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Article abstract

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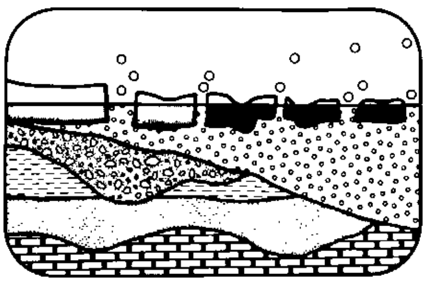

Methane in the Sediments of a Subarctic Continental Shelf

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Abstract
The unconsolidated sediments off eastern Canada contain interstitial methane up to 22,000 ppm. The presence of methane is associated with anoxic conditions found in fine sediments deposited in small basins. The foraminiferal assemblages and Carbon-14 dating of the gaseous deposits indicate rapid rates of sedimentation.

Introduction
The waters of the open subarctic continental shelves generally contain sufficient amounts of dissolved oxygen to support a relatively rapid mineralization of organic matter. Interstitial water, however, may become deficient in oxygen where methane may be one of the major by-products of fermentative degradation of organic matter. Traces of methane in the sediments are common, however, concentrations exceeding the background values, require specific sedimentary conditions not commonly occurring on the botton of epicontinental seas.

This report discusses the environment favorable for excessive accumulation of methane in the sediments of five small basins on the eastern continental shelf of Canada (Fig. 1). Micropaleontological study is integrated with geochemical investigations that help in understanding the environment favourable for the genesis and preservation of methane. The various foraminiferal assemblages present in the cores are used for the synthesis of paleoenvironments at the sediment-water interface during the time of deposition. The geochemical investigations reflect on the post depositional changes in organic matter.

Large amounts of methane in nearshore sediments have been found in a number of localities. Emery and Hoggan (1958) found methane in concentrations ranging from 1,180 ppm at the surface to 241,000 ppm at the depth of close to four metres of a sediment core collected from Santa Barbara Basin. At the east coast of North America the sediments of Chesapeake Bay contains methane up to 150,000 ppm (Reeburg, 1969). Here most of the methane is present in gaseous form, owing to the relatively shallow depths of water (30 m).

The relationship of methane genesis with the marine environment on a regional scale for the Canadian east coast has been discussed by Vilks *et al.* (1974): Rashid *et al.* (1975); Vilks and Rashid (1976) and Keen and Piper (1976). These studies indicate that methane can accumulate in the sediments of subarctic basins under favourable environmental conditions. One of the basic requirements is a sustained anaerobic environment resulting from rapid rates of sedimentation.

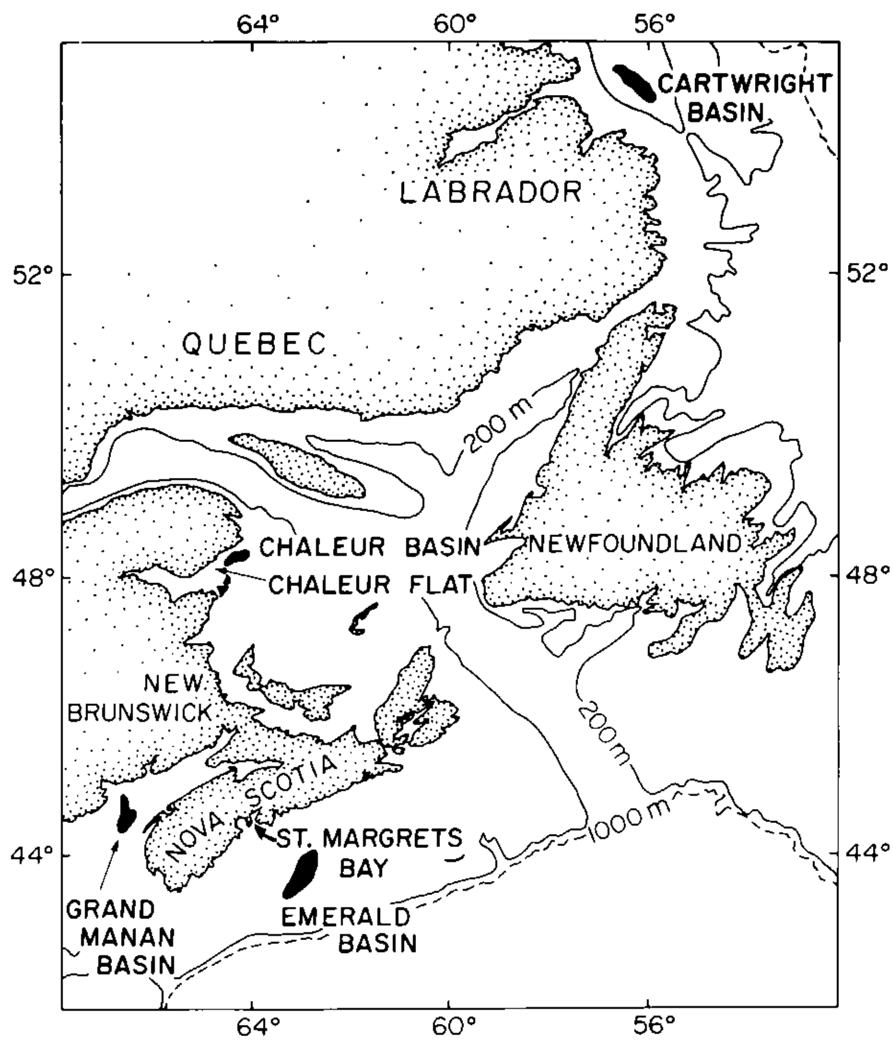

Figure 1
Eastern continental shelf of Canada showing the basins investigated.

The Oceanographic Environment

The continental shelf of eastern Canada is washed predominantly by the Labrador current that migrates in a southerly direction along the coast. These waters originate in Baffin Bay and are characterized by low temperatures and salinities.

On the Scotian Shelf the waters of the Labrador current have been modified by the effluent from the Gulf of St. Lawrence and the offshore slope waters. Frequent incursions of the generally warmer and more saline slope waters have been recorded in the deeper parts of the Emerald Basin (Hachey, 1953), where regardless of season, the temperature may be as high as 12°C.

The waters of the Chaleur Trough, which is located in the Gulf of St. Lawrence, are freshened by the outflow of the St. Lawrence River. The surface salinities in Chaleur Trough range from 22 ppt (parts per thousand) to 29 ppt (Lauzier, 1957) with a constant bottom salinity of 33 ppt (Trites, 1970). The winter temperature is close to zero throughout the water column, except at the bottom, where it is 2°C. During the summer, the surface temperature could be as high as 16°C.

The basic oceanographic features in the Bay of Fundy area are associated with tidal phenomena. The large tides are due to the combined action of a stationary wave and the progressive tidal wave coupled with a funnelling effect and the shoaling of the upper regions of the bay (Hachey, 1961). As a result of the large range in tides, tidal currents are the major components in the overall current system in the Bay of Fundy. In the Grand Manan Basin area of our coring sites, the maximum currents are in the order of 1.5 to 2.5 knots (Trites, 1961). The residual non-tidal circulation in the main portion of the Bay of Fundy is in a counterclockwise direction, thus the water enters the Bay along the coast of Nova Scotia and leaves along the opposite side.

In St. Margaret's Bay the water column is mixed during winter, but in late June the water becomes stratified, with a maximum surface temperature of 20°C and salinity 28.6 ppt in late July (Platt and Irwin, 1968). Occasionally the summer pycnocline may be destroyed by an offshore wind of sufficient strength and duration.

The upwelling combination with hard substratum provide conditions that are favourable for extensive growth of macroalgae, such as kelp. The seaweed zone in St. Margaret's Bay is extensive where the total production of seaweed averaged over the whole bay is about three times the total production of phytoplankton (Mann, 1973). Kelp probably is the major source of organic of debris that may become deposited with the inorganic sediment (Webster *et al.*, 1975).

The Sedimentary Environment

The surface physiography and sediments on the continental shelf of the study area have been modified by the continental glaciers of the last ice age (King, 1970). As a result, the topography of the sea-floor is irregular, having characteristically isolated depressions and banks as the major physiographic features.

The sediment types can be related to bathymetry. The sea-floor of the shallow inner shelf is covered by gravel and the banks of the outer shelf by well-sorted sand alternating with very coarse gravel and boulders. These reworked sediments overlie glacial drift deposited on the erosional surface of Tertiary bedrock (King, 1970; Fillon, 1976). As a result of sediment reworking in the shallower areas, fine sediments are being deposited in the basins.

Each of the basins considered here is under a slightly different environmental setting with correspondingly different post-glacial sedimentary histories. These differences are reflected in the paleontological and geochemical data.

The Cartwright Basin on the Labrador Shelf is the deepest (600 m) and northernmost basin. Excessive concentrations of methane were found in the lower half of a core (Vilks *et al.*, 1974) increasing from 1,545 ppm at 600 cm to 16,000 ppm at 1100 cm (Fig. 2). The per cent mud (sediment <.063 mm) is high throughout the core with a few lenses of coarser sediments. Organic carbon decreases below the surface, but the readily oxidizable plant pigment chlorophyll-a does not occur in lesser amounts in deeper sediments. The extracted humic compounds averaged 67 per cent of total organic matter in the upper half of the core, but the high methane sediments in the lower half contained easily extractable humic compounds on the average of 95 per cent. The comparatively high amounts of preserved chlorophyll and the high recovery of humic compounds suggest a low degree of oxidation of the buried organic matter.

Foraminiferal analysis indicates that the sediments were deposited during post-glacial times. The only planktonic foraminifera, *Neogloboquadrina pachyderma* is found in equal numbers throughout the core, suggesting that the present unrestricted oceanic influence in the basin existed also during the early Holocene lower stand of sea level. The assemblages of the benthonic foraminifera, however, change to increased relative amounts of the inner shelf-estuarine species such as *Elphidium clavatum* in the lower layers of the core. The trend suggests a relatively closer shoreline and lower bottom salinities during the early Holocene when the methane-rich sediments were deposited. The tests of benthonic foraminifera in these are well preserved and occur in large numbers, precluding the possibility of anoxic conditions at the sediment-water interface during the time of deposition.

Chaleur Trough is a narrow basin in the Gulf of St. Lawrence (Fig. 1) defined by the 120-metre isobath with a maximum depth of 180 m. The sediments in the basin consist of very fine clay derived from glacial till that has been reworked during the marine transgression shortly after glaciation. Two sediment cores were analyzed from here; 7B from the basin proper and 37B taken from a margin of the basin (Rashid *et al.*, 1975). The coring sites are 35 km apart, within the same zone of high organic productivity and presumably receive similar amounts of organic matter.

Methane was present in core 7B in concentrations of close to 6,000 ppm in the surface eight cm of sediment, increasing to over 14,000 ppm in the bottom 500 to 508 cm interval of the core (Fig. 3). The sediments of core 37B taken from the margin of the basin, contained methane in background concentrations only (42 to 106 ppm). The per cent organic carbon was high in the methane-rich sediment (1.38 to 1.72%) in comparision to the methane-poor sediments of core 37B (0.20 to 0.72%). The methane-rich sediments are also finer; in core 7B the per cent of mud ranged from 98 per cent to 95 per cent, whereas in the core 37B the fine fraction ranged from 73 per cent to 67 per cent in the lower half of the core increasing to 98 per cent in the upper 100 cm of sediment. The concentration of chlorophyll-a averaged 56μg/gC in the coarse sediments at the bottom of core 37B, but a much higher average of 207μg/gC was present in the finer surface sediments. The gaseous sediments of core 7B contained preserved chlorophyll-a on the average of 146μg/gC without a significant change through the various layers of the core.

The foraminifera in both cores imply the sampling of relatively young sediments that were deposited after the period of the early Holocene sea-level adjustment aproximately 8,000 years ago. Taking 8,000 years as the maximum age of the sediments at the bottom of the core, the rates of sedimentation are at least 60 cm per 1000 years. Through this time the surface waters have been productive, as evidenced by large numbers of preserved frustules of pelagic diatoms. The fine sediments of core 7B also contain well preserved foraminiferal tests. The evidence indicates a rapid burial of the shell material and a low activity of the sediment-feeding macrobenthos. The relatively low rate of post-sedimentary disturbance of the muds favours the fermentation and interstitial trapping of methane.

The Emerald Basin is one of the most prominent basins on the Scotian Shelf. The deepest part of this depression is slightly over 250 m and it is separated from the open sea by a sill of 150 m. The sediment consists of fine clays and silts in proportions of not less than 60 per cent of the total sediment. The sea-floor of the basin may be covered by pockmarks, which are crater-like depressions ranging from 10 to 200 m in diameter. King and MacLean (1970), concluded that the cone-shaped features were created as a result of gas escaping from the Cretaceous strata underlying the unconsolidated sediments.

The concentration of the interstitial gases were analyzed in two sediment cores, one of which was taken from a pockmark (Vilks and Rashid, 1976). Only

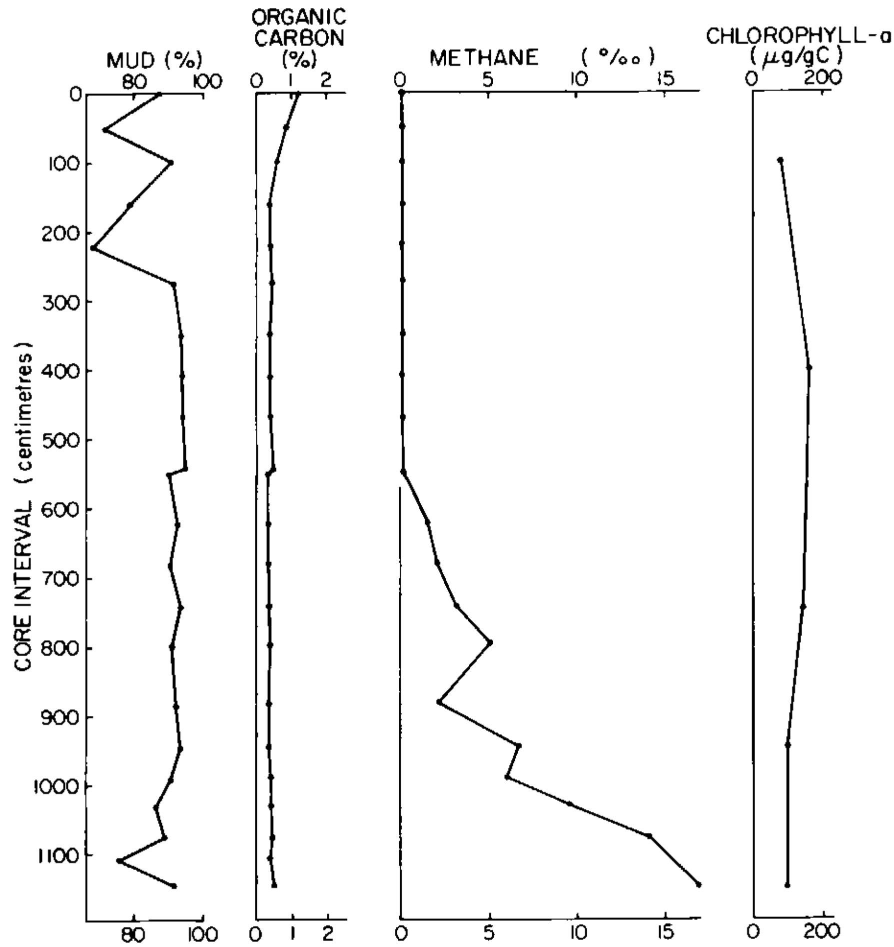

Figure 2
Organic carbon, percent mud, methane and chlorophyll-a in the sediments of Cartwright Saddle.

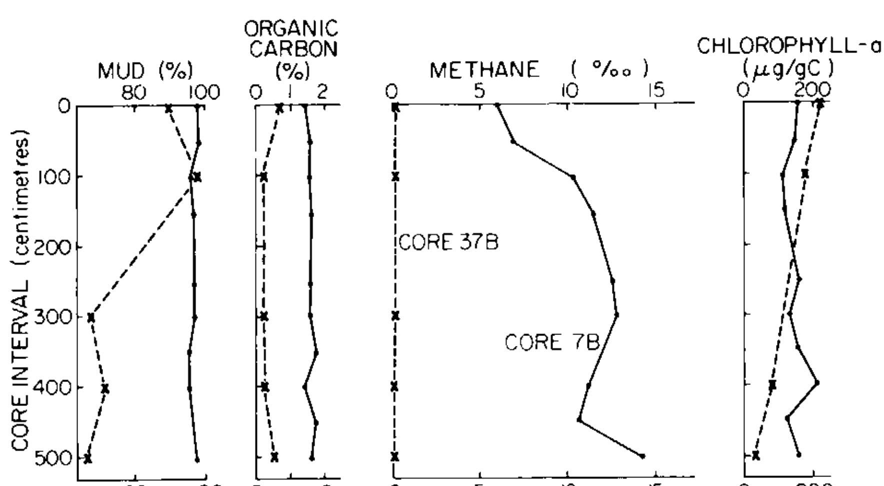

Figure 3
Organic carbon, per cent mud, methane and chlorophyll-a in the sediments of Chaleur Trough.

methane was detected and in concentrations less than 10 ppm, which is a back ground value. Except for the surface layer, organic carbon averaged 0.63 per cent by weight and chlorophyll-a averaged 39.37μg/gC. The concentration of carbon is comparable to the gaseous sediments of the Cartwright Saddle, but the pigment was preserved to a much lower extent.

Foraminifera in both cores change from diverse outer-shelf assemblages in the surface sediments to a practically monospecific nearshore *Elphidium clavatum* assemblage in the lower layers. The upper metre of sediment also contained benthonic and planktonic foraminifera characteristic of outer continental shelves from lower latitudes.

The faunal evidence indicates that a major change in oceanographic conditions took place within the time interval represented by the sediment cores. The early Holocene sediments were deposited in a nearshore-estuarine basin dominated by *Elphidium clavatum*. As the sea level rose, shoreline transgressed and the sill connecting Emerald Basin to the continental slope became sufficiently deep to allow the entrance of slope waters. The onset of this period is represented by the appearance of the lower latitude outer shelf species in the sediment core.

The geochemical data of the Emerald Basin cores do not correlate with paleontological evidence. In spite of the fact that the Emerald Basin was more restricted during the Early Holocene, organic matter and methane were not preserved in amounts greater than at the present. Vilks and Rashid (1976) suggested the the lack of preserved organic matter is caused by high rates of bioturbation at the sediment-water interface and lower rates of sedimentation.

St. Margaret's Bay is one of the largest bays along the coast of Nova Scotia. The Bay contains a small basin with a maximum depth of 90 m and a 50-m sill. Sand, gravel and boulders are found in the nearshore of the open coastline and mud rich in organic ooze in protected bays and the central basin (Bartlett, 1964). Methane concentrations are relatively high throughout a sediment column of eight metres (core 104) collected in the central basin. In the bottom interval these concentrations increase together with larger amounts of chlorophyll-a (Fig. 4).

The species of foraminifera in core 104 are similar to the Gulf of St Lawrence and Labrador Shelf faunas but not to the Bay of Fundy and surface sediments in the Emerald Basin of the Scotian Shelf. The faunal content does not change through the length of the core, indicating stable oceanographic conditions since the early Holocene marine transgression. A radiocarbon date at 580 cm is 5660 years BP also indicating a late Holocene age of the sediments.

The Grand Manan Basin is a depression at the entrance of the Bay of Fundy. The maximum depth of the basin is 230 m with a sill depth of 160 m (Fig. 5). Most of the Grand Manan Basin is underlain by glacial till, however, thin deposits of silt and clay are present in the northeast section of the Basin and thickening towards the coast of New Brunswick (Fader *et al.*, 1976).

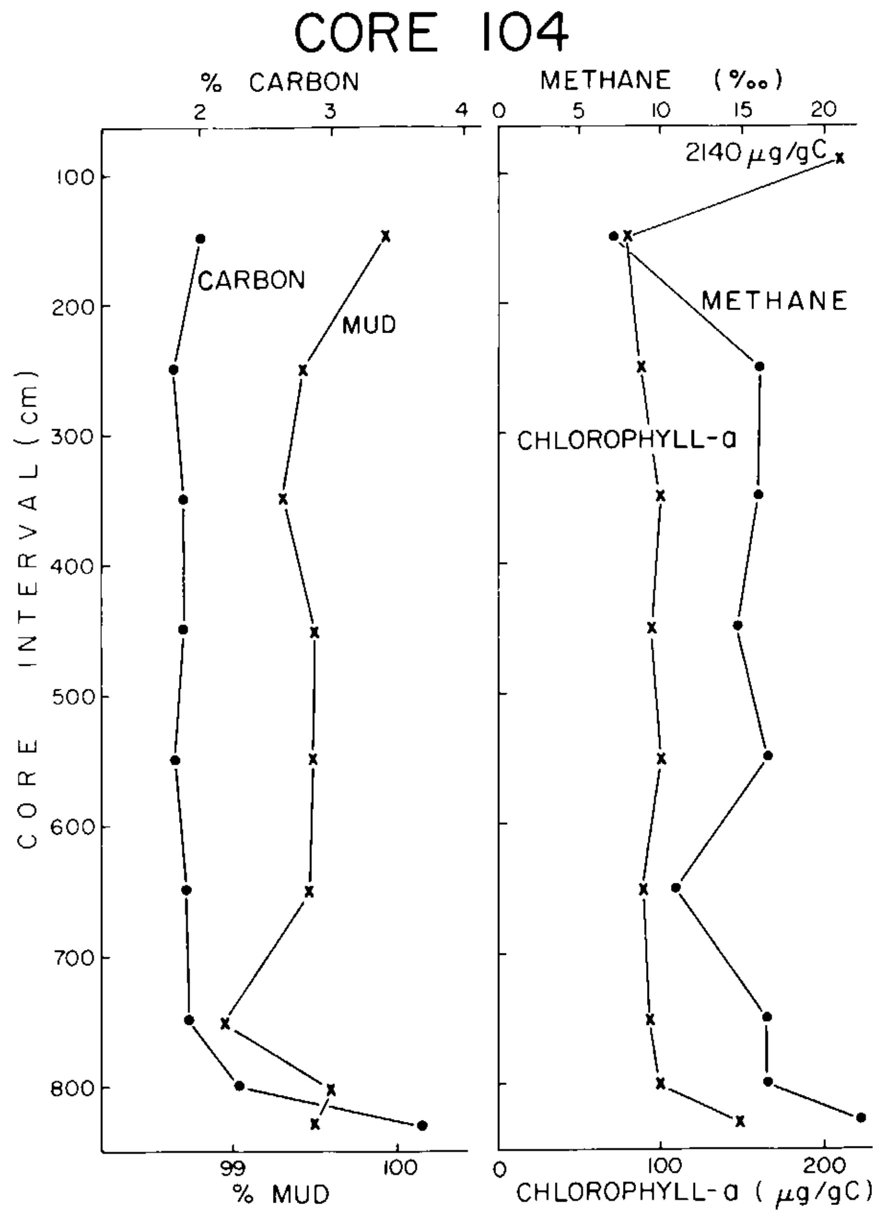

Figure 4
Organic carbon, per cent mud, methane and chlorophyll-a in the sediments of St Margaret's Bay.

The three cores taken from the Grand Manan Basin contain organic carbon less than one per cent which is low for basin sediments (Fig. 6). The per cent of mud and methane are high in cores 128 and 125, but in core 126 methane was found only in background values and the layers of mud are sandwiched between coarser sediments.

The assemblages of foraminifera found in these cores change from the surface to bottom layers. For example, the surface of core 126 contains 22 species, dominated by *Islandiella teretis* which is normally found offshore. The species diversity is 2.19, indicating optimum conditions for foraminiferal growth. At 100 cm the species number is seven, the diversity is 0.86 due to the dominance of the two nearshore species *I. islandica* and *E. clavatum*. At the core level of 200 cm only 22 specimens were present and at 250 cm the sediments were barren of foraminifera.

The core represents a time interval sufficiently long to register major changes in the environment. At the surface the fauna represents the existing conditions that are characteristic of a continental shelf with some slope water influence. The restricted fauna below the surface represent a time interval when the offshore continental slope waters did not enter the area and bottom salinities were lower. The sediments barren of foraminifera were deposited during the period of glaciation.

The sampling locality of core 128 is closer to the central part of the Grand Manan Basin, therefore, sedimentation rates are greater. The relatively short time interval represented by core 128 is demonstrated by the practically unchanging fauna throughout the core. Although the nearshor *E. clavatum* is dominant, the faunal diversity is high in all the intervals sampled.

Summary and Conclusions

Combined micropaleontological and geochemical information was used to study favorable paleoenvironments for the genesis and trapping of methane in the sediments of five small basins. These basins are located on a glacially modified continental shelf and receive fine sediments mainly through the reworking of glacial debris on the nearby banks. Oceanographic features are characterized by a seasonal mixing of the water column as a result of surface cooling.

The exchange rates of water in the basins are sufficient to maintain oxygen levels close to saturation. As a result, oxidized sediments are present at the sediment-water interface and fermentation of organic matter can take place only in the anoxic sediments below this surface layer.

Four of the five basins investigated contained interstitial methane in concentrations up to 22,000 ppm. The presence of methane is associated with fine sediments, but the relationship between methane concentrations and other parameters studied is not simple. In deposits where faunal changes were not recorded and sedimentation was relatively rapid, such as Chaleur Trough and St. Margaret's Bay, there is a positive correlation between the methane and chlorophyll. These sediments contain chlorophyll in concentrations more than 80μg/g carbon and methane more than 7,000 ppm. The faunal and geochemical evidence suggests that, except for losses to the surface, most of the methane recovered from the Chaleur Trough and St. Margaret's Bay has remained *in situ*.

Although the source of methane is organic matter, in our cores the relationship between the carbon and methane is complex. In St. Margaret's Bay organic carbon was found in greater amounts towards the bottom of the core, concurrently with higher concentrations of methane (Keen and Piper, 1976, reported the opposite relationship in a core taken from the same area). In the Grand Manan Basin, the organic carbon occurs in relatively low values, although the methane concentrations are comparable to the St. Margaret's Bay. In the Cartwright Saddle on the Labrador Shelf considerably more methane was found in the deeper layers of the core

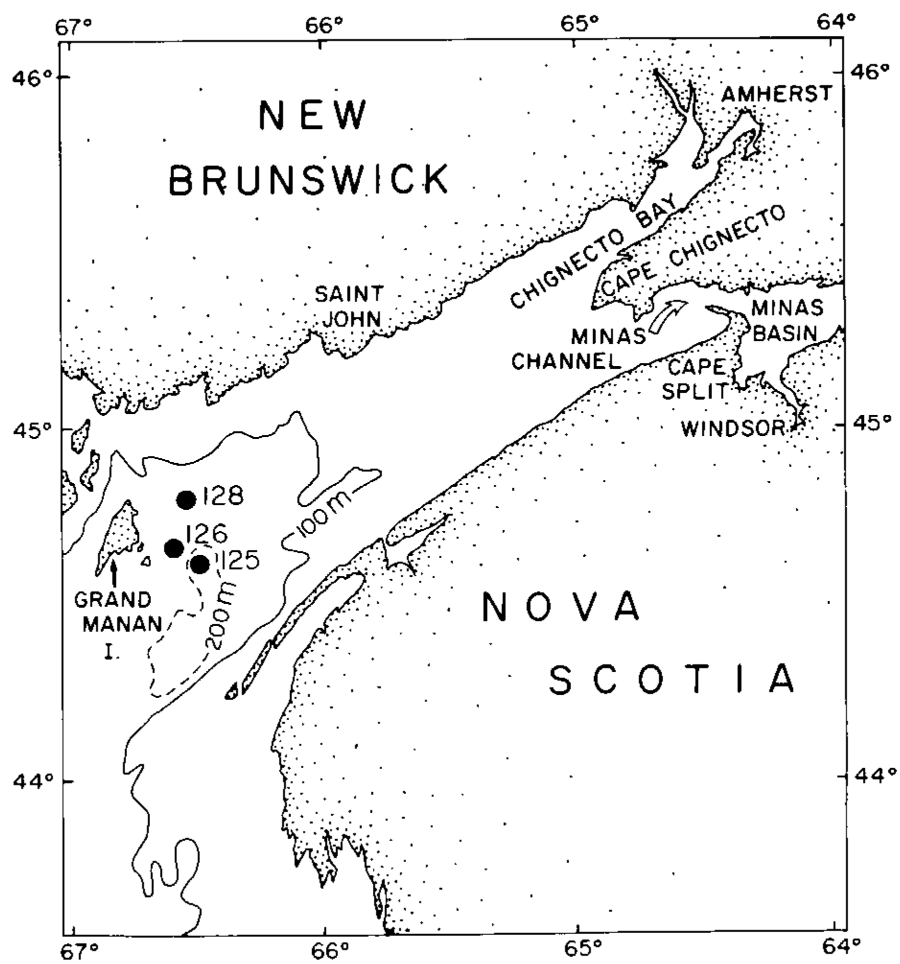

Figure 5
Bay of Fundy showing coring sites in the Grand Manan Basin.

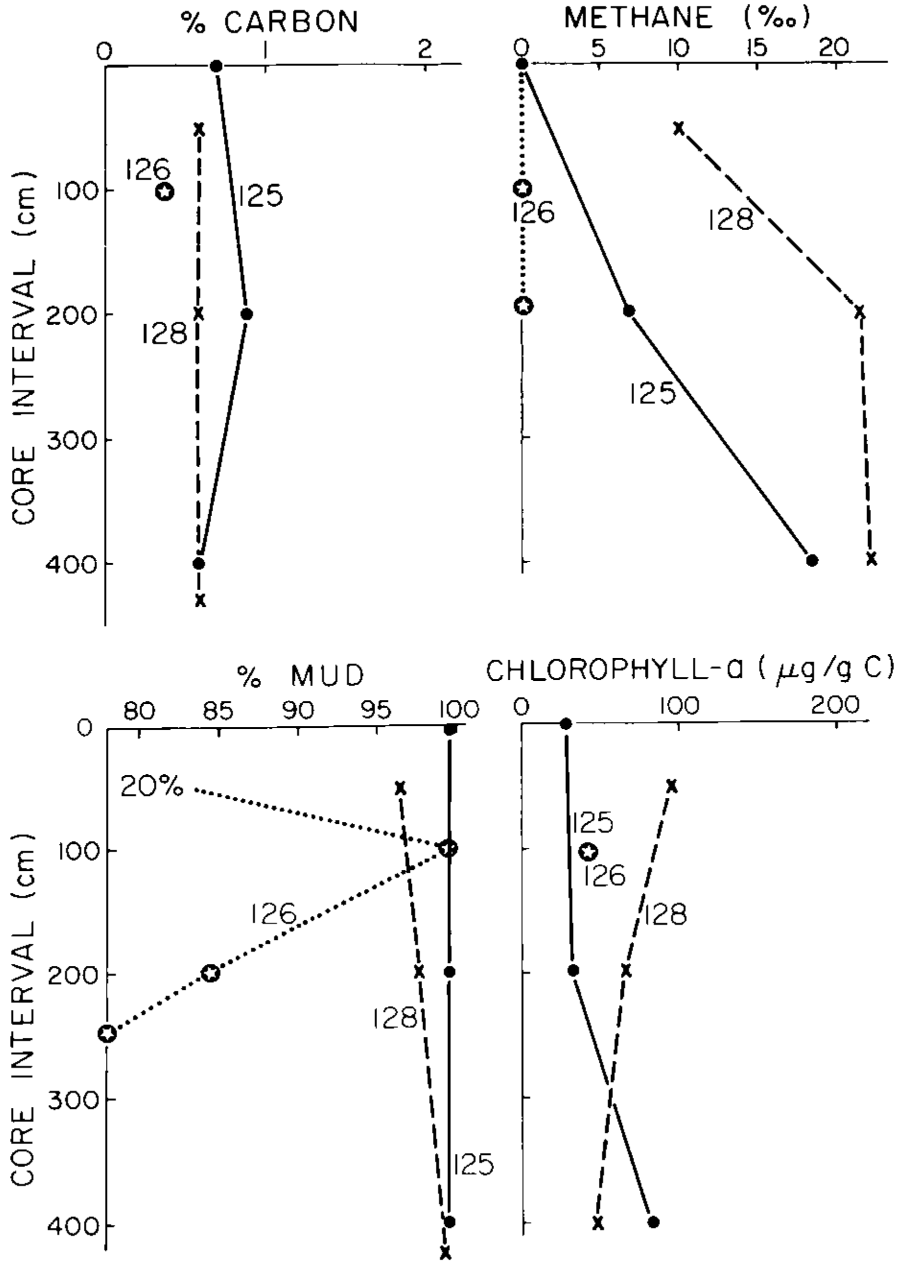

Figure 6
Organic carbon, percent mud, methane and chlorophll-a in the sediments of Grand Manan Basin

with the organic carbon remaining constant at around 0.5 per cent.

Foraminiferal assemblages collected from methane-rich sediments are dominated by nearshore-inner shelf species. Methane was absent from the sediments of Grand Manan Basin, Cartwright Saddle and Emerald Basin in cores where the fauna changed to outer shelf assemblages in the surface layers. The reason for the trend could be twofold: firstly, the change in fauna indicates periods of relatively slow sedimentation with possible discontinuities allowing seepage of gases. Secondly, the outer shelf benthos are normally more diverse than the nearshore benthic communities. The biologic activity at the sediment-water interface is therefore greater with a nearly complete utilization of organic matter by the zoobenthos. In addition, the activity of the bioturbating benthos irrigates the sediments with oxygenated water thus preventing the development of anoxic environment. Under these conditions the chances of the preservation of organic matter and methane in the sediment are diminished.

Anoxic environment is necessary for the genesis of methane. Our studies suggest that such conditions can develop in sediments of a subarctic continental shelf as a result of rapid rates of sedimentation of fine clastics. The migration of interstitial water is extremely slow in clays, therefore, high concentrations of dissolved methane can accumulate.

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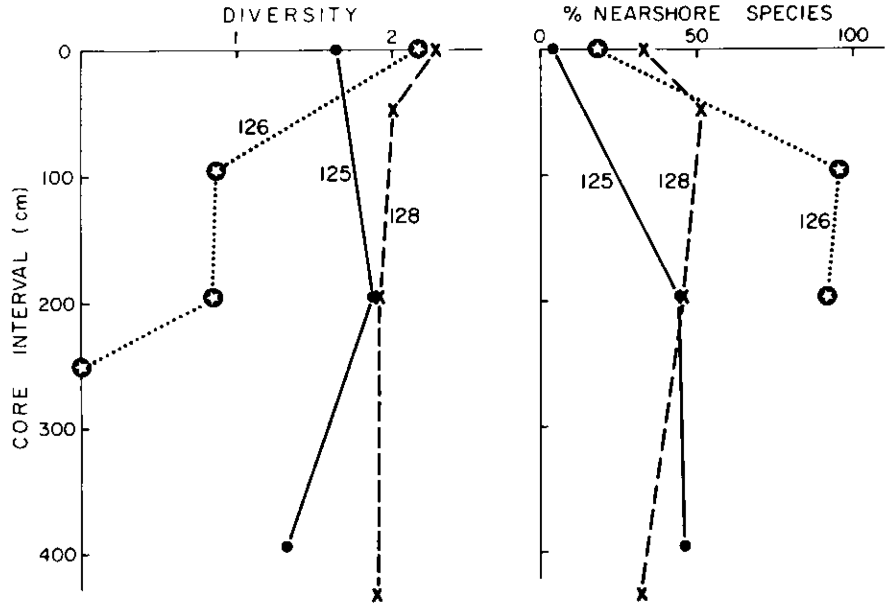

Figure 7
Diversity of foraminifera and the percent of nearshore species in sediment cores from Grand Manan Basin. Diversity = $-\sum_{i=1}^{S} P_i \ln P_i$ *where p is the proportion of the ith species in the sample and S is total number number of species in the sample.*