative to the chitinozoa within the hydrogen-rich kerogen environment of the Baffin Island organic-rich beds.

Nowlan (1987) recorded a conodont Colour Alteration Index of 1 for these beds, confirming their thermal immaturity.

Unnamed carbonate — Akpatok Island

The kerogen types within the Akpatok Island organic beds (Plate 1a) are few, consisting almost entirely of matrix bituminite (amorphous sapropel) and scattered, straw-yellow acritarchs with high to moderate intensity. Thermal immaturity is indicated by λmax values of 450 to 510 nm and Red/Green Quotients in the range 0.39 to 0.45, as well as by a conodont Colour Alteration Index of 1 (Nowlan, 1987). A marine environment is confirmed by the presence of the acritarchs.

Table Head Group — western Newfoundland

Samples from the bedded graptolitic carbonates of the Black Cove Formation at Piccadilly Quarry and East Bay on Port au Port Peninsula (Fig. 7) contain a maximum one per cent of fluorescing organics, comprising algal cysts; tasmanales; very small, yellow, fluorescing algae (probably *Gloeocapsomorpha*); and yellow-orange fluorescing bituminite. Non-fluorescing kerogen consists of bitumen, chitinozoa and graptolites. Based on a graptolite reflectance of 0.45 to 0.56 and a Red/Green Quotient of 0.43 for the algae, these beds are thermally immature to possibly marginally mature. Greater maturation is indicated by fluorescence values in the range 510 to 600 nm.

Green Point Group — western Newfoundland

These finely laminated oil shales are rich in probable algal cysts (Plate 1c), particularly *Gloeocapsomorpha*, and fluorescing bitumen and bituminite. Bitumen is also the major non-fluorescing kerogen. These kerogens are similar to those of mature to overmature Lower Ordovician samples from the Grand Banks (Goodarzi et al., 1985) as both contain different phases of bitumen (gilsonite, grahamite, impsonite; %Roil = 0.23-1.60). The Green Point samples are only marginally mature (Q = 0.50; λmax 450-500 nm) and have excellent source potential because of their high algal and matrix bituminite content. The beds on Port au Port Peninsula have generated only low grade bitumen, whereas those at Green Point contain the varying bitumen phases that indicate hydrocarbon migration through the sediment (Goodarzi et al., op. cit.).

The abundance of *Gloeocapsomorpha* defines these beds as a kukersite deposit (Hutton et al., 1980).

Humber Arm Group — western Newfoundland

Three samples of Humber Arm shales are mature marine sapropelic deposits, containing sparse, bright yellow to orange-yellow acritarchs and possible *Gloeocapsomorpha*, with Red/Green Quotients in the range 1.15 to 1.54, and fluoresence intensities ranging from 590 to 600 nm. Total organic content is estimated to be in the 1 to 3 per cent range, and the thermal maturation level is sufficient for the deposit to be of interest as a source rock.

Winnipeg Formation — southeastern Saskatchewan

Kerogen in organic-poor (<2% TOC) Winnipeg shale is dominated by matrix bituminite with interspersed acritarchs, and is thus similar to, but present in much lower quantity than, the kerogen of the Collingwood beds. Because of the finely dispersed nature of the organic material, optical measurements are most difficult.

One sample from an 'atypical' lamina containing pyritic-phosphatic, concretionary-nodular forms is composed almost entirely of *Gloeocapsomorpha* with only minor matrix bituminite.

Yeoman kukersite — southeastern Saskatchewan

Preliminary organic petrology of the Upper Ordovician sediments has been conducted on high TOC samples collected from three boreholes in Saskatchewan (6-32-8-16W2, 2458.8 m; 8-16-2-14W2, 3037.6 m; and 13-23-1-17W2, 3082.1 m). The kerogen assemblage in all samples is generally the same, with the dominant components being *Gloeocapsomorpha* alginite (a major component of kukersite) and fluorescent bituminite (Plate 1d). Minor amounts of single-celled, *Campenia*-like alginite (up to 10 μ in length), and trace amounts of chitinozoan fragments (0.25-0.40% Ro) and acritarchs are also present.

Gloeocapsomorpha and bituminite (matrix bituminite; Creaney, 1980) associations display genetic relationships and form elongate, flattened bodies in sections perpendicular to bedding; typically occurring with a thickness of 5 to 10 μ and length of up to 50 μ. The *Gloeocapsomorpha* rarely has visible, internal, multi-celled structures.

The fluorescence colours for *Gloeocapsomorpha* and bituminite are typically orange to brown. Measurements yield λmax values between 600 and 680 nm and Red/Green Quotients of <2.0, indicating a level of maturity within the oil window. The *Campenia*-like organisms yield a λmax of 500 to 520 nm, Red/Green Quotients between 0.40 and 0.50, and bitumen reflectance values of about 0.15 to 0.20 per cent, all indicating marginal maturity (about equivalent to 0.50% vitrinite reflectance).

ORGANIC CHEMISTRY

There has recently been considerable interest in the geochemistry of Ordovician oils and source rocks because many show distinctive features compared to samples of other ages. These features include: a very high concentration of n-alkanes up to nC^{19} with a strong odd carbon number predominance; very low concentrations of acyclic isoprenoids such as pristane and phytane; and a high concentration of monocyclic alkanes (Martin et al., 1963; Tissot et al., 1977; Zumberge, 1983; Fowler et al., 1986; Reed et al., 1986; Hoffmann et al., 1987). Several authors have discussed the similarities between Ordovician samples showing these characteristics from localities in different parts of the world, including North America (e.g., Reed et al., 1986; Fowler et al., 1986; Hatch et al., 1985; Longman and Palmer, 1987), Australia (Foster et al., 1986; Hoffmann et al., 1987) and Estonia (Reed et al., 1986). The distinctive chemistry of the organic matter in these Ordovician sediments is considered to be principally determined by the main contributing organism which is *Gloeocapsomorpha prisca* Zalessky 1917 (Reed et al., 1986; Foster et al., 1986; Hoffmann et al., 1987). However, not all Ordovician source rocks show these features and some authors have discussed samples with properties that are less characteristic of the Ordovician (Fowler and Douglas, 1984; Vlierboom et al., 1986; Longman and Palmer, 1987).

The similarities and differences in the geochemistry of several Canadian organic-rich rocks of Ordovician age are described below. A cursory attempt has been made to relate them to previously published work on rocks of Ordovician or other ages from around the world.

Rock-Eval pyrolysis

All samples were screened using a Rock-Eval/TOC instrument (Espitalié et al., 1977) in order to characterize the type, quantity and level of thermal maturity of the samples. Analysis of a relatively large number of samples has broadly defined the extent of the stratigraphic section of particular interest and also has provided information as to distribution of properties within the section.

Procedures

A standard program was used for the pyrolysis. The S1 peak was obtained at 300°C, and the S2 was measured during heating at a rate of 25°C/min. and collected to a temperature of 600°C. The S3 peak was collected to a temperature of 390°C.

Two Rock-Eval analyzers were used over several years at the Institute of Sedimentary and Petroleum Geology, Calgary, in acquiring the background data of this report. The earlier apparatus did not respond linearly to the S2 peak; consequently, calibrations were made and corrections applied to reduce the error until the results were in agreement with other analyses and could be usefully interpreted (Snowdon, 1984). Samples processed on this analyzer were from the Ontario Collingwood beds. Samples from all other areas, and many from the Collingwood beds, were analyzed on a newer pyrolyzer which responds linearly to the S2 peak. A minimum double run was standard throughout. The calibration standard had nominal values of S1 = 0.04, S2 = 0.87, S3 = 0.63, Tmax = 437°C and TOC = 1.65%.

Total organic carbon (TOC) was obtained for the earlier samples in Leco WR12 analyzers after pulverizing to 150 microns and treating in both cold and hot 6N hydrochloric acid to remove mineral carbon. For the majority of the samples, TOC content was determined by combusting all the carbon in separate oxidation ovens built into the Rock-Eval analyzers and operated at 600°C in air. In order to ensure uniform results and that all the organic carbon was burned, samples were ground to an approximate 150 micron size.

The results from many hundreds of analyses are not reproduced herein, but can be obtained from the appropriate Open File Reports: Collingwood (Macauley, 1987a, incorporating data from several sources); Boas (Macauley, 1986); Baffin and Akpatok islands (Macauley, 1987b); and western Newfoundland (Macauley, 1987c). Those from the Williston Basin, not yet published (Osadetz et al., 1989), are available at the Institute of Sedimentary and Petroleum

Geology, Calgary. For comparative purposes, the more significant Rock-Eval parameters are summarized in Table 1. Both the range of values encountered and an averaged value are included for each of the following parameters: total organic carbon (TOC), temperature of maximum hydrocarbon evolution (Tmax), Hydrogen Index (HI), Oxygen Index (OI), Production Index (PI), and Yield Ratio (YR).

Discussion of Rock-Eval pyrolysis parameters

The total organic carbon (TOC) contents ranged from quite low (<1%) to very high (>30%) with the majority of results typically in the 3 to 8 per cent TOC range. Because the level of thermal alteration is immature to low for the majority of the samples (see below), the observed TOC values represent close to the original TOC contents, that is, little organic carbon has been lost through the generation and migration of petroleum products.

Most of the kerogen is indicated to be Type II (marine/liptinitic) with two examples (those containing *Gloeocapsomorpha*) exhibiting Type I algal values. This is to be expected for rocks that predate the higher land plants from which Type III kerogen is generated.

Type II kerogens

The widest range of the Rock-Eval parameters occurs in the Collingwood Member of southern Ontario (Table 1) where a regional eastward increase of thermal maturation from western Lake Huron to the Whitby area, in conjunction with a local eastward increase from St. Joseph Island to Cockburn Island, can be mapped (Fig. 8). From west to east, average Tmax increases from 430°C to 442°C, Hydrogen Indices decrease from 553 to 242 (Fig. 9), the Production Index (PI) increases from 0.06 to 0.22, and the Yield Ratio (YR) decreases from 5.96 to 3.15 kg/t/%TOC. TOC remains fairly constant, except for the Whitby area where a reduction of one per cent from the general values can be attributed to petroleum generation and probable expulsion from moderately mature beds. Farther to the east in the Ottawa area (Fig. 3), the Billings Formation (Table 1, Fig. 9), equivalent to or slightly younger than the Collingwood, is overmature (Macauley et al., 1985).

Although not sampled and analyzed under this project, black shales of the Utica-Lorraine (Lachine-Lotbinière) formations of the St. Lawrence Lowland (Fig. 3) have been recorded in the mature to overmature range on the basis of reflectances from asphaltic pyrobitumens (Sikander and Pittion, 1978; Ogunyami et al., 1980), although no maceral descriptions were included in the reports. The maturity of these rocks could be attributed in part to depth of burial, but additional thermal input appeared necessary in some areas. Islam's (1981) confirmation of increased thermal maturation on Gaspé Peninsula as a result of igneous intrusion can be used to infer a high level of maturation for the Mictaw black shale beds (Fig. 3), as previously indicated by Macauley (1984). Interpretation of chitinozoa, graptolite and scolecodont reflectance values, presented by Bertrand and Heroux (1987), reveals that the Macastey shales on Anticosti Island (Fig. 3) are highly mature to overmature.

Whether or not the maturation variations in the Collingwood beds in southern Ontario relate directly to burial depth or to modification by igneous effects is not readily evident. Sanford et al. (1985) have mapped two tectonic megablocks (Fig. 3). The islands of Lake Huron are located on the western or Bruce Megablock, whereas the Collingwood–Whitby areas are on the much more tectonically active eastern or Niagara megablock. Although the plate tectonics proposed by Sanford et al. (op. cit.) do not appear to have affected deposition of the Collingwood oil shales, their thermal maturation may well have been modified by heat flow patterns governed by later tectonism.

Both the geochemical and petrographic data confirm that the Collingwood organic beds are marine Type II, sapropelic (amorphous) deposits. Sporadic HI values within the Type I range may reflect hydrocarbon movement within the beds or could indicate pockets of Type I kerogen.

All Rock-Eval parameters exhibit significant ranges in values across southern Ontario, with their averages directly reflecting the ranges and the variations in thermal maturation levels. At any specific location, where the maturation level can be considered uniform for a thin deposit such as the Collingwood, the ranges of parameter values can be attributed to mineral matrix effects (Clementz, 1979) and/or to variation in kerogen types (Sacheli, 1985). Macauley (1987a) cross-plotted TOC, Tmax and HI in an attempt to understand the ranges of the variables from sample to sample. Hydrogen Indices were found to be essentially independent of TOC content except for some scattered reduced HI values where TOC was less than 4 per cent (Fig. 10). Tmax and HI are directly proportional for the least mature beds, become somewhat independent at marginal to low maturation levels as conversion to bitumen occurs, and are inversely related for low to moderate maturation where petroleum generation is taking place (Fig. 11). Tmax generally decreases as TOC increases, probably related to the distribution of the kerogen macerals and the consequent ease or difficulty in heating, breaking down and breaking away from the mineral matrix. In the case of the Collingwood beds, there does not appear to be a predictable TOC level below which kerogen does not pyrolyze readily because of minimum content or mineral matrix effect, as these beds are

TABLE 1

Synopsis of Rock-Eval data

Formation/Location	No. of Samples	TOC	Tmax	HI	OI	PI	YR
Collingwood Member	41	5.29	430	553	22	0.07	5.96
St. Joseph Island		2.3-8.9	425-432	490-632	13-35	.06-.13	5.2-6.8
Collingwood Member	21	5.61	434	526	19	0.09	5.73
Drummond Island		3.6-10.3	427-439	454-602	10-34	.07-.12	5.1-6.5
Collingwood Member	15	5.00	437	464	18	0.12	5.23
Cockburn Island		2.4-10.5	430-441	353-529	7-32	.06-.21	4.3-5.7
Collingwood Member	54	5.49	440	523	17	0.06	5.63
Manitoulin Island		2.5-8.3	435-444	305-677	6-24	.04-.09	3.3-7.2
Collingwood Member	47	5.64	438	525	19	0.07	5.63
Collingwood area		2.9-10.9	432-441	201-666	9-41	.05-.16	2.4-7.4
Collingwood Member	17	4.33	442	242	20	0.22	3.15
Whitby area		2.9-7.6	439-446	95-345	6-40	.11-.33	1.3-6.7
Billings Formation	12	2.56	466	26	10	0.57	0.57
Ottawa area		0.9-4.3	456-478	14-35	4-20	.42-.71	0.4-0.7
Boas oil shale	5	15.91	423	617	47	0.05	6.48
Southampton Island — laminated beds		9.7-22.6	421-427	557-682	29-68	.05-.06	5.9-7.0
Boas oil shale	12	4.02	426	543	72	0.03	5.58
Southampton Island — massive beds		1.9-7.4	424-432	464-620	37-121	.02-.04	4.8-6.5
Unnamed carbonate	5	1.28	429	446	68	0.03	4.65
Akpatok Island		0.5-2.1	424-433	339-529	52-78	.03-.04	3.7-5.5
Unnamed organic beds	11	11.75	420	571	46	0.03	6.02
Baffin Island — laminated beds		8.6-14.8	409-428	462-691	22-80	.03-.07	4.9-7.3
Unnamed organic beds	6	5.11	422	556	36	0.03	5.76
Baffin Island — massive beds		2.9-8.1	415-427	520-597	29-49	.02-.04	5.4-6.2
Unnamed organic beds	8	1.49	427	408	32	0.02	4.21
Baffin Island — organic shale		0.5-2.5	425-430	267-573	18-57	.02-.02	2.7-5.5
Table Head graptolitic beds	6	0.55	441	270	28	0.15	3.17
Newfoundland		0.5-0.6	439-442	234-295	23-33	.14-.17	2.8-3.4
Green Point Group	3	8.13	439	712	8	0.02	7.31
Newfoundland — Port au Port Peninsula		7.8-8.4	435-441	688-753	6-10	.02-.03	7.1-7.7
Green Point Group	3	4.61	443	605	17	0.05	6.38
Green Point		4.1-5.0	441-444	571-650	13-19	.05-.06	6.0-6.9
Humber Arm Group	2	1.06	448	363	36	0.18	4.24
Newfoundland		1.0-1.11	446-450	340-386	20-52	.17-.18	4.1-4.3
Yeoman Formation	23	11.55	453	793	6	0.02	8.26
Williston Basin — samples >3% TOC		3.2-26.4	447-458	209-943	2-16	.01-.09	2.2-9.5
Yeoman Formation	19	1.24	451	513	47	0.15	5.65
Williston Basin — samples <3%		0.4-2.4	440-459	131-883	14-127	.01-.65	1.9-9.2
Winnipeg Formation	7	0.29	444	356	-	0.03	3.66
Williston Basin 8500 ft (2591 m) ±		0.2-0.5	441-447	225-480	10-513	.00-.05	2.9-5.4
Winnipeg Formation	9	0.72	436	438	-	0.05	4.71
Williston Basin 7500 ft (2286 m) ±		0.3-0.5	430-440	272-585	12-533	.00-.10	2.9-5.4
Winnipeg Formation	2	5.47	438	866	23	0.01	8.79
Williston Basin 4500 ft (1372 m) ±		0.5-10.4	435-442	807-924	16-28	.00-.01	8.1-9.5

always dominated by matrix bituminite kerogen. In contrast, Rock-Eval parameters react distinctively for kerogen contents above 5 per cent compared to those below this level, coincident with a change in the dominance of either lamalginite or matrix bituminite in the lacustrine Type I lamosites of the Carboniferous, Albert Formation (Macauley, 1987d).

In addition to the above-described Collingwood oil shales, most of the Ordovician organic-rich beds contain geochemical Type II kerogens, including those on the islands of the Northwest Territories, the Table Head and Humber Arm groups of western Newfoundland, and the Winnipeg Formation of the Williston Basin. Not all exhibit the same levels of thermal maturation.

Hydrogen Indices for the organic-rich beds of Southampton, Akpatok and Baffin islands are all typical for Type II kerogens (Fig. 12). The laminated oil shales have HI values within the 500 to 600 range whereas for the more

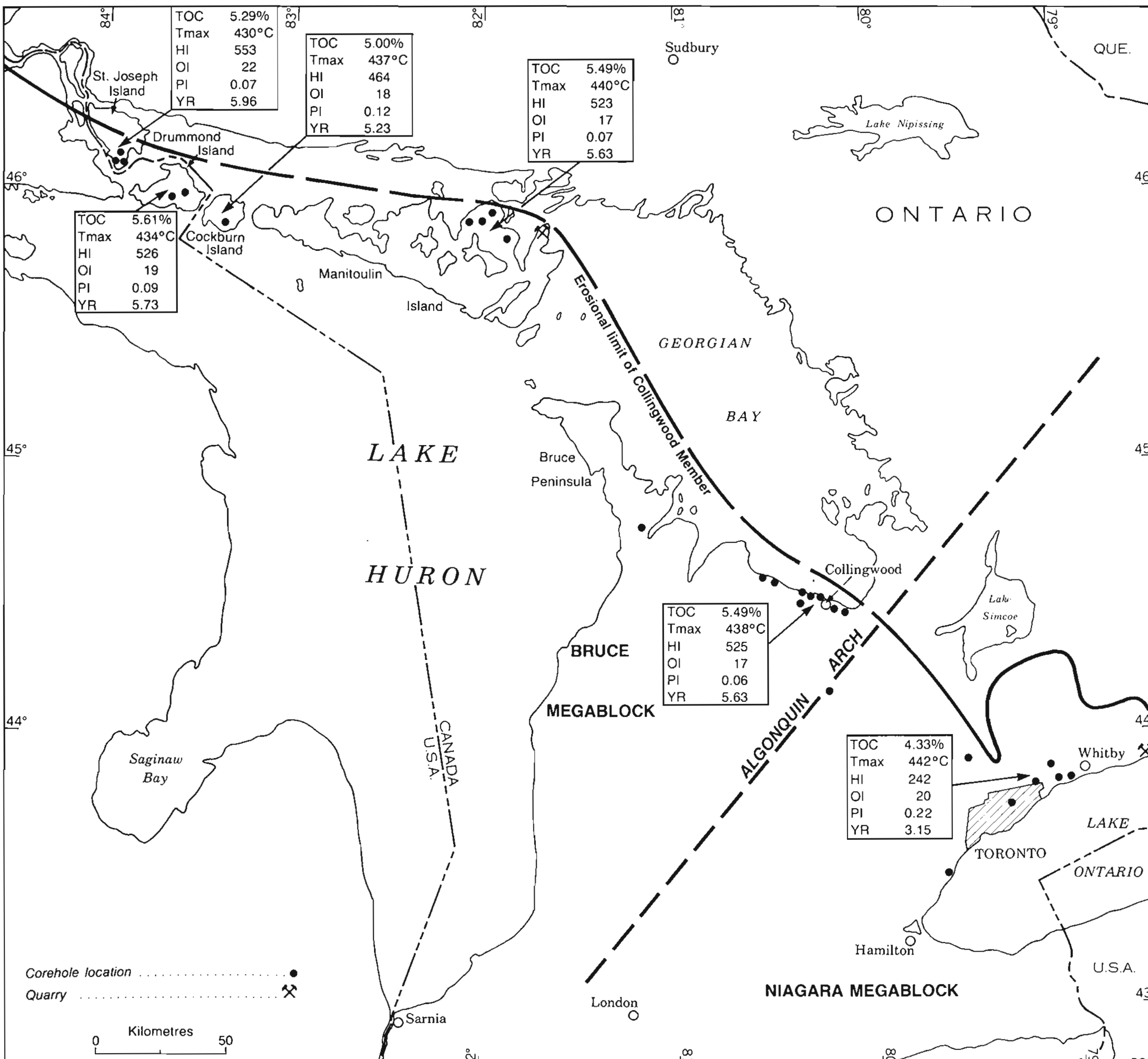


Figure 8. Geographic distribution of Rock-Eval results for the Collingwood Member, southern Ontario.

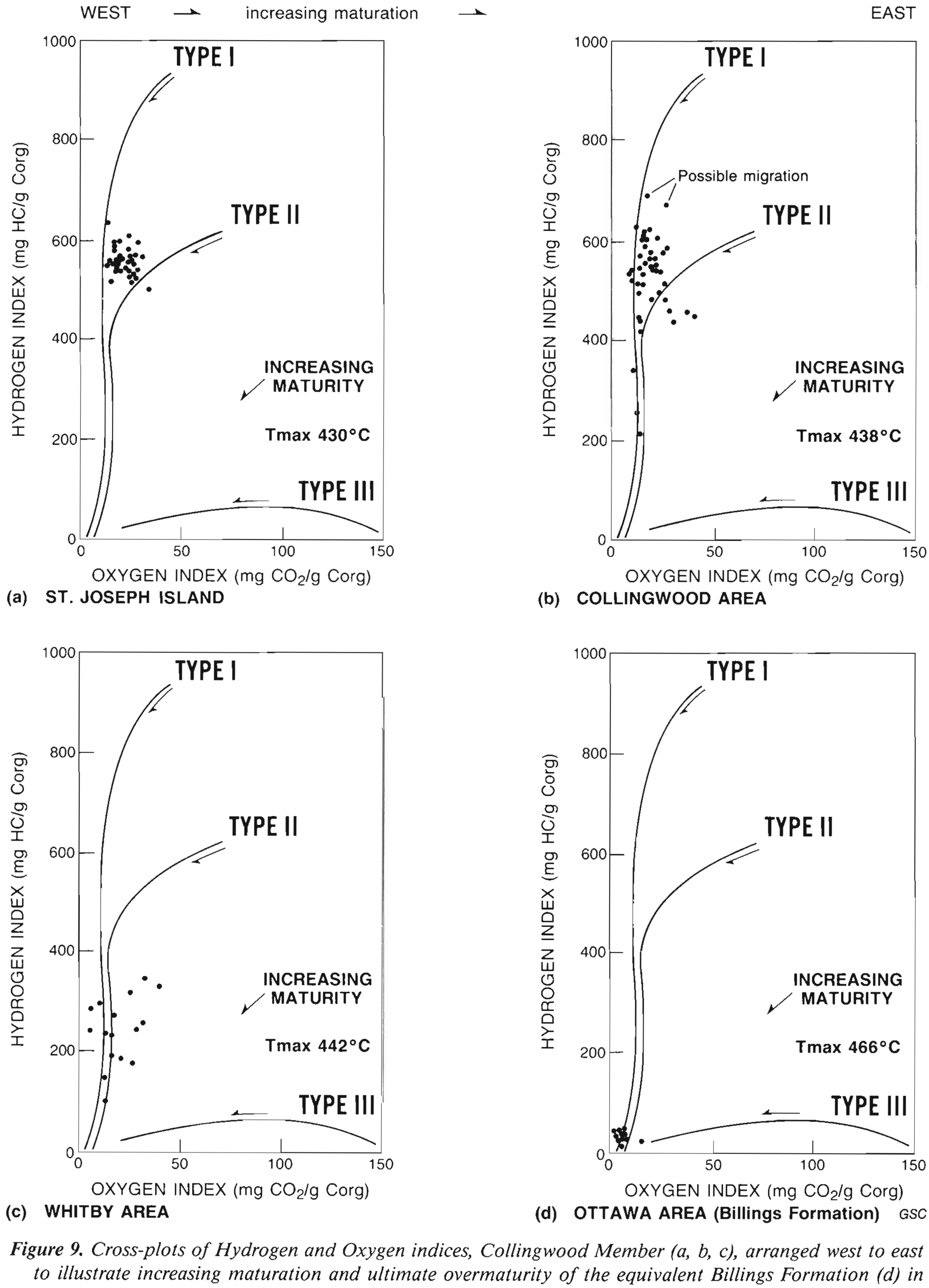


Figure 9. Cross-plots of Hydrogen and Oxygen indices, Collingwood Member (a, b, c), arranged west to east to illustrate increasing maturation and ultimate overmaturity of the equivalent Billings Formation (d) in the Ottawa area. (From Macauley, 1987a; Macauley and Snowdon, 1984.)

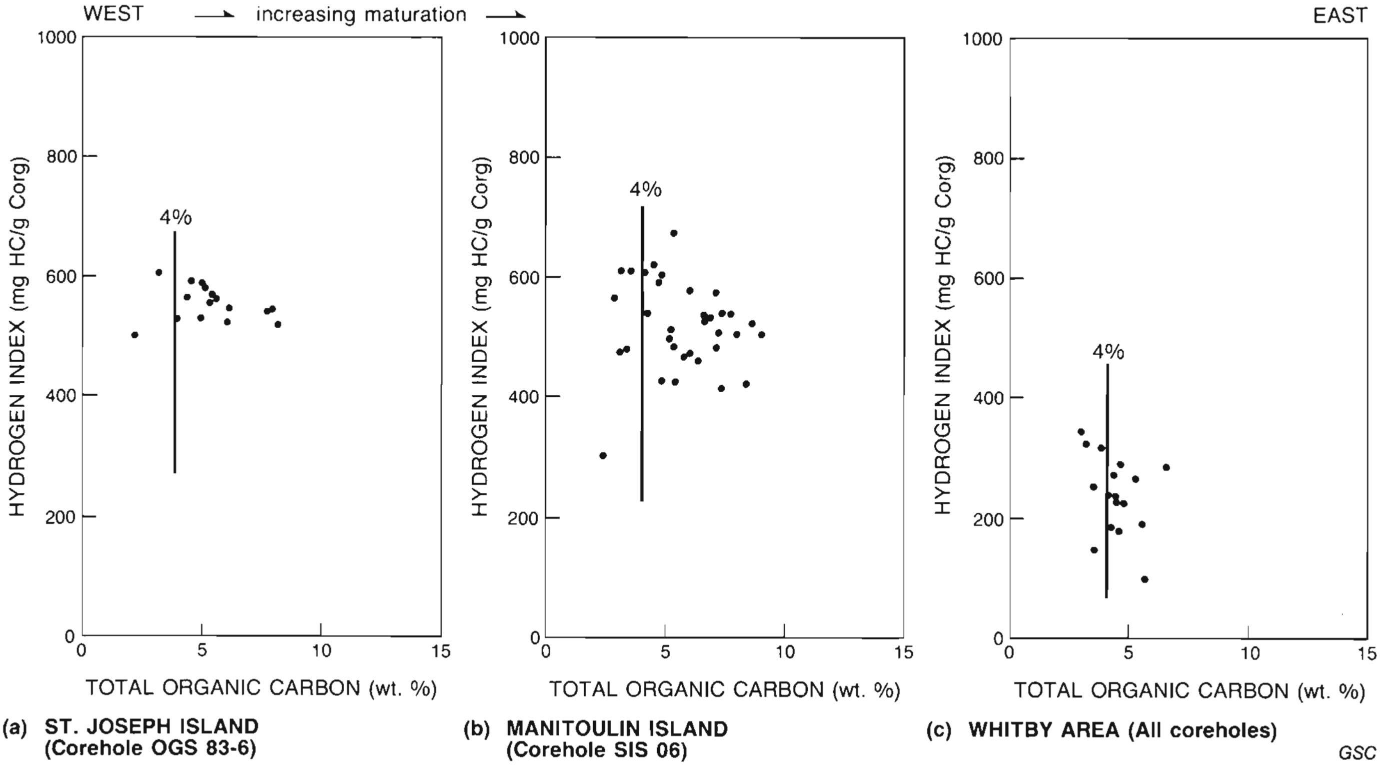


Figure 10. Representative cross-plots of Hydrogen Indices versus TOC, Collingwood Member, arranged west to east, illustrating the independence of the two parameters irrespective of maturation level. (From Macauley, 1987a.)

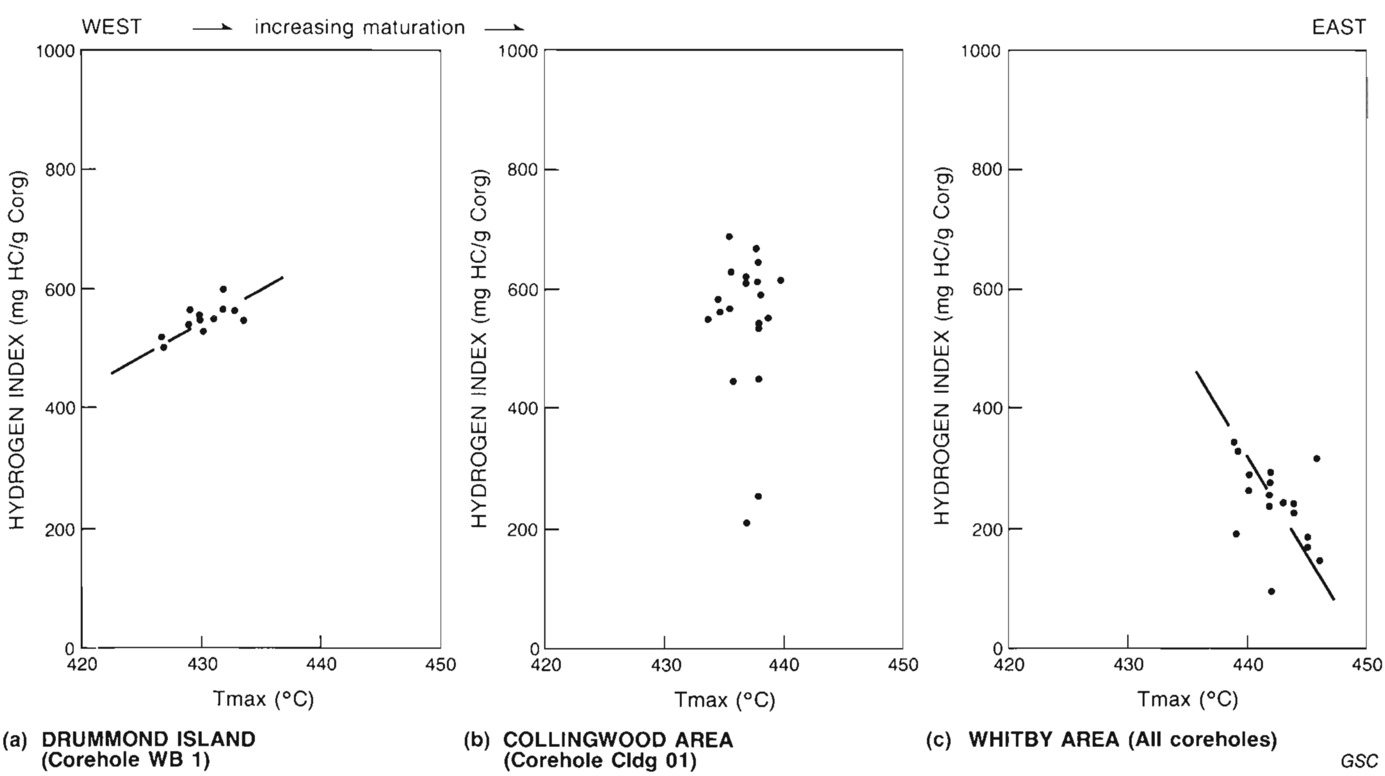


Figure 11. Representative cross-plots of Hydrogen Indices versus Tmax, Collingwood Member, arranged west to east, illustrating the reversing relationship of these parameters with increasing maturation. (From Macauley, 1987a.)

massive beds, generally with somewhat less organic carbon content, 400 to 500 is a more common HI range. Because no significant differences in maceral content were revealed by a study of the organic petrography, the lower HI values can be attributed to alteration of the kerogen during deposition or to matrix effect, but cannot be attributed to increased maturation. The yield ratios, the hydrocarbon recoveries relative to TOC, are within the expected range of marine, Type II sapropelic kerogens, as indicated in Macauley et al. (1986).

Tmax values for these northern deposits are all below the 430°C initiation level for petroleum generation, indicating thermal immaturity. This is confirmed by low Production Indices of 0.05 or less.

Only two samples of Table Head graptolitic shale and one of the Humber Arm Group contain sufficient organic carbon for the pyrolysis results to be considered reliable for interpretation. Hydrogen Indices fall below the norm for Type II kerogens (Table 1). This, coupled with Tmax values above 440°C average, and Production Indices of 0.15 and 0.18 respectively for the two units, indicates a low to moderate level of thermal maturity. Both intervals may have been source beds in western Newfoundland.

Osadetz and Snowdon (1986) have established that the thin organic beds of the Icebox Member of the Winnipeg Formation are thermally mature Type II source rocks where TOC content increases to a general maximum value of 1.5 per cent at the top of the beds. The interrelationship of the Hydrogen and Oxygen indices (Fig. 13a) demonstrates the Type II character, and increasing maturation with depth is indicated by decreasing Hydrogen Indices and Yield Ratios with increasing Production Indices (Table 1). Osadetz et al. (1989) will present a more detailed discussion of these data.

Two samples from much shallower beds (Table 1, Fig. 13a) contain characteristic immature Type I kerogen, and are from strata recognized petrographically as *Gloeocapsomorpha* beds. These samples are, as previously stated, from beds atypical of the Winnipeg shale, and the thicknesses and areal distribution of such strata are probably very limited. Because the areal extent of this possible source for either Type II or Type I kerogen is not yet known, the importance of the zone as a hydrocarbon source is not fully understood.

Oxygen Indices for the above Type II kerogens generally indicate thermal immaturity to low levels of maturation at most, although the excessively high (>150) OI values for the organic-poor Winnipeg shales may be more indicative of a mineral-matrix effect.

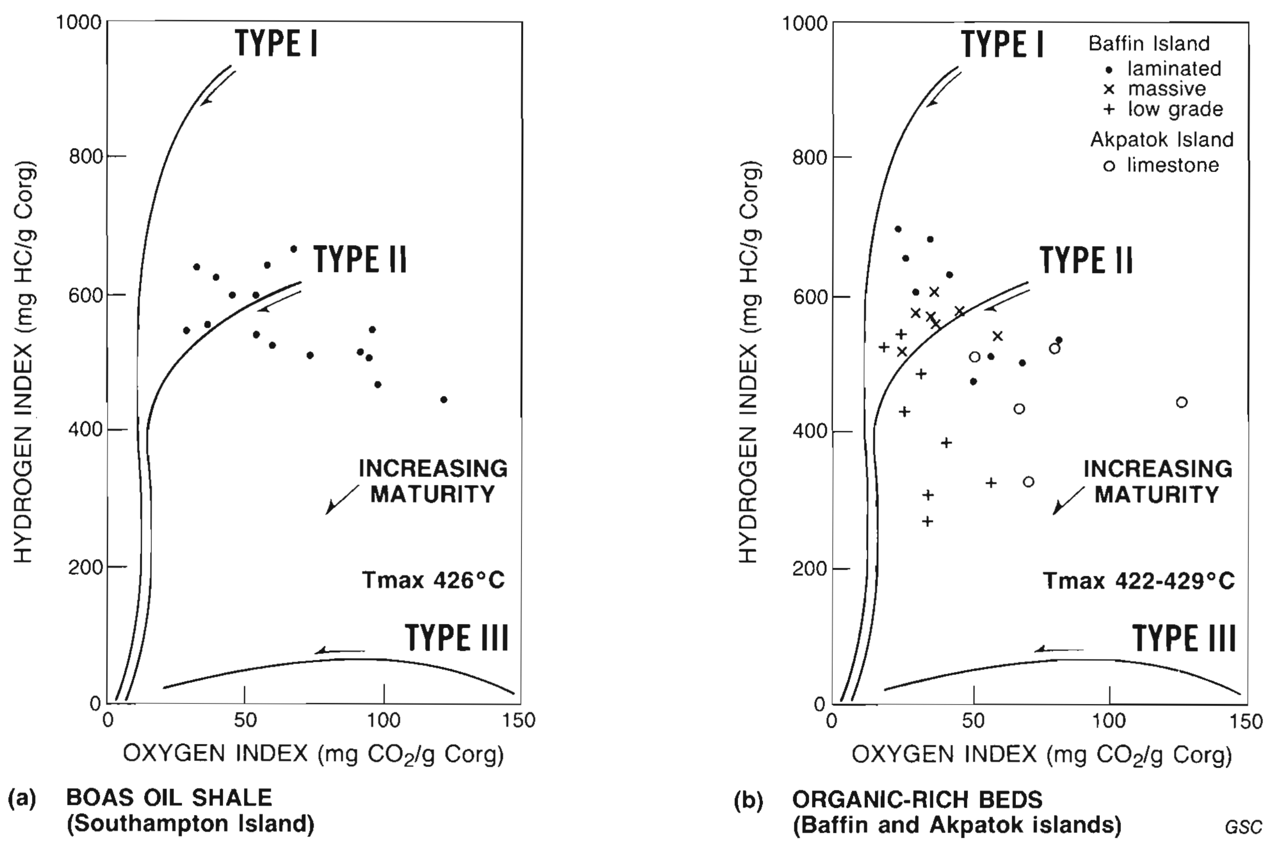


Figure 12. Cross-plots of Hydrogen and Oxygen indices, eastern Canadian arctic islands. (After Macauley, 1986; 1987b.)

Type I kerogens

Yeoman kukersite layers in southeastern Saskatchewan are established as marine algal deposits characterized by *Gloeocapsomorpha*. Hydrogen Indices, many exceeding 900, geochemically define the organic matter of these layers as Type I (Fig. 13b), with excellent Yield Ratios, often above 7 kg/t/%TOC (Table 1). The values of these indices are well above the range attributed to Type II sapropelic kerogens (Macauley et al., 1986) but some samples have values that are below both the indices (900 and above) and recovery ratios (exceeding 9 kg/t/%TOC) that are typical of lacustrine Type I lamalginites. Low Oxygen Index values are also indicative of the algal nature of the kukersites.

Average Tmax values of 448° to 453°C (Table 1), depending on organic carbon content, are well within the generally accepted oil generation window. Tmax, which has most use as a maturity parameter for Type III and, to a lesser extent, for Type II organic matter, is almost invariant for Type I kerogen (Espitalié, 1985). This results because much of the Type I kerogen is composed of saturated alkanes in long chain configurations and the amount of energy required to break volatile components away is constantly high (about 80 kcal/mole or 335 KJ/mole to break a carbon-carbon bond) until the chain length is quite small and the kerogen becomes essentially inert. Thus, while the level of maturity of the Ontario Collingwood samples is interpreted as being higher at considerably lower Tmax values, the Yeoman kukersite is less mature at a much higher range of Tmax. Because the oxygen content is low, there is less opportunity for pyrolysis at lower temperatures through the breaking of the more easily ruptured carbon-oxygen bonds. Thermal immaturity of the Yeoman organic-rich (>3% TOC) beds is indicated by extremely low Production Indices. High Tmax values have also been reported for sediments from the Canning Basin, Western Australia, where organic matter is mostly *Gloeocapsomorpha* (Foster et al., 1986). A similar explanation was given for their results.

Oxygen content increases as hydrogen decreases (Fig. 13b). Hydrogen Indices form two distinct groups relative to TOC content (Fig. 14). A wide range of HI values were recorded where TOC is less than 3 per cent, and it is these samples that also contain the greater oxygen levels. This result can be interpreted as a mineral-matrix effect; however, all Rock-Eval parameters, especially the Production Indices, indicate a maturing Type II kerogen content for some of these lower organic beds and a Type I kerogen content for others.

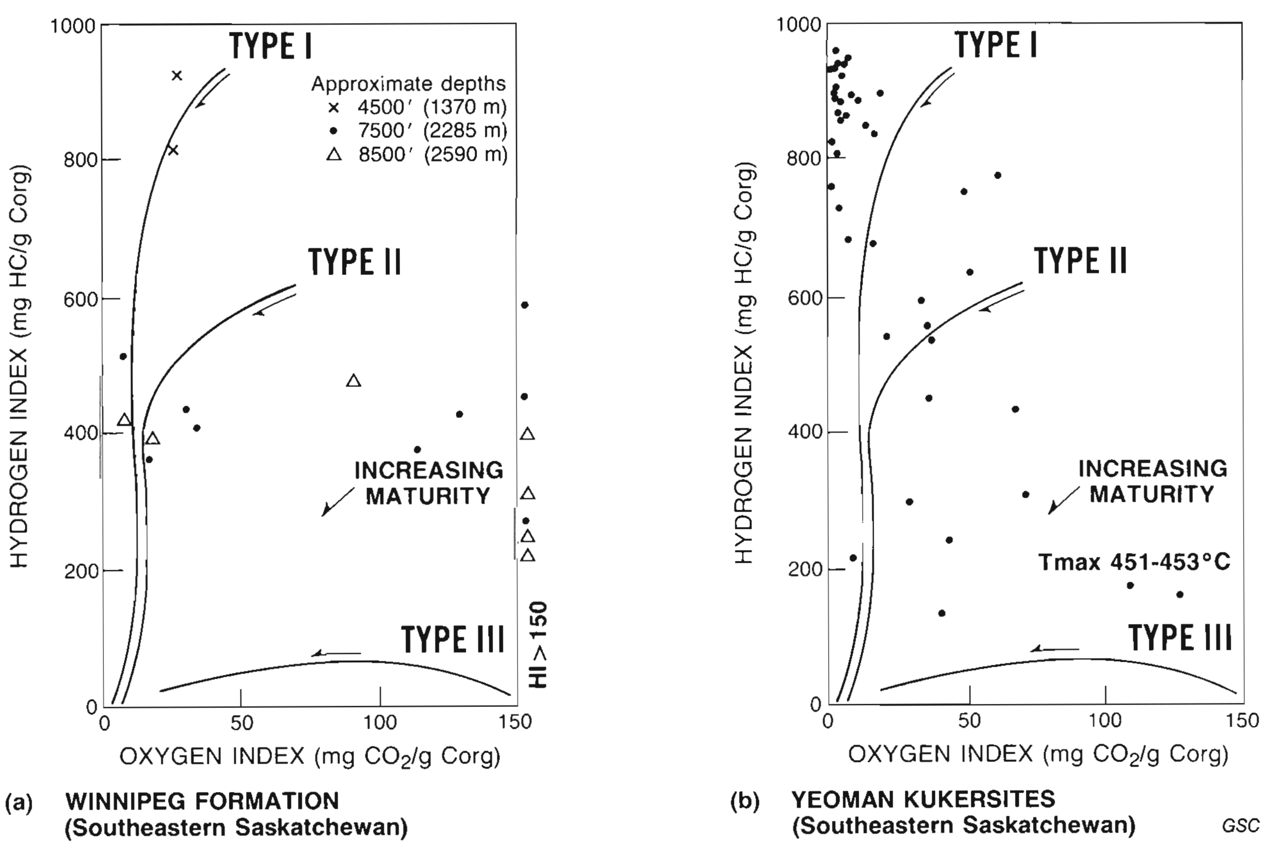


Figure 13. *Cross-plots of Hydrogen and Oxygen indices for the Winnipeg Formation (a), and the Yeoman kukersites (b), Williston Basin, southeastern Saskatchewan. (Data courtesy of K.G. Osadetz.)*

One can speculate that *Gloeocapsomorpha* formed all the initial kerogen and that bacterial oxidation related to variations in the depositional environment, has altered some of the organic detritus to Type II kerogen.

Hydrogen Indices for the Newfoundland Green Point beds are higher than expected for Type II kerogens but, ranging from 570 to 753, are less than anticipated for Type I organic matter (Fig. 15). Tmax values are in the range of mature beds for Type II, yet Production Indices indicate little petroleum generation. Macauley (1987c) stated that these beds are, geochemically, poor Type I or high quality Type II deposits. Increasing maturation from west (Port au Port Peninsula) to east (Green Point) can be interpreted from the Rock-Eval data (Table 1). The presence of *Gloeocapsomorpha* confirms the presence of a Type I component within a Type II bituminite matrix. Increasing eastward maturation is confirmed by the presence of additional bitumen products in the Green Point samples. In essence, the Port au Port beds are virtually immature, grading to marginally mature to the east. These beds have not likely generated any significant petroleum products, although they have been suggested as the source of the Parsons Pond oil (Weaver and Macko, 1988).

The Green Point beds are particularly interesting because of the effect of admixed kerogen types on Rock-Eval pyrolysis results. A similar problem has been described by Kalkreuth and Macauley (1987) for admixed kerogens in continental bog – lacustrine deposits.

Saturate fraction gas chromatograms

A limited number of samples were selected for more detailed geochemical analysis of their $C_{15}+$ saturated hydrocarbons. Those samples that showed high TOC values or Hydrogen Indices tended to be chosen. Hence, there is the possibility that future work will show that the conclusions drawn from these analyses were influenced by this sampling bias.

The saturate fraction gas chromatograms of the Ordovician samples can be divided into three groups, based upon a combination of their n-alkane and acyclic isoprenoid (i.e., pristane and phytane) distributions. As discussed below, these are not strict groupings as some samples show "in between" characteristics. Typical gas chromatograms are shown in Figure 16 and some parameters are given in Table 2.

The first group of chromatograms are those of the Upper Ordovician, Red River kukersite samples from the Williston Basin in Saskatchewan (Fig. 16a). These chromatograms are dominated by n-alkanes up to C_{19} showing an odd carbon number predominance, and have a much lower abundance

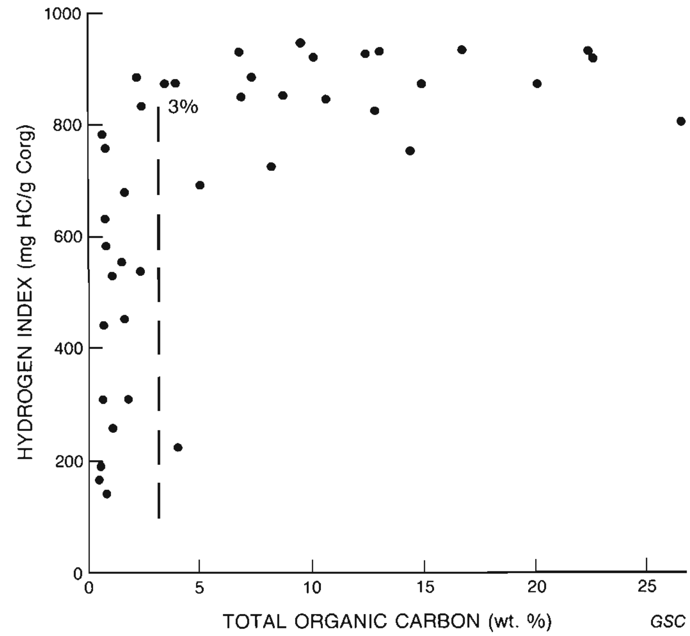


Figure 14. Cross-plot of Hydrogen Indices versus TOC contents, Yeoman kukersite beds, Williston Basin.

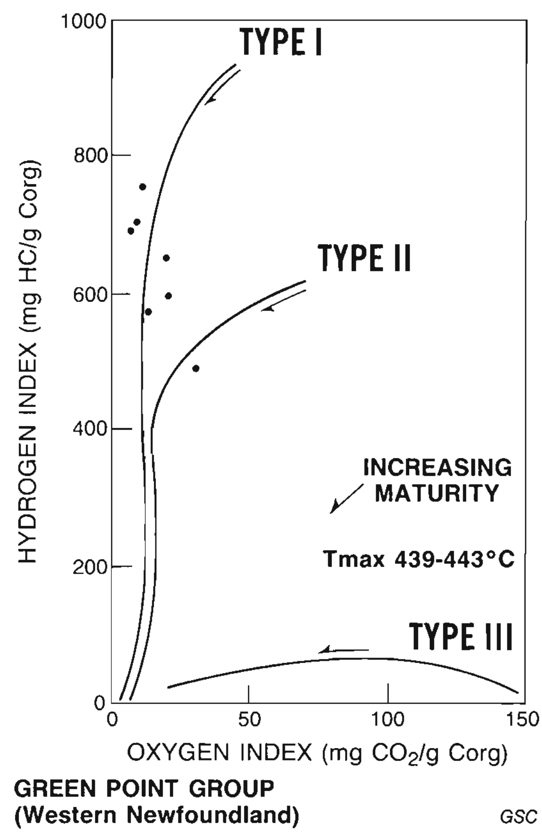


Figure 15. Cross-plot of Hydrogen and Oxygen indices, Green Point Group, western Newfoundland. (After Macauley, 1987c.)

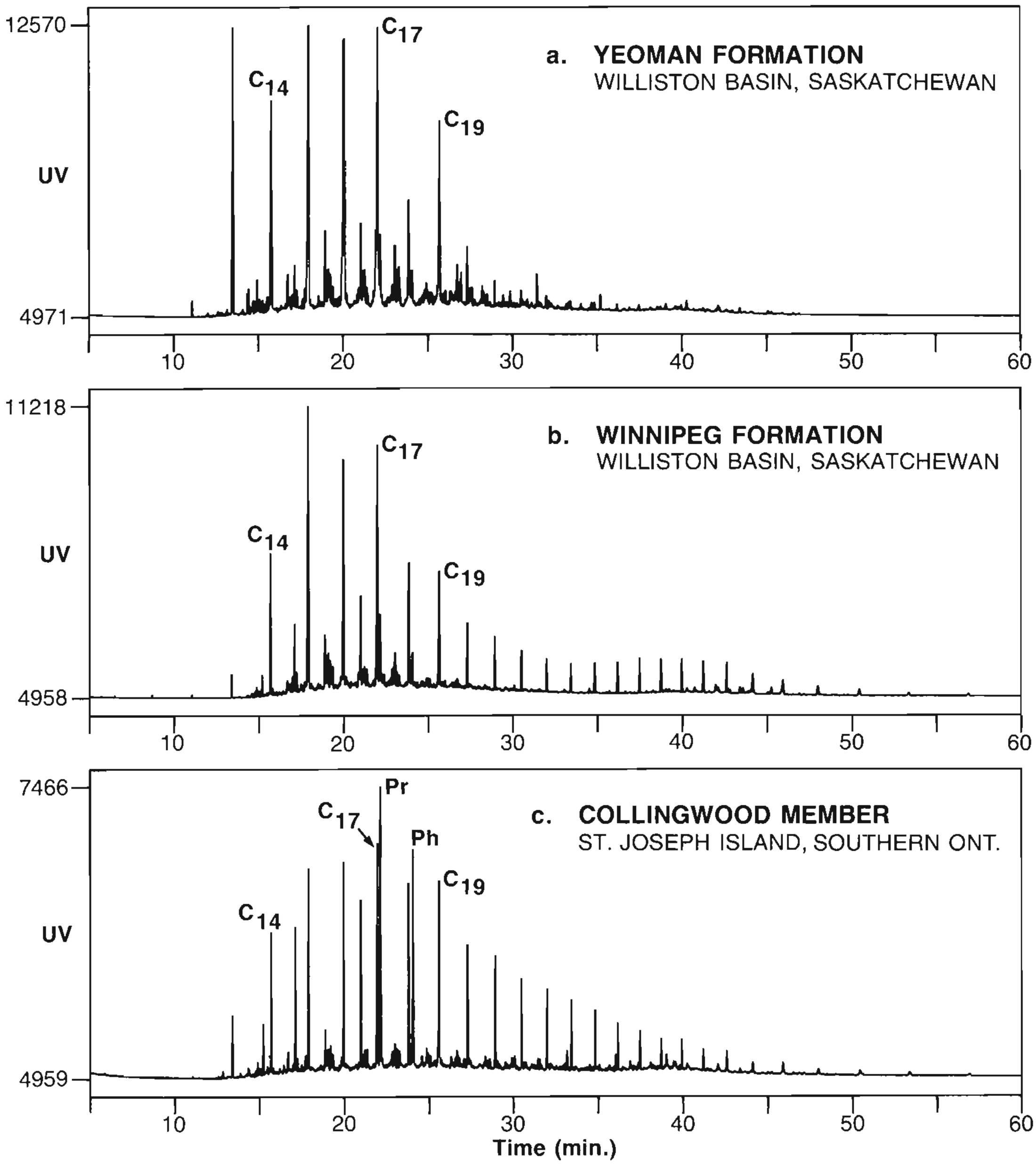
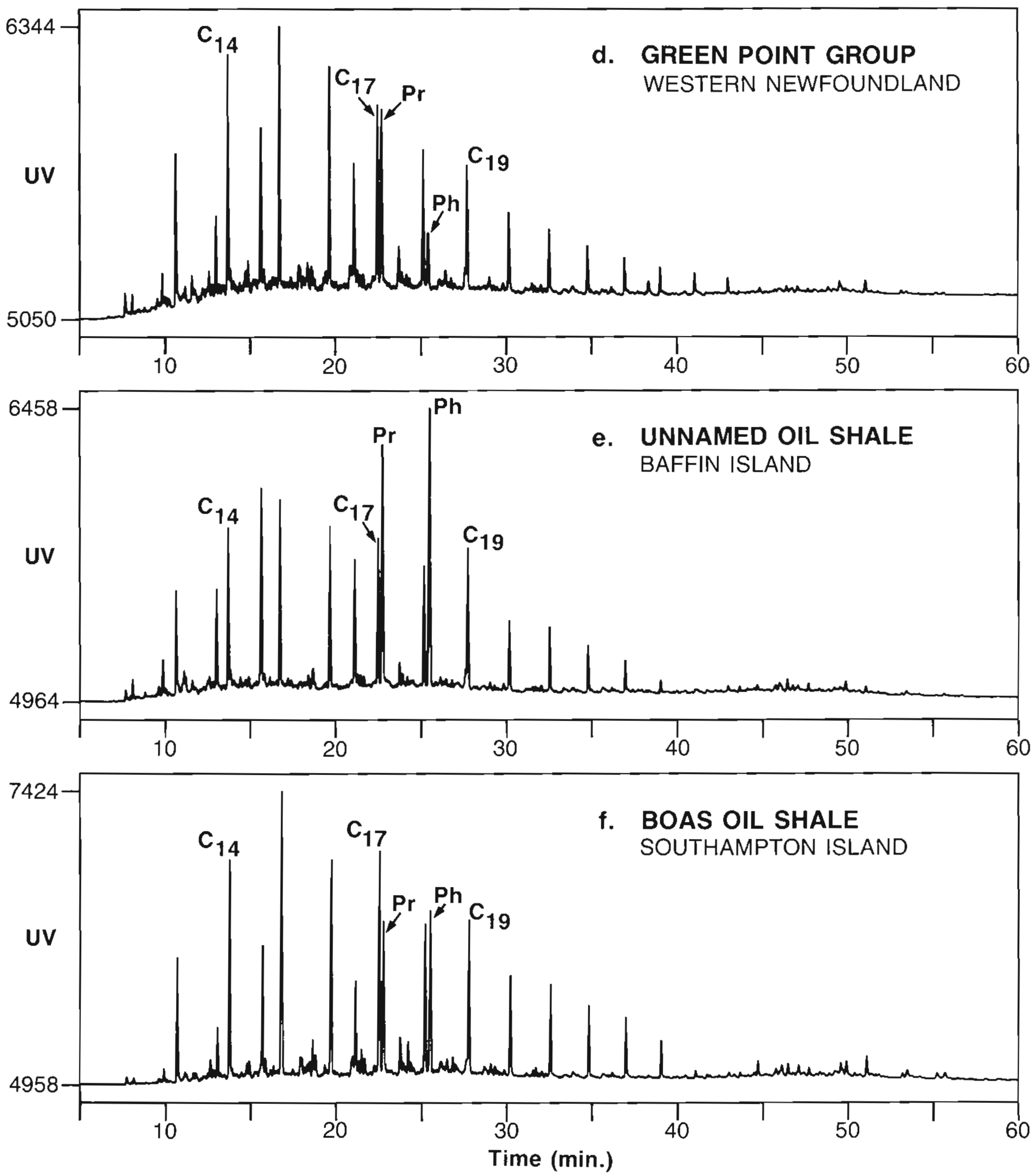


Figure 16. Representative saturate fraction gas chromatograms of Ordovician samples: a. Kukersite from the Yeoman Formation, Williston Basin, Qu'appelle Hornung well, 1391.11 m; b. Icebox Member, Winnipeg Formation, Williston Basin, Flint Cutarm well; c. Collingwood shale, St. Joseph Island, southern Ontario, OGS 83-6, 163.28 m; d. Green Point Group, western Newfoundland, sample GP3; e. Laminated beds, lower organic unit, Baffin Island, NWT, sample BI3; f. Laminated Boas oil shale, Sixteen Mile Brook, Southampton Island, NWT, sample SMB3.

of higher molecular weight n-alkanes with no odd carbon or even number preference. Acyclic isoprenoids are present in very low concentrations relative to the n-alkanes (Table 2). The ratio of pristane to phytane for these samples (where it is possible to measure it) lies between 1.5 and 2.3 (Table 2). This type of distribution is observed in Ordovician oils from the Williston Basin (Martin et al., 1963; Zumberge, 1983; Reed et al., 1986; Brooks et al., 1987; Longman and Palmer, 1987). It has also been observed in both oils and sediments from elsewhere in the U.S.A. (Reed et al., 1986; Fowler et al., 1986; Illich and Grizzle, 1983; Rullkotter et al., 1986; Hatch et al., 1985) and Australia (Kurylowicz et al., 1976; Foster et al., 1986; Hoffmann et al., 1987). This group of samples is considered to be most characteristic of the Ordovician.



The second type of gas chromatogram exemplifies the Collingwood shale (Fig. 16c) and most of the Newfoundland samples. A gas chromatogram of the Humber Arm Formation (not illustrated) sample shows evidence that it has been affected by weathering processes. These chromatograms differ from those of the kukersites by showing higher concentrations of $C_{19}+$ n-alkanes and acyclic isoprenoids (Fig. 14, Table 2). The less mature Collingwood samples (that is, from the western part of Ontario) show a slight odd carbon number predominance for their C_{15}-C_{19} n-alkanes but most samples show a smooth distribution. For the Collingwood samples, the pristane/nC_{17} ratio decreases with increasing maturity (this can be observed by plotting pr/nC_{17} versus Tmax). Even the most mature Collingwood samples (e.g., 6117, OGS. SIS03 33.4 m from the Whitby area) have higher amounts of acyclic isoprenoids relative to the n-alkanes than the kukersite samples. Cambrian and Ordovician oils from southwestern Ontario, which are believed to have been sourced from the Collingwood shales, show similar chromatograms (Powell et al., 1984), as do lower Paleozoic oils from Ohio (Cole et al., 1987), although Ordovician oils farther south in the Michigan Basin tend to give chromatograms more similar to those of the kukersite samples (e.g., Illich and Grizzle, 1983; Rullkotter et al., 1986; Longman and Palmer, 1987). The Parsons Pond oil seep north of Green Point, western Newfoundland (Fig. 6), suggested by Weaver and Macko (pers. comm., 1987) to be sourced from Green Point strata (Fig. 16d), also gives a chromatogram that falls into the Collingwood category.

Samples of Winnipeg shale from the Williston Basin of Saskatchewan give chromatograms (Fig. 16b) that have features intermediate to those described above. They have a low concentration of $C_{19}+$ n-alkanes, in common with the kukersite samples, but their C_{15}-C_{19} n-alkanes show no odd or even carbon number preference. They also have a higher abundance of acyclic isoprenoids than the kukersite extracts (Table 2).

The third group of chromatograms were derived from the samples from the Northwest Territories (Fig. 16e-f). They show n-alkanes up to nC_{19} in higher concentrations than their higher molecular weight homologues, but there is a gradual rather than sudden decrease in abundance after nC_{19}. All the samples show an odd carbon number predominance between nC_{15} and nC_{19}, with the Boas River (Fig. 16f) samples showing an odd predominance up to nC_{23}. It is because of their pristane to phytane ratio values, and, to a lesser degree, their abundance of acyclic isoprenoids relative to n-alkanes, that these samples are principally distinguished from the others. The Northwest Territories samples all have pristane/phytane values of less than one (Table 2), which may indicate that they were deposited under more reducing conditions than the other Ordovician samples (Powell and McKirdy, 1973; Didyk et al., 1978). Most of the NWT samples also show a very high abundance of acyclic isoprenoids relative to the n-alkanes (Table 2). The Sixteen Mile Brook and Gore Point samples from Southampton Island show lower pr/nC_{17} values than the other NWT samples (although still high compared to most of the Ordovician samples in this study), despite being of similar maturity, indicating that the environment of deposition may have been slightly different. These samples resemble Ordovician samples from Nevada and Oklahoma in their high abundance of acyclic isoprenoids and low pr/ph ratios (Fowler and Douglas, 1984). However, as will be discussed below, the NWT samples have more in common geochemically with reef-hosted oils and their source rocks from the Middle and Upper Silurian of the Michigan Basin and Middle Devonian of the Alberta Basin (Summons and Powell, 1987).

Discussion of gas chromatograms

All the gas chromatograms described above show n-alkane distributions consistent with a pre-land-plant origin. An n-alkane distribution dominated by odd carbon numbered C_{15}-C_{19} members, such as that shown by the kukersite samples, is most likely derived from decarboxylation of the fatty acids of marine algae with some possible direct inheritance of algal and bacterial hydrocarbons (Martin et al., 1963; Powell and McKirdy, 1972; Philippi, 1974; Tissot et al., 1977). Some details of this type of n-alkane distribution, such as the continuation of the odd carbon number predominance down to nC_9 (Martin et al., 1963; Tissot et al., 1977; Reed et al., 1986; Rullkotter et al., 1986) and the sudden decrease in abundance after n-C_{19} (Fowler and Douglas, 1984), are characteristic of Ordovician samples and, therefore, are likely to be a function of the biochemistry of *Gloeocapsomorpha*. The smoother distributions of n-alkanes shown in the Collingwood, Winnipeg and Newfoundland chromatograms are probably due to the addition of n-alkanes randomly generated from kerogen, diluting those derived more directly from the precursor organisms. When these samples were immature, they probably had a similar odd carbon number predominance to that of the less mature (western) Collingwood samples. The higher amounts of $C_{19}+$ n-alkanes in these samples are presumably a result of a more diverse input to these samples than to the kukersite sediments (a result of more bacterial activity?).

The higher concentrations of $C_{19}+$ n-alkanes in the NWT samples are probably a function of their unusual depositional environment. Pre-Devonian samples showing high concentrations of $C_{19}+$ n-alkanes relative to their lower molecular weight homologues have been reported from the Cambrian of the Officer Basin, South Australia (McKirdy and Kantsler, 1980), and from the Silurian of the Michigan Basin (Vogler et al., 1981; Illich and Grizzle, 1983; Powell et al., 1984; Rullkotter et al., 1986). McKirdy and Kanstler (1980) thought that the higher molecular weight n-alkanes were possibly derived from the reworking of algal debris by anaerobic bacteria in a microbial ecosystem inhabiting a hypersaline environment. The NWT samples show other geochemical characteristics in common with samples containing organic matter deposited in a hypersaline environment (see below).

The principal source of phytane, pristane and lower molecular weight isoprenoids in sediments is thought to be the phytyl side-chain of the chlorophyll-a molecule (e.g., Volkman and Maxwell, 1986), although there are other possible sources such as archaebacterial phospholipids (Nissenbaum et al., 1972; Brassell et al., 1981), algal tocopherols (Goossens et al., 1984), and pristane from zooplankton (Blumer et al., 1963). The very low concentration of acyclic isoprenoids relative to the n-alkanes in the kukersites is a distinctive feature shown by many Ordovician samples throughout the world. Reed et al. (1986) suggested that it was a consequence of *Gloeocapsomorpha prisca* being a non-photosynthetic organism and hence containing no chlorophyll. Hoffman et al. (1987) have disputed this and suggested that the low abundance of acyclic isoprenoids could be due to a "swamping" effect caused by *Gloeocapsomorpha* being an extremely lipid-rich organism. As previously mentioned, the pr/nC_{17} ratio of the Collingwood samples decreases with increasing Tmax values, indicating a dilution effect with increasing maturation.

TABLE 2

Solvent extract and GC data

Williston Basin samples are from conventional exploration borehole cores; Ontario samples are from shallow coreholes except the Bowmanville BQ-A samples which were from the Bowmanville Quarry; the Northwest Territories and Newfoundland samples are all from outcrops.

ISPG Lab. No.	Identification	Location	Depth (m)	%TOC	HC Yield (mg/g)	%HC	Pr/C_{17}	Pr/Ph	PI
6330	Winnipeg Crown	Williston, Winnipeg Fm.	2281.73	1.03	10.6	45.5	0.46	1.63	0.06
6331	Winnipeg Crown	Williston, Winnipeg Fm.	2282.65	1.07	6.0	26.4	0.50	1.69	0.03
6329	Winnipeg Crown	Williston, Winnipeg Fm.	2285.69	1.15	7.3	30.7	0.22	1.44	0.04
6333	Flint Cutarm	Williston, Winnipeg Fm.	1374.95	0.53	11.8	32.9	0.36	1.74	0.00
6332	Flint Cutarm	Williston, Winnipeg Fm.	1391.11	10.41	2.9	26.6	0.34	2.13	0.01
6621	Lake Alma	Williston, Yeoman Fm.	3071.0	1.17	860.8	57.6	0.07	1.05	0.58
6622	Shell Yeoman	Williston, Yeoman Fm.	2453.7	16.27	17.4	58.8	0.10	1.73	0.02
6623	S. Lake Alma	Williston, Yeoman Fm.	3176.2	17.71	4.9	46.2	0.12	2.26	0.00
6624	S. Lake Alma	Williston, Yeoman Fm.	3082.0	12.18	11.9	49.4	0.19	1.21	0.01
6625	Bromhead	Williston, Yeoman Fm.	2876.0	1.44	800.7	54.3	0.27	0.44	0.64
6626	Beaubier	Williston, Yeoman Fm.	3076.5	15.49	2.3	26.3	0.12	1.41	0.00
6627	Hoffer	Williston, Yeoman Fm.	3141.8	4.63	41.5	39.0	0.09	1.43	1.10
6628	Qu'appelle	Williston, Yeoman Fm.	1732.0	23.98	8.0	44.7	0.19	3.54	0.02
6629	Oungre	Williston, Yeoman Fm.	3037.6	0.45	1400.0	80.8	0.08	1.28	0.90
6630	Froude	Williston, Yeoman Fm.	2446.5	15.28	6.8	53.2	0.09	1.83	0.01
6631	Froude	Williston, Yeoman Fm.	2445.6	17.07	24.5	53.3	0.08	1.42	0.02
6632	Well Lake	Williston, Yeoman Fm.	2990.2	15.64	12.6	40.9	0.08	1.57	0.01
6633	Well Lake	Williston, Yeoman Fm.	2989.7	5.09	470.3	45.8	0.07	1.01	0.60
6638	Drummond Island	Ontario, Collingwood Fm.	119.17	10.34	32.0	41.3	1.66	1.37	0.08
6639	Cockburn Island	Ontario, Collingwood Fm.	328.94	9.04	23.4	38.5	0.68	1.50	0.08
6640	St. Joseph Island	Ontario, Collingwood Fm.	163.28	8.39	39.5	39.1	1.43	1.44	0.08
6130	Manitoulin Island	Ontario, Collingwood Fm.	19.3	2.51	86.3	39.4	1.02	1.22	0.12
6637	Manitoulin Island	Ontario, Collingwood Fm.	112.90	5.70	40.0	55.4	0.71	1.39	0.08
6122	CLGD03	Ontario, Collingwood Fm.	53.15	10.90	29.2	37.0	1.30	1.23	0.06
6642	Bowmanville BQ-A	Ontario, Collingwood Fm.	-	2.72	125.9	71.2	-	1.59	0.21
6132	CLGD07A	Ontario, Collingwood Fm.	73.1	6.80	55.8	42.5	0.93	1.66	0.06
6641	CLGD06A	Ontario, Collingwood Fm.	43.58	10.65	49.3	46.5	0.96	1.67	0.09
6117	Whitby area	Ontario, Collingwood Fm.	33.4	4.13	167.2	63.7	0.53	1.83	0.23
6504	Table Head TH4	Newfoundland	-	0.61	96.2	53.6	0.48	1.66	0.17
6501	Green Point GP1	Newfoundland	-	8.07	28.5	48.4	1.90	2.93	0.03
6502	Green Point GP3	Newfoundland	-	4.88	23.2	29.7	1.12	2.75	0.06
6503	Humber Arm HA3	Newfoundland	-	1.20	127.6	52.9	0.76	1.46	0.22
6500	Cambro-Ord OC2	Newfoundland	-	1.21	70.9	50.7	0.33	2.09	0.09
6491	Baffin Island 4	Northwest Territories	-	12.86	15.8	17.6	2.00	0.80	0.05
6492	Baffin Island 7	Northwest Territories	-	10.54	13.2	12.0	2.01	0.90	0.04
6499	Baffin Island 13	Northwest Territories	-	3.05	30.0	30.0	1.99	0.92	0.02
6487	Sixteen Mile Brook 3	Northwest Territories	-	31.16	8.8	11.2	0.64	0.88	0.06
6489	Gore Point 1	Northwest Territories	-	17.27	16.6	15.6	0.73	0.77	0.04
6488	Boas River 2	Northwest Territories	-	6.29	37.0	10.0	2.55	0.71	0.03
6370	Boas River 4	Northwest Territories	-	6.25	50.0	22.8	2.36	0.73	0.02
6634	Akpatok 2	Northwest Territories	-	-	-	-	2.00	0.92	0.04
6490	Akpatok 3	Northwest Territories	-	1.94	17.4	17.1	3.82	0.94	0.04

However, it is widely known that the abundance of acyclic isoprenoids relative to n-alkanes decreases during catagenesis (Tissot and Welte, 1984) and the Collingwood samples probably do not differ significantly in this respect from any others. The low concentration of acyclic isoprenoids in the kukersites is not explained by such an effect, as these samples show no evidence of having generated bitumen despite their high Tmax (see below). Even the Collingwood samples that appear to have generated bitumen have higher pr/nC_{17} values than the kukersites. This suggests that a difference in the environment of deposition or in the source of the organic matter of these samples is affecting this ratio.

Timing of bitumen generation for the Williston Basin kukersites versus the Collingwood shales

One interesting feature shown by these samples is the higher maturity required to generate bitumen from the Williston kukersite compared to the Collingwood shale samples. All the maturation parameters determined during the course of this study (e.g., optical measurements such as intensity of fluorescence, Tmax, and sterane and hopane ratios) indicate that the Collingwood shale organic matter has undergone less thermal stress than the kukersites. However, from microscopic observations and from parameters such as the Production Index and extract yields (Table 2) it is evident that the Collingwood samples have generated bitumen whereas the kukersite organic matter has not. Since the inorganic matrix of both sets of samples is predominantly carbonate, this difference in the apparent maturity needed to initiate the generation of hydrocarbons appears to be related to organic matter composition rather than lithology.

There are some chemical differences between the organic matter in the two sets of samples, which may be related to their different depositional environments. When examined microscopically the organic matter in the kukersite samples is observed to be almost entirely composed of algal bodies squashed parallel to the bedding plane, suggesting that it was little affected by diagenetic processes. The organic matter in the Collingwood shales is almost entirely amorphous, indicating that it was deposited under conditions favourable to microbial reworking during early diagenesis. This has lowered the hydrocarbon potential (as indicated by the Hydrogen Indices) and partially oxidised (higher Oxygen Indices) the Collingwood organic matter. Hence, the Collingwood shales have Type II and the kukersites have Type I organic matter. It could also explain the higher abundance of $C_{20}+$ n-alkanes and acyclic isoprenoids in the Collingwood, compared to the kukersites, as these could have been introduced by bacteria. A similar relationship between the amounts of $C_{20}+$ n-alkanes and cyclic isoprenoids has recently been noted by Longman and Palmer (1987). The suggestion by Reed et al. (1986) that *Gloeocapsomorpha* contained no chlorophyll may, therefore, be correct.

The difference in organic matter type would then explain why the Collingwood has generated hydrocarbons and the kukersites have not despite the greater maturity of the latter. It is well established that greater temperatures are needed to generate hydrocarbons from Type I than Type II organic matter (e.g., Tissot and Welte, 1984; p. 588-592). This is because in Type I kerogens the majority of bonds that need to be broken are the very stable C-C bonds, which require higher activation energies than heteratomic bonds, more of which occur in Type II kerogens.

Polycyclic biomarker characteristics of southern samples

Generally, the maturities indicated by biomarker ratios for samples (other than those from the Northwest Territories) agree well with those from other parameters (e.g., Tmax, intensity of fluorescence, etc.). There are some variations which may reflect minor differences in depositional conditions but these will not be discussed here.

Almost all the samples show a predominance of C_{29} over C_{27} and C_{28} steranes. This is another frequently reported characteristic of Ordovician organic matter (e.g., Fowler and Douglas, 1984; Vlierboom et al., 1986; Rullkotter et al., 1986; Longman and Palmer, 1987) although Hoffman et al. (1987) reported a more equal distribution of C_{27} and C_{29} steranes in their Australian samples. The two kukersite samples that show apparently greater amounts of C_{27} than C_{29} steranes contain very low amounts of C_{27}-C_{29} steranes and were difficult to measure, so the ratios may be incorrect. In post-Silurian sediments, a predominance of C_{29} steranes would be considered by some workers to indicate a major higher land-plant contribution (Huang and Meinschein, 1979). In the case of these Ordovician sediments the C_{29} predominance could indicate that *Gloeocapsomorpha* was a cyanobacteria (blue-green algae) since these organisms are known to show a predominance of C_{29} sterols (e.g., De Sousa and Nes, 1968; Reitz and Hamilton, 1968; Paoletti et al., 1976; Matsumota et al., 1982; Volkman, 1986).

The relative abundance of regular steranes and diasteranes is believed to depend on lithology. Diasteranes are derived from diasterenes, formed from sterenes by acid (clay) catalysed reactions (Rubinstein et al., 1975; Sieskind et al., 1979). Although the kukersites have been described as "black kerogenous limestones and dolomites" (Kohm and Louden, 1978), the samples analyzed here show a higher abundance of diasteranes relative to regular steranes than the Collingwood samples, which are also mostly carbonate (Snowdon, 1984). This suggests that the kukersites contain more clay minerals than the Collingwood shale. Longman and Palmer (1987) also noted a predominance of diasterane over regular steranes in oils from the Williston Basin. They considered that since these oils were sourced from the kukersite beds, which "contain little or no clay"; clay minerals need not always be present for the occurrence of rearranged steranes. The greater range in values for the Collingwood samples may partly reflect their greater range in maturity. Diasteranes are more stable than regular steranes so there is an increase in the diasterane to regular sterane ratio with increasing maturation (Siefert and Moldowan, 1978). Some of the variation can be attributed to the different amounts of clays in the Collingwood samples. For example, sample 6130 from Manitoulin Island (OGS SIS07 19.3 m) has a diasterane to regular sterane ratio of 2.63 and was reported by Snowdon (1984) to be 60.6 per cent dolomite and 10.3 per cent illite. Sample 6122 from the Collingwood area (OGS CLG D03 53.15 m) has a diasterane to regular sterane ratio of only 0.83 and was reported by Snowdon (1984) to be 56.8 per cent calcite and 4.2 per cent illite. According to their Tmax values, these samples are of similar maturity (although biomarkers indicate that 6122 is slightly more mature) so that the difference in their relative amounts of diasteranes may reflect their illite content. The Newfoundland samples show a wide variation in their diasterane to regular sterane ratio, indicating that they may be from diverse lithologies. For example, the Table Head 4 sample is suggested from this ratio to be very clay-rich whilst the two Green Point and the Cambro-Ordovician samples are more carbonate-rich. However, this does not agree with the X-ray diffraction data given by Macauley (1987c) for these samples which show that the TH-4 sample contains only trace amounts of clays. This may be further evidence that factors other than the presence of clay minerals influence the formation of diasteranes.

None of these samples show anything unusual in their terpane distributions, such as the presence of 28,30-bisnorhopanes. The Collingwood samples do contain significantly higher concentrations of gammacerane than the other samples.

Biomarkers in the Northwest Territories samples

It was indicated during the discussion of their saturate fraction gas chromatograms that the organic-rich rocks from the Northwest Territories are very different geochemically from the other Ordovician samples. They have more in common with certain reef-hosted oils and their source rocks from the Middle and Upper Silurian of southwestern Ontario and the Middle Devonian of the Alberta Basin. In their saturate fraction gas chromatograms this is shown by their n-alkane distributions, their low pr/ph ratios, and their high abundance of acyclic isoprenoids relative to n-alkanes. This similarity is even more striking when their biomarkers are considered.

All the NWT samples contain in their aromatic fractions the 1-alkyl-2,3,6-trimethylbenzenes reported by Summons and Powell (1987) in carbonate source rocks that were deposited under highly reducing and probably hypersaline conditions. These compounds are thought to be derived from a carotenoid found in the Chlorobiaceae family of sulphur bacteria (Summons and Powell, 1986). The concentration of these compounds compared to other aromatics is highest in the Southampton Island samples, which also contain much higher amounts of sulphur compounds than the Akpatok and Baffin Island samples.

The Southampton Island samples show a predominance of C_{29} steranes with low amounts of C_{28} steranes. The Baffin Island samples show a more equal distribution of C_{27} and C_{29} steranes with C_{28} steranes in much lower abundance. Summons and Powell (1987) reported that the Michigan Basin and Alberta oils have "a distribution with the C_{27} and C_{29} components dominating and in equal abundance". This is not dissimilar to what was found for the NWT samples. Summons and Powell noted 4-methylsteranes in their oils and these also were detected in the NWT samples. These compounds have also been detected in Precambrian oils with a presumed carbonate source rock (Fowler and Douglas, 1987). These compounds are usually considered to be derived from 4-methylsterols found in dinoflagellates (Boon et al., 1979). However, since dinoflagellates are unknown before the Permian (Brasier, 1979) they are unlikely to be the source of these compounds in these older strata.

The Sixteen Mile Brook and Gore Point samples also show a 17α(H), 21β(H)-hopane distribution similar to the Silurian oils of the Michigan Basin with a lower abundance of the C_{33} compared to the C_{32} or C_{34} members (Fowler, 1984; Rullkotter et al., 1986). The Boas River and Baffin Island samples show a different distribution of these compounds with the C_{33}-C_{35} 17α(H), 21β(H)-hopane in much lower abundance than their C_{31} and C_{32} homologues. The NWT samples also resemble the Michigan Basin Silurian samples by having a high concentration of gammacerane. One difference between the Michigan Basin Silurian samples and the NWT samples is that according to the present data the latter do not appear to be as rich in $C_{20}+$ acyclic isoprenoids.

In conclusion, it is evident from the above discussion that the NWT organic matter was not derived from *Gloeocapsomorpha*, as had previously been suggested by Foster et al. (1986), but from other algal and bacterial sources. Its similarity to other samples, such as those examined by Summons and Powell (1987), suggests that it was deposited in a highly reducing hypersaline carbonate environment. There was some minor variation in the conditions between deposits.

COMPARISONS, CONTRASTS AND COMMENTS

A wide age range from Early to Late Ordovician can be assigned to these organic-rich strata. The Lower and Middle Ordovican units are confined to western Newfoundland whereas the Winnipeg beds of the Williston Basin are placed close to the Middle – Late Ordovician time boundary. Of the remaining units, the Williston Basin kukersites, the Collingwood oil shales, the upper sequence of organic beds on Baffin Island and possibly those on Akpatok Island fall within a Late Ordovician time frame (late Edenian – Maysvillian). **Each of these units represents, in its own way, the effects of a major tectonic event during the Late Ordovician** (Fig. 17). Overthrusting of the klippen occurred at this time in western Newfoundland. The Baffin Island lower organic-rich zone is somewhat older, probably deposited in the Trentonian (Barneveld) Stage.

Although not paleontologically established herein, a general time coincidence of the Yeoman and Collingwood organic zones can be interpreted from many publications. Yeoman oil shales were deposited discontinuously in a basin center and represent minor fluctuations in the pycnocline resulting from irregular sea-floor subsidence, with immediate resumption of carbonate sedimentation as aerobic conditions returned. The Collingwood Member was deposited on a basin flank and is part of a complete carbonate – organic zone – terrigenous clastic cycle. In southern Ontario, the entire Ordovician sequence thins rapidly northward as the Collingwood outcrop belt is parallel and proximal to Precambrian rocks exposed on the northern shores of Lake Huron. At Lac St. Jean (Fig. 3), only a few metres of carbonate separate organic-rich Ordovician beds from the Precambrian. In both Williston Basin and southern Ontario, the depositional sequence is complete.

Conodont identifications confirm the time equivalence of the Collingwood and Boas organic units, but the Boas beds lack the overlying clastic interval and a depositional hiatus exists between the Boas and the overlying carbonate. There is a distinct probability that the Boas upper unit of laminated

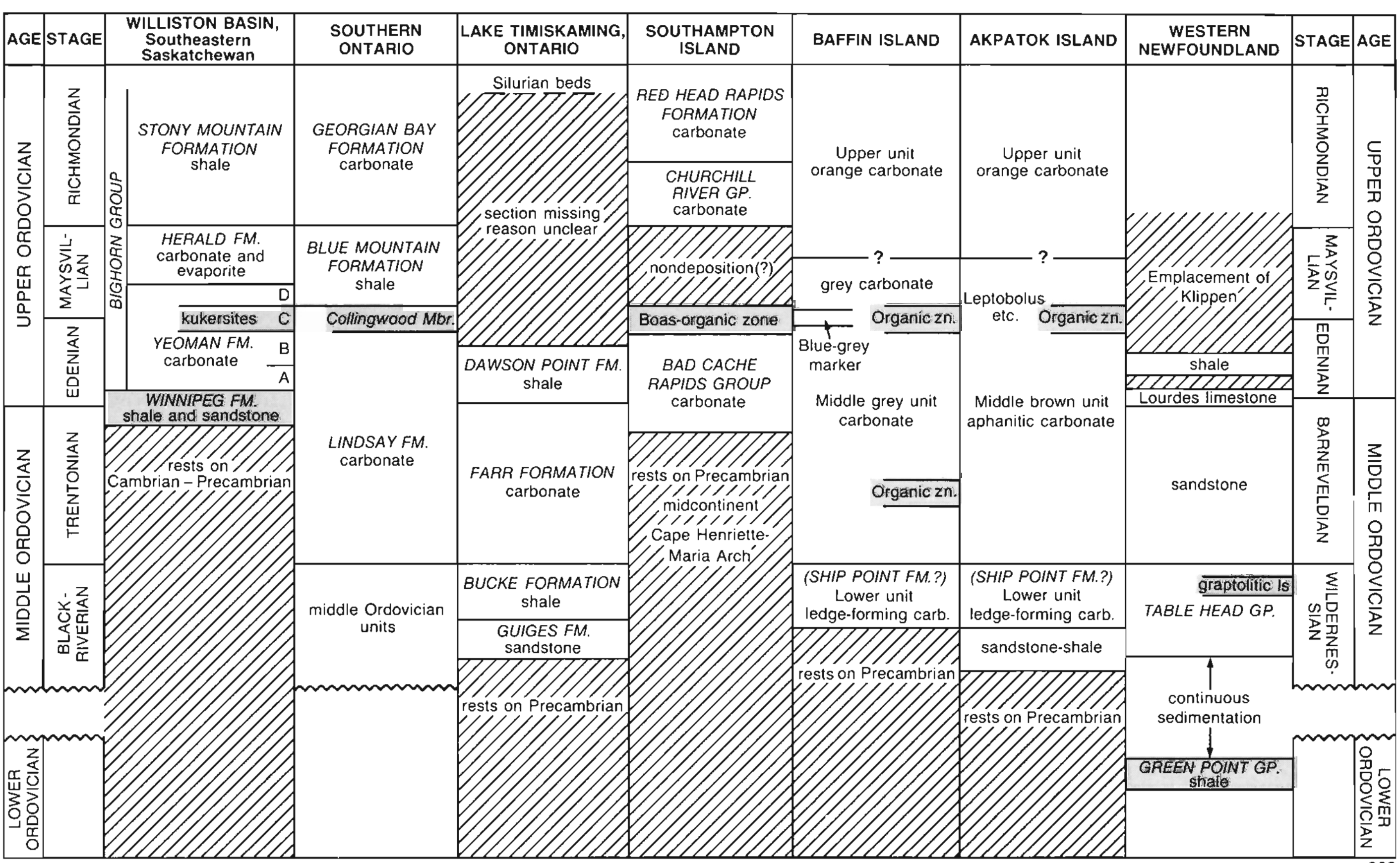


Figure 17. Stratigraphic correlation chart, illustrating the possible regional geological event of late Edenian to early Maysvillian time, during which semi-contemporaneous organic beds (shaded) were deposited.

oil shales was laid down during a long period of virtual nondeposition and thus represents a greater time interval than does the Collingwood. Where best developed, Boas oil shales are separated from Precambrian rocks by a few metres of organic-poor carbonate at most. Sanford and Norris (1973) indicate an equivalent hiatus in the sedimentary record in the Moose Basin (Hudson Bay Lowland, Fig. 1); however, equivalent organic-rich beds are missing at the south end of Hudson Bay, probably through nondeposition.

Precise correlation cannot as yet be made between the sections on Akpatok, Baffin and Southampton islands but, to some extent, the correlation of the organic zones can be interpreted. On Akpatok Island, a complete section extending from Middle into Upper Ordovician has been defined by macrofaunal determinations. The upper, orange coloured unit of that section is Richmondian and certainly younger than the Boas and Collingwood beds. Although a specific zone of the Akpatok section has been correlated with the Boas on the basis of macrofauna, no conodont determinations are as yet available to provide a specific, uniform, faunal comparison. Nor has the presence of highly organic, 'papery', laminated beds been established in this section. Lithologically, there is no apparent break in the depositional history on either Akpatok or Baffin Island. Two distinct organic intervals are recognized in the Ordovician sequence of southern Baffin Island. Faunal control for this area is as yet confusing because of the early assumption that only one sequence was involved. From comparison with strata on Akpatok and Rowley islands, the Baffin Island section must cover a significant Middle–Upper Ordovician interval. Most of the section on Baffin Island has been assigned to the Barneveld or post-Barneveld stages. The lower of the Baffin organic intervals, which appears to have been deposited within the Barneveld (Trentonian) Stage, is from twenty to thirty metres above the Precambrian. At Amadjuak Lake, only a thin section may underlie the uppermost organic interval of probable late Edenian to early Maysvillian age. The Baffin Island organic beds appear comparable to those of the Boas and Collingwood as deposits flanking a basin. Whether or not depositional hiatuses occur within either the Baffin or Akpatok Island sections has not been ascertained, but there is no indication of erosional unconformity effects.

Ordovician organic-rich beds are dominated by marine Type II sapropelic (amorphous) kerogens, but Type I deposits, characterized by *Gloeocapsomorpha*, are present in two areas. As is anticipated for rocks of this age, nowhere is there evidence of Type III humic organics. Rock-Eval pyrolysis generally differentiated Types I and II, and defined their maturation levels; however, maceral identification was necessary to supplement some Rock-Eval data for which several interpretations were possible. Differences within the Type II kerogens became evident from the saturate fraction gas chromatography, which revealed that the northern deposits (Southampton, Baffin and Akpatok islands) could be grouped separately from those to the south. **These results demonstrate clearly that no single geochemical or petrological investigative technique can define completely the character of an organic-rich sediment.**

Although two Type I deposits, the Upper Ordovician Yeoman beds of Williston Basin and the Lower Ordovician Green Point Group of western Newfoundland, are recognized, the stratigraphic relationships of these two units are not the same. The Yeoman kukersites are distinctly Type I by all criteria, that is, high Hydrogen Indices, low Oxygen Indices, excellent Yield Ratios, maceral dominance of *Gloeocapsomorpha*, and saturate fractions characteristic of Ordovician oils. These kukersites are immature at relatively high Tmax values. In contrast, the Green Point beds exhibit an admixed kerogen that contains *Gloeocapsomorpha* in lesser amount along with considerable bituminite, has Hydrogen Indices and Yield Ratios intermediate between typical Type I and II values, and is marginally matured at lower Tmax values than those of the Yeoman beds. Green Point saturate fractions more closely resemble those of the other Newfoundland and Ontario Type II kerogens. A derivative relationship of Type I and II kerogens may be inferred from the recognition of Type II beds associated with the Yeoman kukersite and of *Gloeocapsomorpha* locally in the Winnipeg shale.

Collingwood organic beds contain the typical matrix bituminite of sapropelic kerogens. Virtually all geochemical parameters plot within the characteristic Type II sphere of the van Krevelen diagram. Occasional samples have Hydrogen Indices considerably in excess of 600 and Yield Ratios greater than 7 kg/t/%TOC, indicating a Type I affinity. Of particular note is the general increase in oxygen observed between the Type I kukersites discussed above and this Type II deposit. Saturate fraction chromatograms not only differentiate the Collingwood samples from the kukersites, but also show significant variation to equivalent strata within the nearby Michigan Basin (Fig. 1). The previously proposed Collingwood source for southern Ontario Cambrian and Ordovician oils (Powell et al., 1984) is here reaffirmed.

Easterly increasing thermal maturation of the Collingwood beds is reflected in all parameters, including decreasing Hydrogen Indices and Yield Ratios, increasing Tmax values, and commensurate changes in composition of the saturate fraction, especially the decreasing pristane/nC_{17} ratio.

Although only small amounts of organic carbon have been recorded from Winnipeg beds, the principal kerogen can be defined as Type II. The atypical presence of *Gloeocapsomorpha* may be significant to define this organism as the source organic matter of the typical Type II matrix bituminite of this unit.

In western Newfoundland, kerogens of both the Table Head and Humber Arm groups are marine Type II kerogens of sufficient thermal maturity to have generated oil and be the source for the petroleum shows in the Ordovician beds of that area. Of particular note is the occurrence of suspected *Gloeocapsomorpha* remnants.

These geochemically typical Type II amorphous kerogens are independent of, and different from, the Type II mixed deposits (marinites of Hutton, 1986), which are admixes of sapropelic and humic organic residues.

Considerable discussion has taken place, both in the literature and this report, as to the role of *Gloeocapsomorpha* in marine source beds relative to the much more common amorphous matrix bituminite kerogen. The prime concern is whether this alga, by degradation and maturation, is the principal source of the amorphous material. This question parallels the one posed for continental Type I deposits, namely, is the *Botryococcus*-like telalginite of torbanites the precursor of the lamalginite of lamosite deposits? Kalkreuth and Macauley (1987) noted degrees of degradation and differential maturation of "*Botryococcus*" remains within single samples of Pennsylvanian aged torbanites and concluded that some of the lamalginite must have been derived from that source.

Differences between the Yeoman kukersites and Collingwood amorphous kerogens are revealed by petrographic examination, by Rock-Eval pyrolysis and by the chemistry of the saturate extract fractions. Nevertheless, a case can be made for a common precursor organic material. The kukersites were deposited in the depositional center of a basin over limited geographic areas in local depocenters of limited duration, and were followed by carbonates of similar character to those below. In contrast, Collingwood beds were deposited in an area of lesser subsidence apparently flanking the basin, may have encompassed a greater time span, and are part of a transitional sequence from carbonate upward to terrigenous deposition. In neither case does any significant time period appear to be unrepresented. These differences in depositional history may well be reflected by the differences in the final kerogen products.

Because of differences in depositional environments, microbial reworking may have been restricted to the Collingwood oil shales during early diagenesis and may have in part depleted the hydrogen content while partly oxidizing the organic matter. Bacteria were possibly much more able to play a major role in the formation of the final kerogen product in these shales than in the much more restricted environment of the kukersites. The few higher than expected Hydrogen Indices in Collingwood samples may indicate remnant Type I organic content. The effects of bacterial action can explain adequately the differences in saturate fraction chemistry for the two deposits.

Of possibly even greater significance is the recognition of admixed kukersite-amorphous matrix bituminite in the Green Point oil shales of western Newfoundland, along with the suspected remnants of *Gloeocapsomorpha* in other Newfoundland Type II deposits. Another relevant consideration is the wide range of Rock-Eval parameters in the Icebox Member of the Winnipeg Formation, for which an admix of kerogen types must also be interpreted. More detailed studies of these complex organic-rich beds should help to unravel the relationship of these two marine kerogen forms.

Kerogens of the Ordovician beds of the Northwest Territories cannot be distinguished from those of Collingwood by either Rock-Eval pyrolysis or petrographic maceral determinations. A minor difference is a slightly higher range of Oxygen Indices for the organic matter in the northern deposits. Their origins appear to be similar (particularly for the Boas and Collingwood oil shales), as end deposits at the cessation of a carbonate phase. In contrast, terrigenous clastics did not follow the organic-rich interval in the northern area. The similarity of the Michigan Basin Silurian and western Canadian Middle Devonian oils to the oil products of the NWT areas is surprising. The former are well defined within evaporitic salt and anhydrite sequences, whereas there is neither indication in the present sedimentary record of evaporite beds in association with the NWT kerogenous intervals nor reason to suspect a hypersaline depositional environment. Subsequent solution removal of salt is always a possibility, but none of the associated breccia, slump structures, etc. have been recognized. This does not preclude their initial presence. Both salt and anhydrite are present in Lower to Middle Ordovician sequences of the western Arctic Islands (Drummond, 1973).

Although Collingwood oil shales can be reasonably related back to *Gloeocapsomorpha*, the chemistry of the generated oil products does not support this relationship for the NWT samples. Also, there must be more than one source for Type I lamalginite as all lamalginite cannot be related directly back to a telalginite source.

SIGNIFICANCE TO FRONTIER EXPLORATION

No attempt will be made here to review the exploration potential of the various frontier areas as this has been done in excellent detail by a number of authors in "Future

Petroleum Provinces of Canada," Memoir 1 of the Canadian Society of Petroleum Geologists (R.G. McCrossan, ed., 1973). Although it is not a recent publication, the pace of exploration in the offshore has been sufficiently slow that the concepts presented in the memoir are still generally valid. Most of the beds described herein have previously been mentioned as potential sources for petroleum, but the present discussion of kerogen character and levels of thermal maturation will add significantly to their evaluation as source beds.

Collingwood beds have already been established as the source of Cambrian and Ordovician petroleum accumulations in southern Ontario (Powell et al., 1984), yet over much of the area, these organic-rich strata are still of low enough thermal maturity to be attractive oil shale beds (Johnson et al., in progress). The Yeoman kukersite beds of the Williston Basin are insufficiently mature to have been the source of oil accumulations in southern Saskatchewan; however, they may have sourced significant amounts of petroleum in the deeper parts of the basin in the northern United States, as hydrocarbons have been produced from these areas for some time.

Hudson Bay Basin

The Hudson Bay and Moose River basins are separated by the mid-continent Cape Henrietta Maria Arch (Fig. 1). Sanford and Norris (1973) projected Ordovician deposition in unbroken continuity across this arch, which was a feature at that time, although they depicted depositional thickening of the Ordovician into the presently recognized basin areas. Sanford and Norris (op. cit.) indicated a loss of uppermost Ordovican beds by erosion prior to the deposition of Silurian strata, and also by nondeposition of the lower units as younger beds overlapped onto the Precambrian surface at the southern limit of the Moose River Basin. They also advocated continuity of sedimentation across the two basinal areas and across the Bell Arch on Southampton Island (Sanford et al., 1985) and thence to the deposits on Baffin Island (Fig. 1). In a comparison of this region to the Michigan Basin, they also suggested that production from Ordovician strata may not occur beyond the limits of Devonian cover, in which case an area of 230,500 square kilometres (89,000 square miles) would be prospective within a total area of 971,300 square kilometres (375,000 square miles) of Phanerozoic cover.

The organic-rich massive carbonate and the overlying, thinly laminated, very organic-rich beds of the Boas oil shale are known only on Southampton Island. Although these are excellent potential source beds, their geographic distribution may be limited. They, or their equivalent, are in part missing by nondeposition against emergent Precambrian rocks at both the north and south limits of the basinal areas. Several onshore exploratory tests have been drilled in the Moose River Basin and on the southwestern flank of the Hudson Bay Basin. Three tests have been located offshore within Hudson Bay, although none has explored the deepest part of the basin. As yet, there has been no indication of Boas-type organic-rich beds in any of the drillholes, thus indicating a possible limited areal extent for the Boas deposit. This does not preclude the possibility that other, equivalent, isolated units, probably flanking the basins, have not yet been penetrated.

Boas oil shales on Southampton Island are immature. Rock-Eval analyses (conducted at ISPG, Calgary) of one of the offshore well sections failed to find organic-rich intervals and also indicated that minor organic carbon is of insufficient maturity to have generated hydrocarbons. Thus, prospects now seem limited to the deepest parts of the basin.

Foxe Basin

Only thin sections of Ordovician–Silurian strata are exposed on the periphery of the Foxe Basin (Fig. 1) on Southampton Island (Heywood and Sanford, 1976), on Melville Peninsula (Trettin, 1975), and on Baffin Island (Blackadar, 1967; Macauley, 1987b). Petroleum potential has been discussed for the nearby Hudson Bay Basin (Sanford and Norris, 1973), the Arctic Islands to the west (Drummond, 1973), and for Baffin Bay-Davis Strait to the east (McMillan, 1973). The Foxe Basin was probably omitted from these reviews because only a thin Paleozoic section bounds the basin and there has been no apparent reason either to suggest the presence or absence of overlying younger sediments in the offshore area.

Ordovician potential source beds are present on Southampton Island, but these are suspected to be of local distribution. Good potential source rocks are also known in two zones on Baffin Island, but again the areal extent of these deposits is unknown. Potential source rocks are not present on Rowley Island at the north end of the basin; however, their possible equivalence in part to some of the organic carbonates on Akpatok Island, and thus to the Boas oil shale, is encouraging when assessing the possible presence of these organic beds in the southern part of Foxe Basin.

All the organic-rich beds surrounding Foxe Basin are immature. Those on Baffin Island are within a sequence of poorly consolidated sediments and exhibit the lowest range of Tmax values among all the deposits studied. There is little likelihood that any significant thickness of younger beds ever overlay the Ordovician strata of southern Baffin island. If Foxe Basin has any potential for hydrocarbon accumulations, these Ordovician potential source beds would have had to have been buried to a much greater depth than is indicated from the surface exposures.

Baffin Bay – Davis Strait – Labrador Sea

McMillan (1973) has pointed out that Baffin Island and Greenland formed a single landmass during Ordovician time and only much later were separated to form the intervening Baffin Bay and Davis Strait waterways. With the sea-floor spreading, only isolated remnants of Ordovician strata can be expected within this offshore frontier area. A similar conclusion may also be applicable to the previously reviewed Foxe Basin. A thin Ordovician carbonate section has been penetrated at one location in the Labrador Sea. Highly mature to overmature kerogens, similar to those of the admixed Type I-II Green Point Group organic-rich beds of western Newfoundland, have been described (Goodarzi et al., 1985) from Lower Ordovician beds extending from the Grand Banks (Sherwin, 1973) to the southeast of Newfoundland. Whether these sections are depositional or erosional remnants is currently open to question.

If Ordovician beds are present to any significant extent in these areas, source beds should be anticipated. Equivalents of the Type II deposits of Baffin and Akpatok islands would have been downwarped sufficiently to have generated hydrocarbons. An effective search for the 'bituminous' beds described by Roy (1941) on Blunt Peninsula (Fig. 4) would be beneficial to the assessment of source potential for Davis Strait (Fig. 1) to the east. Although the source rocks are overmature where examined on the Grand Banks, petroleum products may have been preserved if they migrated to reservoirs that were subjected to less severe thermal conditions.

Gulf of St. Lawrence

For his discussion of exploratory potential, Williams (1973) divided the Gulf of St. Lawrence into northerly (Anticosti) and southerly (Maritimes) basins (Fig. 1, dotted line). In excess of 7600 m (25,000 ft) of Carboniferous strata are present in the deepest parts of the Maritimes Basin within the southern Gulf of St. Lawrence where lower Paleozoic rocks are not considered to be prime exploratory targets.

Two distinct source areas are recognized in the Anticosti Basin part of the Gulf. In the east and southeast are the Upper Ordovician Macastey shales of Anticosti Island and their equivalents in the St. Lawrence Lowland (Fig. 3). These organic-rich beds are within a thick sequence of lower Paleozoic sediments, dominantly Ordovician-Silurian with thin Cambrian and Devonian sections. These organic beds are highly mature to overmature, both as a result of depth of burial (over 3700 m of lower Paleozoic strata are mapped near southwestern Anticosti Island; Williams, 1973) and of igneous heat effects.

In western Newfoundland, several Lower to Middle Ordovician intervals of potential source beds range from immature to marginally and moderately mature, depending on the nature of the contained kerogen. Organic-rich beds are not described from strata of equivalent age on Anticosti Island and in the St. Lawrence Lowland. During deposition of the Macastey Formation, the Taconic Orogeny was taking place and the klippen were being formed by west to east overthrusting in western Newfoundland; consequently, Upper Ordovician equivalents of the Macastey (and thus of the Collingwood) are missing from that area.

Both the stratigraphic section and the levels of thermal maturation vary significantly from Newfoundland to Anticosti Island across 'Logan's Line', the structural element separating the Anticosti and Maritimes basins (Williams, 1973). Following Williams' interpretation, the section encountered in Anticosti Basin under the gulf waters will be similar to that of the Anticosti area rather than a westerly extension of the Newfoundland Ordovician geology. As such, Ordovician source beds will most likely be thermally overmature.

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PLATE 1

Petrographic characteristics of the various deposits under fluorescent or white light microscopy

A. Spinous, broken acritarch (A) in a predominantly clay matrix. Regions exhibiting a greater fluorescence intensity, are indicative of matrix-bituminite; lipid substances adsorbed onto clay mineral surfaces; 'upper unit', Akpatok Island (UV light source).

B. A section of a bituminite (B; degradation product of alga) lens cut approximately perpendicular to bedding, set in a carbonate matrix; Collingwood Member, Ontario (UV light source).

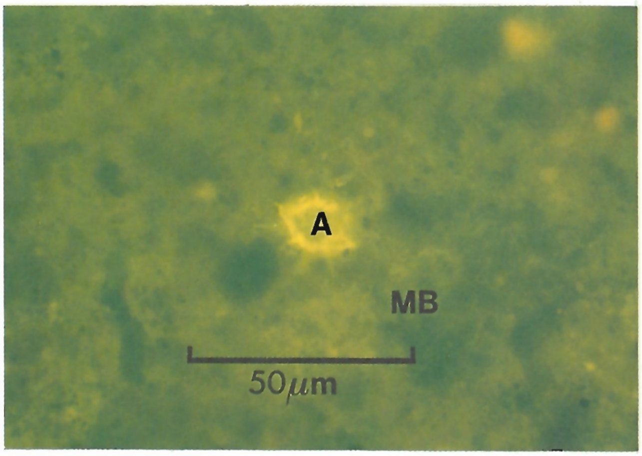
C. Kerogen assemblage consisting of small, rounded, algal bodies (G) which display affinities to cup-like structures of colonial alginities; Green Point Group, western Newfoundland (UV light source).

D. *Gloeocapsomorpha* (G and G1), parallel to bedding, in a silty marl matrix. Note the (1) faint structure typical of colonial alga preserved in G; and (2) the variability in fluroescence emissions between G1 and G; Red River Formation, Saskatchewan.

E. *Gloeocapsomorpha prisca*, Green Point Group, western Newfoundland (UV light source).

F. Chitinozoan (high-reflecting, string-like organic matter) set in a matrix of bituminite and matrix bituminite, Baffin island (white light source).

PLATE 1



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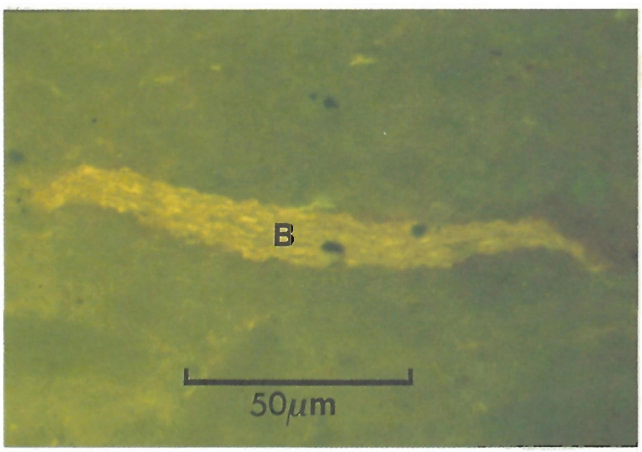

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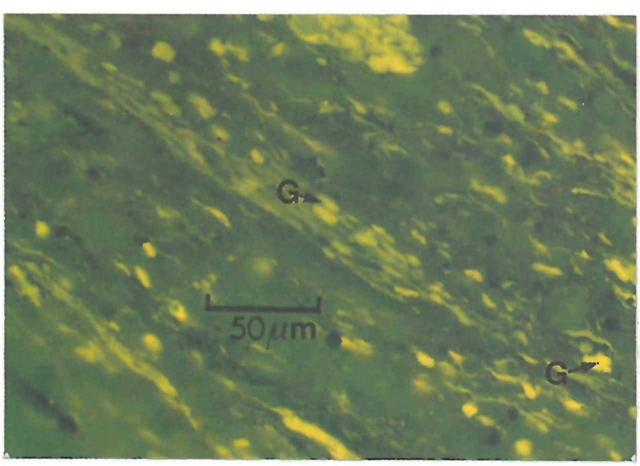

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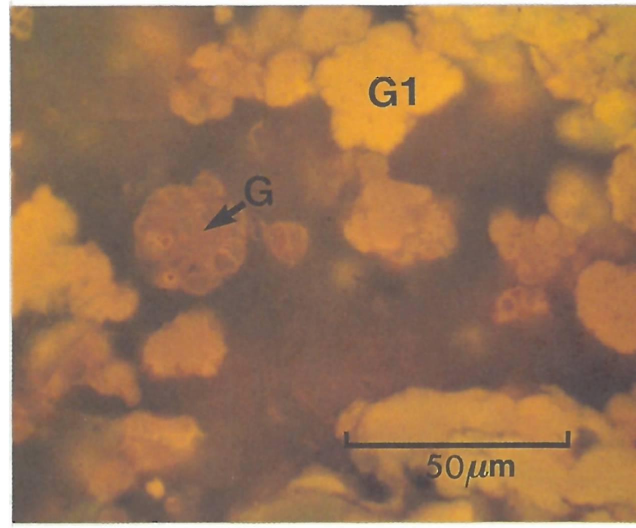

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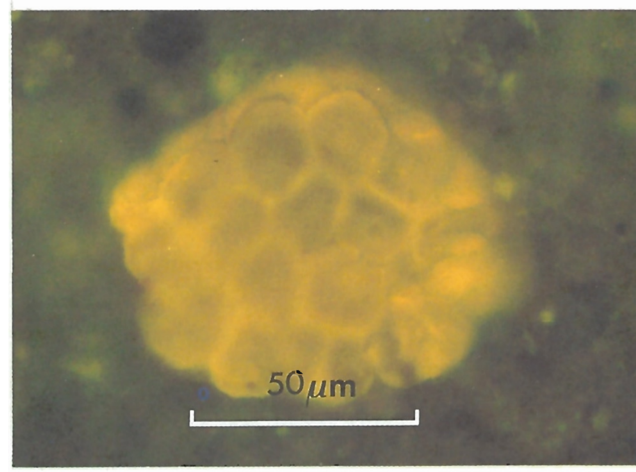

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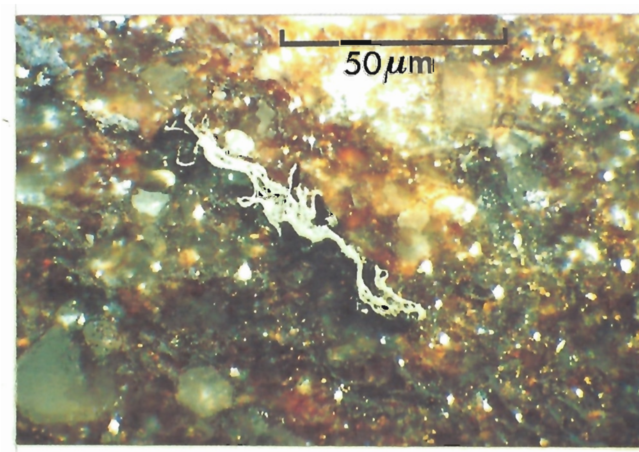

F