

Regional Review of the Nova Scotian Outer Margin

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REGIONAL REVIEW OF THE NOVA SCOTIAN OUTER MARGIN

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INTRODUCTION

This paper reviews the literature pertaining to the marine geology of the outer continental margin off Nova Scotia, eastern Canada. It was carried out as part of a more detailed study of the late Quaternary stratigraphy and sedimentation of the area (Stow 1975, 1976, 1977a, b), and is now written to include some of the results of that work. The final section is the author's interpretation of the depositional history of the outer margin (Stow 1977a and in preparation). Several studies are still in progress in the region. It is hoped that the present synthesis will be of use to these, and also serve to summarize some of the more interesting features of outer margin deposition.

GEOLOGY OF EASTERN CANADA

Mainland eastern Canada bordering the West Atlantic Ocean lies within the Appalachian orogen (Fig. 1). It has been affected by a series of orogenic disturbances of varying intensities and ages in different parts (Neale *et al* 1961, Poole 1967); and now comprises areas of highlands, uplands and lowlands rarely exceeding 600 m in elevation. The rocks are mostly Palaeozoic in age with metamorphosed Precambrian outcrops in Cape Breton, southern New Brunswick and Newfoundland representing crystalline basement (Williams *et al* 1972, 1974). Flysch sequences are common, comprising quartz metawacke, slate, graywacke and argillite; and are followed by Carboniferous to Triassic molasse - carbonates, red beds, some coal measures and diabase sills and dykes; and the Devonian granite uplands of Nova Scotia. The extension of this geology offshore has been reviewed by Sheridan and Drake (1968), Williams *et al* (1974) and King *et al* (1975).

Other regions of eastern Canada which are of importance as source areas for the outer continental margin sediments are the St. Lawrence lowlands (Loring and Nota 1973) and the Laurentian region of the Grenvillian province (Wynne-Edwards 1972). The former comprises low-lying (mostly below 200 m), flat-bedded, Palaeozoic sediments (shales, limestones, and dolomites) and minor alkali igneous rocks. The latter is a rocky, stream-dissected plateau of about 600 m elevation and more than 1000 m in places. It is made up largely of old, hard, Precambrian crystalline rocks including granites, granodiorites, anorthosites, gneisses and schists, overlapped by thin Ordovician limestones and shales.

QUATERNARY HISTORY AND SEA-LEVEL CHANGES

There have been several extensive studies of the Quaternary of North America (Flint 1951, Wright

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Glasgow, Scotland.

and Frey 1965), and of late Quaternary glaciations in eastern Canada (Prest and Grant 1969, McDonald 1971, Dreimanis 1971, Grant 1975, Tucker 1976). The chronology of events is not entirely clear as much of the record on land is patchy and incomplete.

It appears that the Wisconsin glaciation was less severe than earlier ones, and local ice caps were developed over eastern Quebec, New Brunswick, Nova Scotia (Grant 1971, Grant and Prest 1975), and Newfoundland (Jenness 1960, Brookes 1970). Ice-flow centres on the present continental shelf have been proposed by Grant (1971) and Gravenor (1974). The effect of these various ice centres was to divert the Laurentide ice through the Laurentian Channel to the Atlantic Ocean. A major ice stream was proposed for this area by Hughes *et al* (1977).

King (1969) and King *et al*. (1972) have noted a submarine moraine complex on the inner Scotian Shelf, which they believe marks the terminal position of the late Wisconsin ice sheet. Relict iceberg furrows in the Laurentian Channel are direct evidence for an ice front and berg-carving, probably in Wisconsin times (King 1976).

Sea-level changes on the eastern Canadian continental margin have been complex. The pattern of ice retreat in the Maritimes has been shown to relate to a rising sea level from about 18,000 to 11,000 years B.P. (Prest and Grant 1969, Prest 1970). Wightman (1976) discussed evidence of emergence in northern Nova Scotia and surrounding areas. He showed that emergence decreased in a southeast direction across the Province. Specific loci of glacial rebound at St. John and Chaleur Bay, New Brunswick, were related to nearby outflows of Laurentide ice, and significant rebound in northern Newfoundland was thought due to the proximity of Labrador ice. Submergence in the eastern Prince Edward Island-Cape Breton region, he interpreted as a result of ice thinning adjacent to deep ice in the Gulf of St. Lawrence Channel. The various problems related to isostatic rebound after glacial loading and crustal warping are discussed by Walcott (1972) Farrel and Clark (1976) and Beaumont (1977).

It seems clear from evidence of submerged terraces on the outer Scotian Shelf that the maximum low stand of sea level in this area was about 120-m between 19,000 and 15,000 years B.P. (Shepard 1963, Stanley *et al* 1968, King 1970). The existence of salt marshes and freshwater peat on Georges Bank suggest that this was a tree-covered island at about 11,000 years B.P. Vilks and Rashid (1976) infer marginal marine to estuarine conditions for Emerald Basin at about 15,000 years B.P. from foraminiferal and geochemical evidence. Much of the Scotian Shelf, then, was exposed to sub-aerial influences through the last glacial period. Earlier

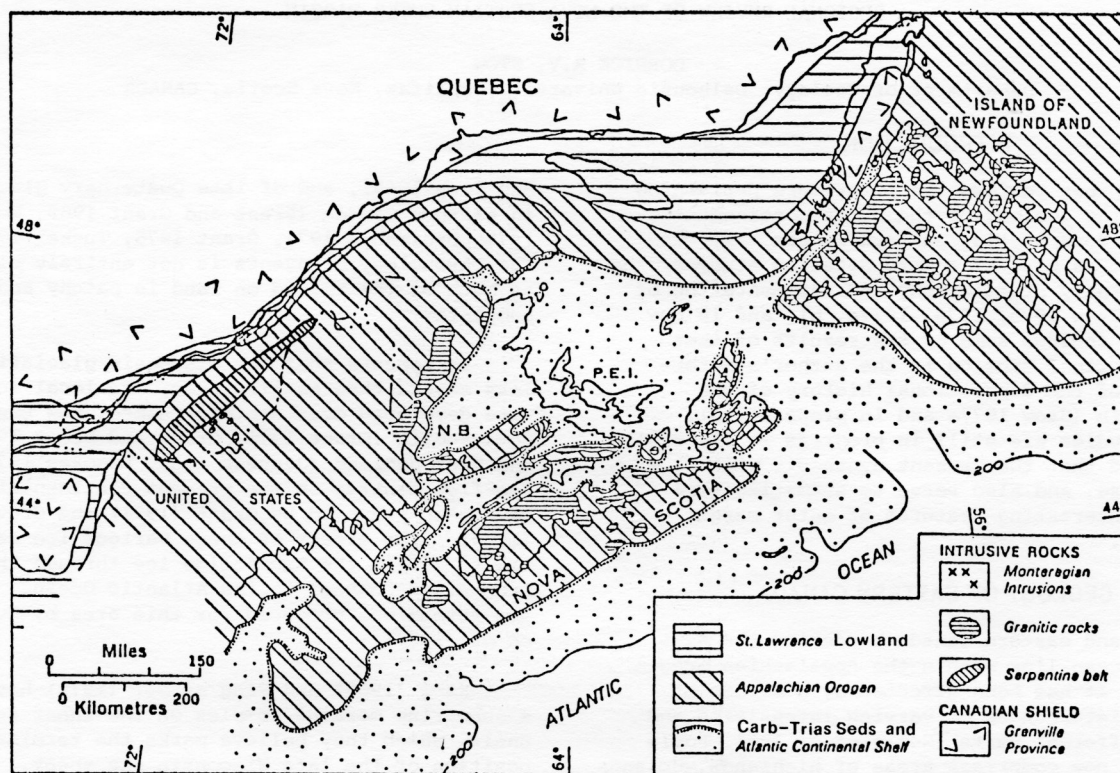


FIG. 1 Main geological elements of eastern Canada (after Rose *et al.*, 1970).

stands of sea level are more difficult to interpret (Emery and Uchupi 1972).

MORPHOLOGY OF THE CONTINENTAL MARGIN

The Scotian Shelf (Fig. 2) southeast of Nova Scotia, extends for 700 km from the North East Channel to the Laurentian Channel; it is 100 km wide in the southwest and 250 km wide off Cape Breton. Stanley and Cok (1968) described an inner shelf with rough topography, a central shelf with an irregular pattern of basins, and a broad, flat outer shelf. The shelf is deeper than 375 m in Emerald and La Have Basins and becomes emergent as Sable Island some 200 km from land. The shelf break occurs at about 100 m off Sable Island and Banquereau Banks, 180 m to the south of Emerald and La Have Basins and 140 m in the south west. It is cut by several submarine canyons, the largest being the Gulley (Marlowe 1967, 1969).

The Laurentian Channel separating the Scotian Shelf from the Grand Banks connects the Gulf of St. Lawrence with the Atlantic Ocean. It extends for 400 km from the Cabot Strait to the shelf break, with an average width of 100 km and depth of 400 m. Its origin is related to the regional structure, and has been shaped by early fluvial and later glacial processes (King and MacLean 1970, Loring and Nota 1973); and has probably served as a major drainage route since at least the early Tertiary.

The Grand Banks shelf south of Newfoundland is also divisible into three parts (Slatt 1976). The

inner shelf has a series of elongate, southwesterly trending troughs up to 400 m deep, including the Avalon Channel and the Haddock and Halibut Channels which extend to the shelf break. The shoals and basins of the central shelf are mostly between 80 and 300 m deep, and the broad, flat outer shelf lies at 50 to 100 m. The shelf break occurs at 100 to 120 m and is indented by numerous submarine canyons mostly on the southeast.

A detailed morphological map of the outer margin (Fig. 3) has been compiled (Stow 1977a) from existing charts of the area (Canadian Hydrographic Services 1970, Edgar and Piper, in press, Webb, pers. comm), and from bathymetric data gathered on Bedford Institute of Oceanography cruises over the past few years. The slope gradients are generally steep (4° to 5°), and the Slope-Rise boundary occurs at between 1,200 and 1,700 m. The Rise may be divided into upper, middle and lower portions with gradients of 2° , 0.5° to 1.0° , and 0.25° to 0.5° respectively. The combined width of the Slope and Rise is about 350 km, after which the Rise gradually merges with the Sohmm Abyssal Plain (Heezen *et al* 1959).

The Slope and Rise south of the Scotian Shelf and southwest of the Grand Banks are dissected by numerous submarine canyons. A few of these indent the shelf break, but many head in waters greater than 400 m in depth, and mostly die out on the rise. The southwest part of this margin has gentler gradients and is less dissected by canyons. Stanley *et al* (1972) suggested that greater sediment supply to the Sable Island Bank led to more slumping in this area, giving rise to more canyons. Piper (1975)

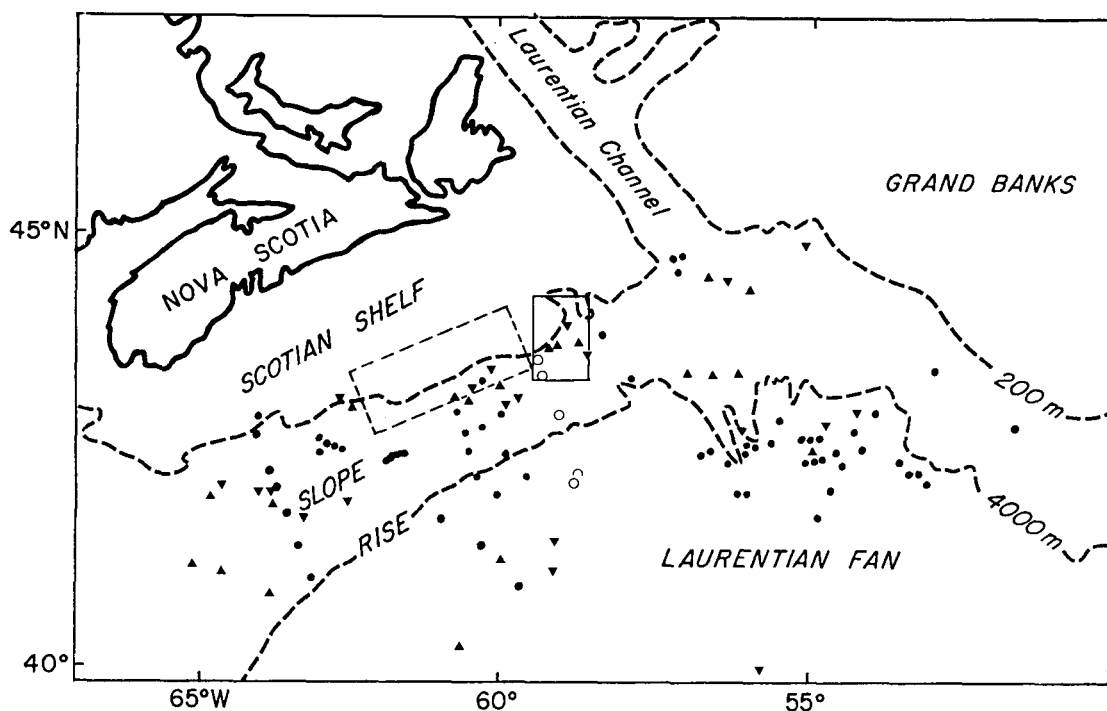


FIG. 2 Map of outer Scotian margin showing core locations. Cores at Dalhousie (black circles); at Lamont-Doherty Geological Observatory (black triangles); and reported in Stanley *et al.*, 1972 (open circles). Areas of special study with dense sediment sampling by Silverberg, 1965 (dashed rectangle); and by Marlow, 1967 (solid rectangle).

believed that many of these canyons were kept open by rip-current supply of littoral sands to the canyon heads during low stands of sea level.

The Laurentian Fan extends 100 km further seaward than the adjacent rise (Edgar and Piper, in press). The Slope and upper Fan have an irregular, slump-scarred surface. There are many small tributary channels and several larger valleys between slump blocks, with irregular cross sections. On the lower Fan these pass into three meandering valleys with terraced floors and prominent levees. The extreme asymmetry of this channel-levee system is probably related to the deflection of turbidity currents by Coriolis force and the Western Boundary Undercurrent.

The elongate or pointed shape of the Laurentian Fan is different from the more common, smaller, arcuate, deep-sea fans, but appears similar to several of the larger ones such as the Bengal Fan (Curry and Moore 1971), the Indus cone (Jipa and Kidd 1974) and the Mississippi fan (Huang and Goodell 1970). The fan shape might be a function of the amount and type of sediment supplied (Piper 1975).

Large quantities of clayey sediment will be transported further seawards than sandy material; large, fine-grained turbidity currents are also more likely to overflow their channels and construct high levees, which then effectively funnel coarser material to the base of the slope and beyond. Recent work by Uchupi (pers. comm., 1977) suggests that the entire Fan makes a left hook between 43° and 42°

North, presumably due to the highly asymmetrical levee development.

GEOPHYSICAL SETTING AND GEOLOGICAL HISTORY

Much geophysical data is available from the eastern North American continental margin. Keen *et al.* (1975) used the results of gravity, magnetic, reflection and refraction data across the Scotian slope to produce a model of ocean-continent transition for this region. They attributed gravity and magnetic slope anomalies to the "edge effect", as well as to possible intrusion of ultrabasic material at the start of oceanic rifting. They also concluded that the basement ridge complex, which was interpreted by Emery *et al.* (1970) as a relict structure of the original rift, may have arisen by migration of sediments from beneath the shelf to the foot of the slope. This process was probably not completed until Tertiary or Quaternary times. However, Sherwin (1973) and King (1975) interpreted ridge complex as salt diapirs from Lower Jurassic evaporites.

Opening of the Atlantic is thought to have commenced in the Lower Jurassic (Pitman and Talwani 1972), so that considerable time has been available for the development of a thick marginal sediment sequence. Parsons (1975) identified 10 to 12 km of sediment, with the major Mesozoic depocentre south of Sable Island and the Cenozoic depocentre over the Laurentian Fan area.

King (1975) discussed the geosynclinal development of the region and interpreted the margin as a miogeoclinal-eugeoclinal couplet. The Mesozoic and

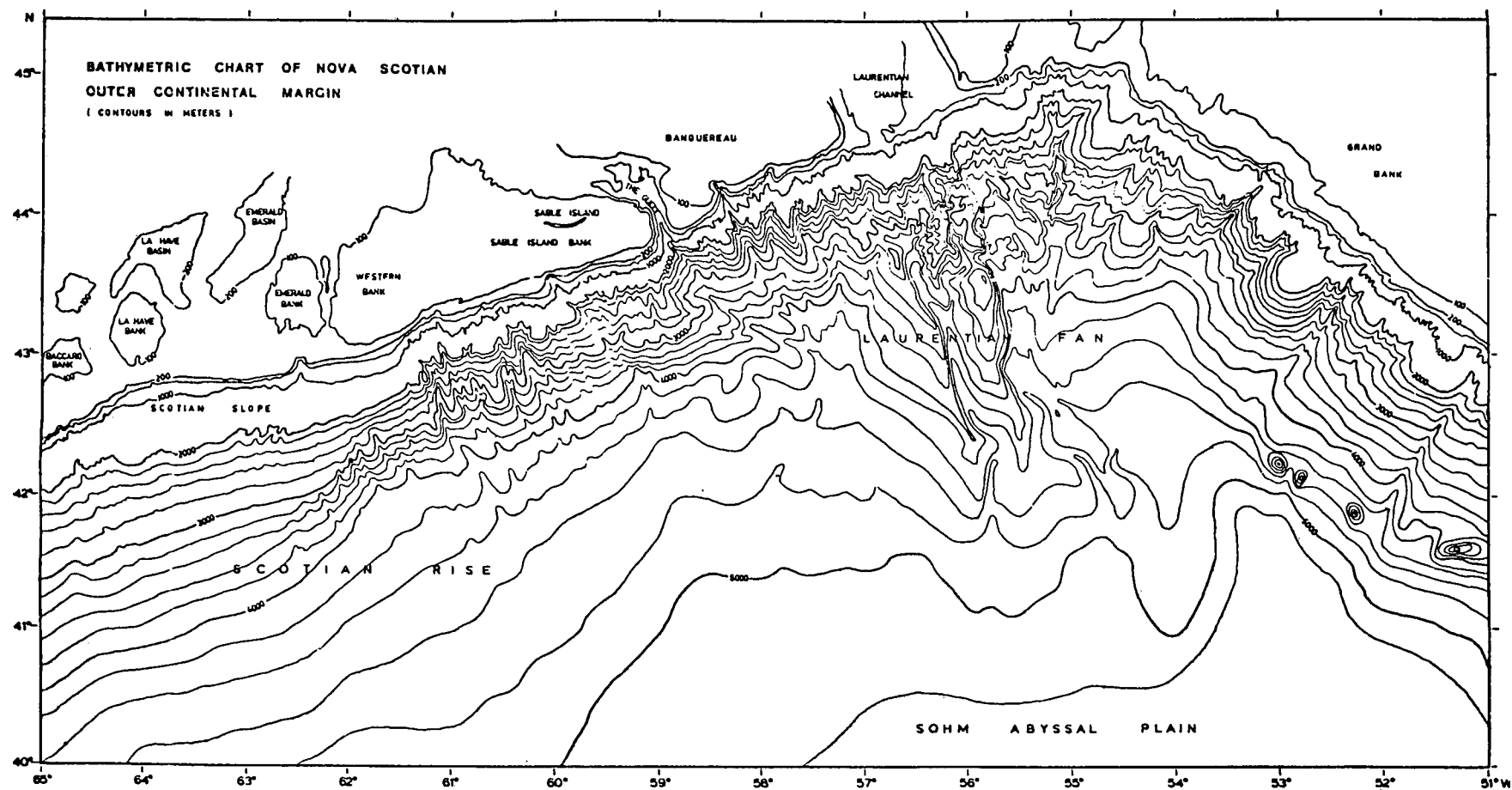


FIG. 3 Bathymetric chart of Nova Scotian outer continental margin (from Stow 1977a).

Cenozoic sediments of the central and outer shelf (King and MacLean 1975, 1976) form the miogeocline; the modern and former slopes are a transition zone, and the huge prism of seaward-dipping, interbedded hemipelagites and turbidites of the Laurentian Fan and adjacent rises (Emery *et al* 1970) form the eugeocline.

McIver (1972) and Jansa and Wade (1975a, b) presented an interpretation of the geological history of the Scotian Basin. Continental red beds and evaporites were deposited during Triassic and early Jurassic times, while the remainder of the Jurassic had normal marine sedimentation. Cretaceous tectonic activity provided a strong influx of clastic sediments in deltaic and marine environments across a tilting shelf. Strong progradation due to continental tilting and eustatic sea-level lowering in the Cenozoic led to the building up of the present continental shelf. They believed that sedimentation was relatively continuous from Triassic through Pliocene times. However, four regional unconformities are recognized in the Scotian Shelf and Grand Banks sequences (King *et al*, 1974, King and MacLean 1975), and Parsons (1975) noted palaeocanyons and channels carved into an Eocene paleoslope, which may indicate a period when erosional processes have dominated over depositional.

King and Young (1977) have identified a series of paleoslopes of Cenozoic-Mesozoic age in seismic reflection profiles across the eastern Canadian continental margin. On the western Scotian Shelf, adjacent to the La Have Platform, the paleoslopes are mainly destructional. On the eastern Scotian Shelf and Grand Banks destructional paleoslopes are widely separated in the stratigraphic section by thick areas of constructional slope development.

Numerous slumps, faults and slides have been recognized on the Scotian margin by several authors (Heezen and Drake 1964, Emery *et al* 1970, Heezen and Hollister 1971, King and MacLean 1975). Emery *et al* (1970) also recognized large slides in the Rise sequence which, however, are interpreted as Fan channels by Moore and Curray (1974). Major slump masses probably caused the instantaneous cable breaks observed within a distance of 100 km from the epicentre of the 1929 Grand Banks Earthquake. Channelized turbidity currents from these are presumed responsible for the orderly sequence of cable breaks to the south (Heezen and Ewing 1952, Keunen 1952).

SEISMICITY

Seismicity in this part of eastern Canada has been extremely limited over the last few hundred years (Smith 1962, 1966). Five earthquakes of magnitude 4 or greater (and five aftershocks of the 1929 earthquake) have occurred along the seaward extension of the Glooscap (Cobequid-Chadabucto) fault which crosses the southern end of the Laurentian Channel. A few other earthquakes have been reported from Nova Scotia, Cape Breton, Newfoundland and the Scotian Shelf and Slope, but their magnitude and (or) position make it unlikely that these would have led to significant slumping on the upper Slope.

Woolard (1969) suggested that the apparent trends of earthquakes associated with the Cobequid-

Chedabucto fault, the Appalachian Mountain belt, and the St. Lawrence river were influenced by crustal rebound after glacial loading. However, Sbar and Sykes (1973) recognized earthquake trends along former oceanic fracture zones related to the early opening of the North Atlantic. They believed that the easterly to northeasterly trending, horizontal compressive stress causing earthquakes in eastern North America is generated by the same mechanism that drives the lithospheric plates.

PHYSICAL OCEANOGRAPHY

Surface Circulation

This area of the western North Atlantic is characterized by a complex system of currents (Sverdrup *et al* 1942). The three main surface water masses are: the cold, southerly flowing Labrador current, the Slope water gyre over the Laurentian Fan and Scotian Slope, and the warm Gulf stream flowing towards the north and east along the North American continental margin (Fig. 4a).

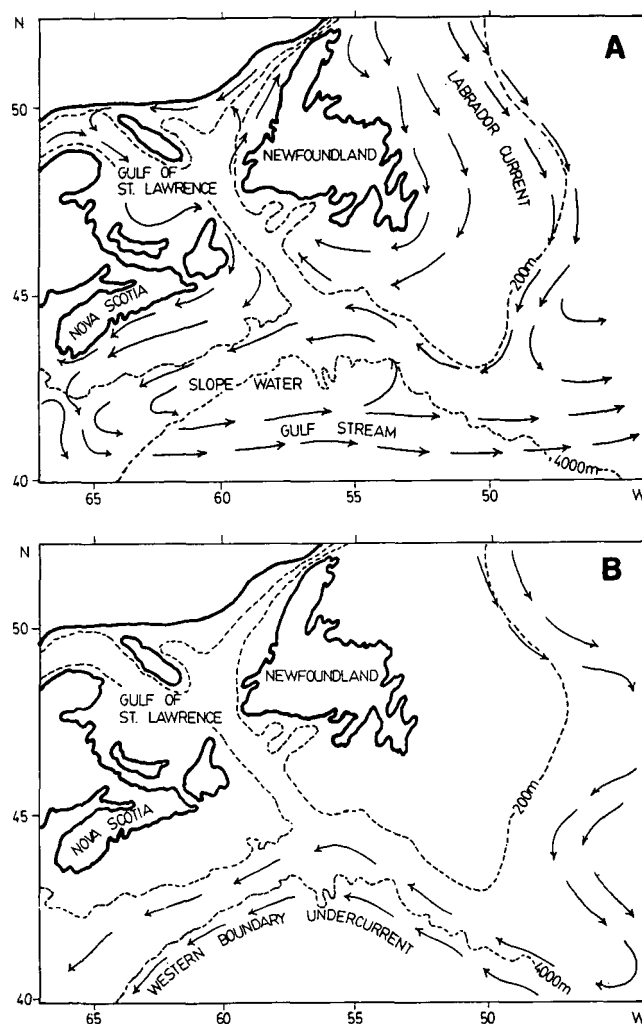


FIG. 4 Surface (A) and deep-water (B) circulation off Nova Scotia.

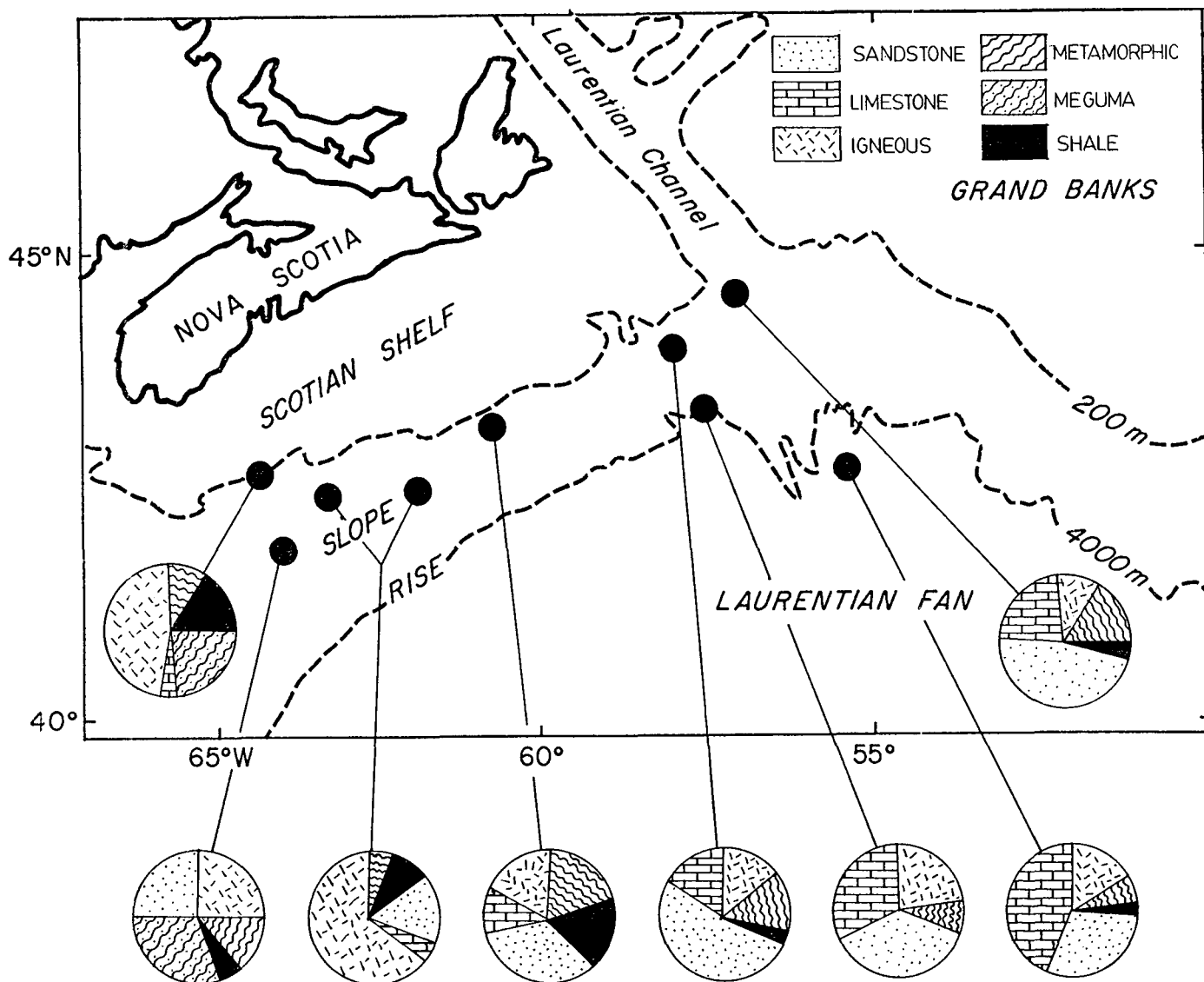


FIG. 5 Composition and distribution of gravel clasts on the outer Scotian margin.

The Gulf Stream has a variable surface velocity of up to 300 cm/s, and appears to reach the ocean floor in parts (Fuglister 1963, Stommel 1965). It meanders widely south of Nova Scotia with amplitudes of about 60 km and wavelengths of 350 km (Fuglister and Worthington 1951). These large meanders move and change shape with a period of about one month (Fuglister 1963), often becoming entirely detached from the main flow. Ruddiman (1968) has been able to delimit the late Holocene meander belt by percentage abundance contours of certain warm water planktonic foraminifera found in the surface sediments.

The Gulf Stream meets the Labrador current near the Tail of the Grand Banks where it is forced southwards and may be intruded by a tongue-like body of cold water reaching as far south as 41°N (Hachey 1961). A weakening of the Labrador current may cause retreat of the cold water northwards and spreading of Gulf Stream water onto the Grand Banks. The Labrador current splits into two parts off eastern Newfoundland, one flowing over the Grand

Banks especially through the Avalon Channel, and the other along the continental slope.

The Slope-water gyre is a continuous band of water from Cape Hatteras to the Grand Banks, lying between the shelf break and the Gulf Stream. It is a mixed water mass with contributions from coastal water, the Labrador current and the Gulf Stream. The Slope water is known to cascade downslope to levels of equal density during times of diminished river flow and winter cooling of the Shelf water contribution. These cold water "cascades" probably contribute to the high suspended sediment content of the nepheloid layer on the Slope and upper Rise (Emery and Uchupi 1972, Eittrheim and Ewing 1972, Eittrheim *et al* 1977).

Deep Circulation

Several subsurface water masses are recognized in this part of the western North Atlantic (Emery and Uchupi 1972):

(i) The Mediterranean water mass lies directly below the surface Western North Atlantic water. It is of limited extent and small geological effect in this area.

(ii) The North Atlantic Deep water comprises 70% of all deep water below 4°C, but only reaches the bottom in the vicinity of the Mid-Atlantic Ridge. It is a mixture of Arctic, Antarctic and Mediterranean waters.

(iii) Norwegian Sea overflow water lies beneath the North Atlantic Deep water and is confined to the western margin of the ocean by the Coriolis effect of earth rotation. It originates at the surface in arctic and subarctic areas of extreme cooling.

(iv) The Antarctic Bottom water is in contact with the bottom over a large area of the western North Atlantic to the south of the Laurentian Fan. Its movement, however, is sluggish and its geological effects probably slight.

During its southward movement the Norwegian Sea Overflow water mixes with the overlying and underlying water masses to form the Western Boundary Undercurrent (Fig. 4b). This deep geostrophic current is required by Stommel's (1957) theoretical model of deep circulation. Details of potential temperature, salinity and density are given by Lynn and Reid (1968). Direct current measurements indicate a southwestward flow at depths between 2 and 4 km (Swallow and Worthington 1961, Rowe and Menzies 1968). The position, direction and speed of the flow is variable but velocities up to 25 cm/s have been reported. Heezen and Hollister (1971) and Hollister and Heezen (1972) present much evidence for the widespread geological effects of the Western Boundary Undercurrent.

SEDIMENTS AND PROCESSES

Sediment Sources

The location of such a large sediment mass directly off the end of the Laurentian Channel suggests that much of the material making up the Laurentian Fan passed through the Cabot Strait and across the broad continental shelf. The St. Lawrence River, with a drainage area of about $1.3 \times 10^6 \text{ km}^2$, is at present, the chief contributor of sediment and fresh water to the Gulf of St. Lawrence (Loring and Nota 1973).

Although water discharge into the Gulf is around $300 \text{ km}^3/\text{year}$ the suspended sediment load is low, about 3×10^6 metric tons/year (Strakov 1967). This low sediment load to water discharge ratio is caused by two factors: the hard, resistant nature and low relief of the Canadian Shield which makes up most of the St. Lawrence river drainage basin, and the sediment trap provided by the Great Lakes. Sundby (1974), in discussing the sediment budget of the Gulf of St. Lawrence, concluded that most of the sediment load entering the Gulf was deposited there, and only very little escaped to the ocean via the Cabot Strait.

During the last glacial period, however, sediment supply to the deep outer margin was much

greater (Pratt, 1968). Ice probably filled the Laurentian Channel to the shelf edge during glacial maxima (Prest and Grant 1969), and a floating ice shelf may have developed over the slope and upper fan. Grant (1976) proposed that the late Wisconsin ice limits were within the Gulf of St. Lawrence. King (1976) noted iceberg scour marks which he believed must have been caused by calving from an ice front within the Laurentian Channel or Gulf of St. Lawrence.

The deeply incised areas of the Scotian Shelf were also related to fluvio-glacial drainage and ice transport (Stanley and Cok 1968, Stanley *et al* 1968, Cok 1970), increasing sediment supply to the Scotian Slope and Rise. There are three depressions crossing the Shelf where major ice tongues were probably situated (the Laurentian Channel, the Gully Trough and the Emerald-La Have Basin area). The distribution and composition of ice-rafted clasts and channel gravels (Fig. 5) supports this interpretation (Stow 1977a). The Gulf of St. Lawrence red beds (sandstones and siltstones) and Carboniferous and Ordovician limestones have acted as the dominant source for the sediments on the upper slope above the Fan and, by resedimentation, for the channel gravels. The minor igneous and metamorphic components of these deposits derive from either Quebec or Newfoundland crystalline rocks. Iceberg calving from a Laurentian Channel glacier and transport towards the southwest has also occurred. There has been further input of material (especially granites and other crystalline rocks) from a glacier situated in the Gully Trough or Canyon. A more major input of material to the western parts of the Scotian margin has come from floating ice tongues over the deeper parts of the Shelf south of Emerald and La Have Basins. These have contributed Meguma-type quartzite and shale as well as Nova Scotian granites and probable Windsor limestones. The Gulf of St. Lawrence sandstones are more or less obscured over the western margin.

The main glacial sediment of the Wisconsin period was deposited along the upper Slope under the influence of southwestward flowing currents. Some bergs moved farther offshore, and other material was locally redistributed downslope by mass gravity flows.

Sand and clay mineralogy has also been used to define source and dispersal patterns for the outer margin sediments. There have been numerous onshore studies of heavy minerals from eastern Canada (Dreimanis *et al* 1957, McLeod 1959, Nielsen 1976), coastal and shelf (Nolan 1963, Conolly *et al* 1967, Loring and Nota 1969, 1973, Cok 1970, Drapeau 1971). Regional syntheses for the margin include those of Neal (1964), Hubert and Neal (1967), Hollister (1967), Emery and Uchupi (1972) and Stanley *et al* (1972). Three assemblages can thus be identified as possible sources: the Scotian Shelf - high in opaques and accessory resistates (zircon, tourmaline, rutile); the Gulf of St. Lawrence and Laurentian Channel - high in metastable minerals (hornblendes and pyroxenes) and accessory apatite; and the Grand Banks Shelf - high in opaques and accessory ultrastable minerals (zircon, sphene) and epidote.

The outer margin heavy mineral provinces identified by Stow (1977a) show close correspondence with the source area assemblages (Fig. 6), and suggest that the dominant dispersal of sands and silts has been perpendicular to the shelf break.

There is also fairly good control in the literature on the clay mineralogy of surrounding regions. Terrestrial sources in eastern Canada have been examined by Allen and Johns (1960), Forman and Bryden (1965), Dean (1975) and Piper and Slatt (1977). Loring and Nota (1973) present some data for the Gulf of St. Lawrence, Connolly *et al* (1967) for the Laurentian Channel and Alam (1976) for the western Grand Banks margin. These studies are summarized by Stanley *et al* (1972) and Piper and Slatt (1977) who identified the following sources for the different clay minerals:

- Illite and chlorite are common high latitude minerals, and common throughout eastern Canada. The Grand Banks margin and Newfoundland tills are rich in chlorite.
- Kaolinite may be derived from the lower Carboniferous and Triassic red beds of the Maritimes, or from offshore lower Cretaceous and younger strata.
- Four possible sources have been suggested for the montmorillonite: the Triassic red beds of the Maritime offshore upper Cretaceous and Cenozoic strata; the Gulf Stream (Pastouret *et al* 1975); and the Western Boundary Undercurrent (Zimmerman 1972).

Stow (1977a) found a first order uniformity of the clay mineralogy on the outer margin with respect to illite, chlorite and kaolinite, which suggests a common provenance for these minerals. A secondary distinction between the Laurentian Fan and Scotian Slope and Rise on the basis of kaolinite/chlorite ratios (Fig. 6) is thought to be due to the influence of chlorite-rich, kaolinite-poor tills of Newfoundland or to an unidentified chlorite-rich source in the Gulf of St. Lawrence. Montmorillonite appears in significant amounts only in the olive gray facies (see below), increases offshore and has a high "valley/peak" ratio (Biscaye 1964). These factors tend to favour a northerly source and transport in the Western Boundary Undercurrent.

Sediment Facies

Earlier work on the late Quaternary stratigraphy and sedimentation of the outer Scotian margin has been at the reconnaissance level (Fig. 2). Stanley *et al* (1972) recognized three facies on the Slope and Rise.

On the Slope a brownish-red "pebbly-sandy clayey silt" was probably deposited by downslope mass movement and ice rafting in Wisconsin times. Locally it is covered by a more homogenous olive-gray clayey silt, abundantly bioturbated, which is also the dominant facies on the Rise. Foraminiferal evidence indicates that the Pleistocene-Holocene boundary occurs within this facies, and the change from red to gray sediment is correlated with the rise of sea level above the shelf edge. The third facies,

a thin, discontinuous layer of very fine sand and muddy sand, is the result of "sand spillover" on the upper Slope due to reworking by Holocene bottom currents.

Piper (1975) recognized similar facies in Scotian slope and rise cores with the addition of early Holocene mud turbidites and late Wisconsin thin, turbidite sands with interbedded red muds. He favoured a slump-initiated turbidity current origin for most of the late Wisconsin red-brown muds. Hollister and Heezen (1972), Bouma and Hollister (1973) and Zimmerman (1972) have interpreted similar sediments from the eastern North American rise as contourites. The thin sands he (Piper 1975) believed were derived from beaches that developed along the outer margins of Sable Island and Banquereau Banks during glacially lowered sea level. They were transported in rip-current generated turbidity currents which fed the Slope canyons.

On the Laurentian Fan he found that the red-brown mud facies, the thin turbidite sands, and channel filling thick sands and gravels extended to the present sediment surface, but only rarely was the olive-gray mud facies present. Piper thus proposed turbidity current deposition throughout the Holocene, initiated by the slumping of unstable sediments which had been ice-rafted onto the upper slope during the last glacial period.

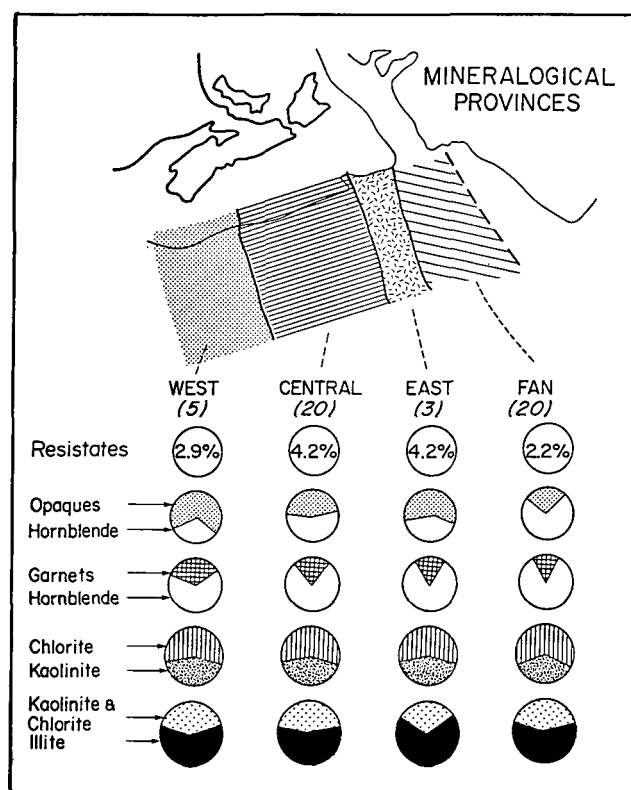


FIG. 6 Mineralogical provinces of the outer Scotian margin from clay and heavy mineral studies. Each column of pie diagrams shows the mineralogy of one of the four regions outlined. The number of analyses for each area are indicated at the top of the columns (from Stow, in press).

The few sediment cores examined by Heezen and Drake (1964) generally contained an upper gray-coloured layer overlying red-brown sediment. The gray layer showed a slight systematic decrease in thickness from the Laurentian Channel (<5m) to the Laurentian Fan (2.5 to 3 m), except in channel cores where it was much reduced to absent. This they interpreted as being due to erosion by turbidity currents. By consideration of foraminiferal evidence Ericson *et al* (1961) concluded that the change from red to gray sediment occurred 15,000 to 25,000 years ago. The source of the red sediment must have been cut off abruptly, either by a retreat of the Laurentide ice front, or due to a rise of sea level.

Connolly *et al* (1967) investigated a suite of cores from the outer Laurentian Channel and identified reddish-brown, glacial marine sediment from the late Pleistocene lying beneath a surface of soft, gray to brown, silty clay. Two thin brick-red

'tills' occurred within the glacial marine sediment and were thought to be time transgressive beds deposited at the floating ice front. Both of these glacial marine facies contain material derived principally from the Carboniferous-Permian sediments of Appalachian Canada, which are known to underlie most of the southern Gulf of St. Lawrence (Loring and Nota 1973).

Needham *et al* (1969) used Carboniferous paly-nomorphs to define the provenance and trace the southward transport of the reddish-brown Pleistocene sediments from southeast Canada to the Blake-Bahama Outer Ridge.

Studies of the Sohm Abyssal Plain sediments to the south of the Scotian margin have been made by Fruth (1965), Horn *et al* (1971) and Schneck (1974). In general, they found interbedded muddy turbidite

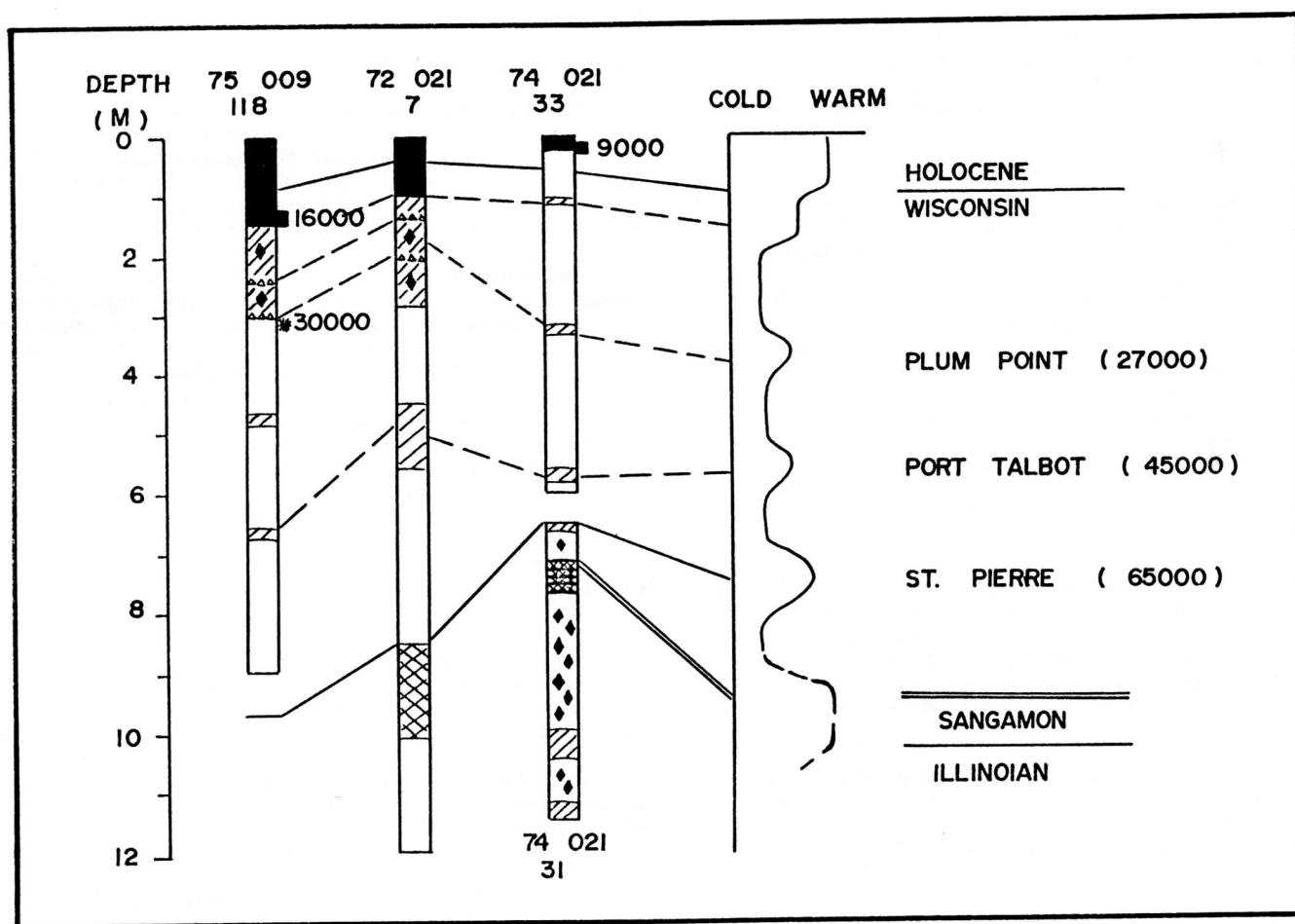


FIG. 7 Correlation and climatic stratigraphy of selected cores from the outer Scotian margin. Figures at the side of the cores indicate C14 dates (black rectangles) and an inferred Lake Gupta magnetic reversal (black star). Olive gray muds (black, oblique hachure, oblique cross-hachure); Red-brown muds (black); brown-gray muds with gravel clasts (black diamonds); Brick-red granular muds (open triangles).

sands and normal pelagic lutites.

Stow (1977a) characterized twelve facies and subfacies in late Quaternary sediments of more than 60 cores (Fig. 2) from the outer Scotian margin, which include those identified in the earlier studies. The six major facies are interpreted as follows (Fig. 7):

- (1) Olive gray, bioturbated, biogenic-rich mud represents "hemipelagic" sedimentation with bottom current reworking during much of the Holocene and Wisconsin interstades.
- (2) Red-brown, silt-laminated muds were deposited over much of the Fan and Rise during the Wisconsin glacial stages from large scale turbidity currents.
- (3) Thin (2 to 20 cm) graded sand beds are found close to channel axes and on small fan lobes, and are frequently associated with the Wisconsin olive gray units. They were probably deposited from sandy, rip-current generated turbidity currents and often show evidence of bottom current reworking.
- (4) Thick (up to 3 m) graded sands and gravels are recovered from channel floors, and represent major turbidity current or other mass flow transport.
- (5) Brown gray muds with gravel clasts were largely ice-rafted onto the upper Slope. Other facies may also contain scattered clasts and coarse sand.
- (6) "Brick-red" granular muds occur as two thin distinct horizons within the top few metres of Slope and Rise cores. Their origin remains problematical, although they are believed to represent sudden episodes of wide-spread deglaciation and iceberg calving in the late Wisconsin.

DEPOSITIONAL MODEL

Early Growth

The major Mesozoic depocentre on the Scotian margin was the Slope and Rise south of Sable Island (Parsons 1975). During that time the area which is now the Laurentian Fan was slowly building up an even sediment pile comprising, perhaps, distal turbidites from small fans developed at the base of the slope, as well as a steady rain of hemipelagic material.

In Cenozoic times the depocentre shifted to the Laurentian Fan region. Large paleocanyons have been identified carving into an Eocene paleo-slope (Parsons 1975, King and Young 1977) which was situated somewhat to the north of the present day slope. Sediment accumulation over the Fan increased and by mid-Miocene time the canyon-dissected slope had prograded close to its present position disgoring sediments onto the basinal plain beyond.

At the onset of the Plio-Pleistocene glaciations a thick pile of sediment had accumulated over the main Laurentian Fan, which may have been crossed with small, suprafan, distributary channels. The main morphological development of the Fan probably began with the first glacial episode about 3 ma B.P.

(Berggren 1972). The sedimentation rate increased considerably due to the proximity of the ice margin and meltwater streams eroding an exposed shelf. The Fan built upwards and a network of channels prograded outwards and acted as sediment funnels, especially for the coarser material. These channels were continually being filled and eroded, but the aggradation in interchannel areas was such that the valleys became progressively deeper.

There may have been at least two periods of different Fan morphology corresponding to the two major glacial episodes recorded by Berggren (1972) from the North Atlantic. There is evidence from buried channels of at least one previous Fan surface on the seismic profiles examined, which may pre-date the last major glacial event, the Illinonian, with a maximum about 400,000 years B.P. The Wisconsin glaciation was mild in comparison, so that sediment distribution probably utilized the previously existing morphology and deposited a thin veneer of Wisconsin sediments over an Illinonian surface.

Wisconsin (Fig. 8)

The dominant Wisconsin facies in most cores is red-brown mud eroded from the Carboniferous and Triassic red beds of eastern Canada and transported to the outer banks and upper slope by glaciers and pro-glacial streams. Redistribution of this sediment to the outer margin was mainly by turbidity currents.

The slumping of unstable sediments on the upper slope and their transformation into large scale turbidity currents appears to have been the most important mechanism. The upper slope is irregular and apparently slump-scarred; earthquake-induced faults and diapiric intrusion may have acted as triggering mechanisms in addition to sediment instability. Wisconsin sedimentation rates are not well known, but estimates of 10 to 30 cm/1000 years have been made from this study. An average sedimentation unit in interchannel areas (graded laminated bed) may be about 3 cm thick, so that the frequency of major slumping would be from 1/100 to 1/300 years. The channelized parts of turbidity currents were evidently powerful enough to deposit very thick, coarse, graded gravel beds several hundreds of kilometres from the shelf break and presumably, therefore, to disgorge sands onto the Rise and Sohm Abyssal Plain beyond. Sorting of the mud from the sand and gravel portions of the currents was very effective.

The direct discharge of large quantities of fine-grained sediment into the water column from the front of a floating ice tongue in the Laurentian Channel may have occurred. Its concentration into thick, cold, bottom flows might be an alternative way of producing large, dilute turbidity currents. The nature and importance of this mechanism has not yet been assessed, but quasi-continuous or (?) episodic turbidity flows of this sort may meet the physical requirements of the turbidity current model developed (Stow and Bowen, in prep).

Thin turbid layer flows (Moore 1969) and the seaward diffusion of meltwater "plumes" are mechanisms proposed by Stanley *et al* (1972) and Alam (1976) for the outer Scotian margin. Both of these processes would probably result in very low rates of

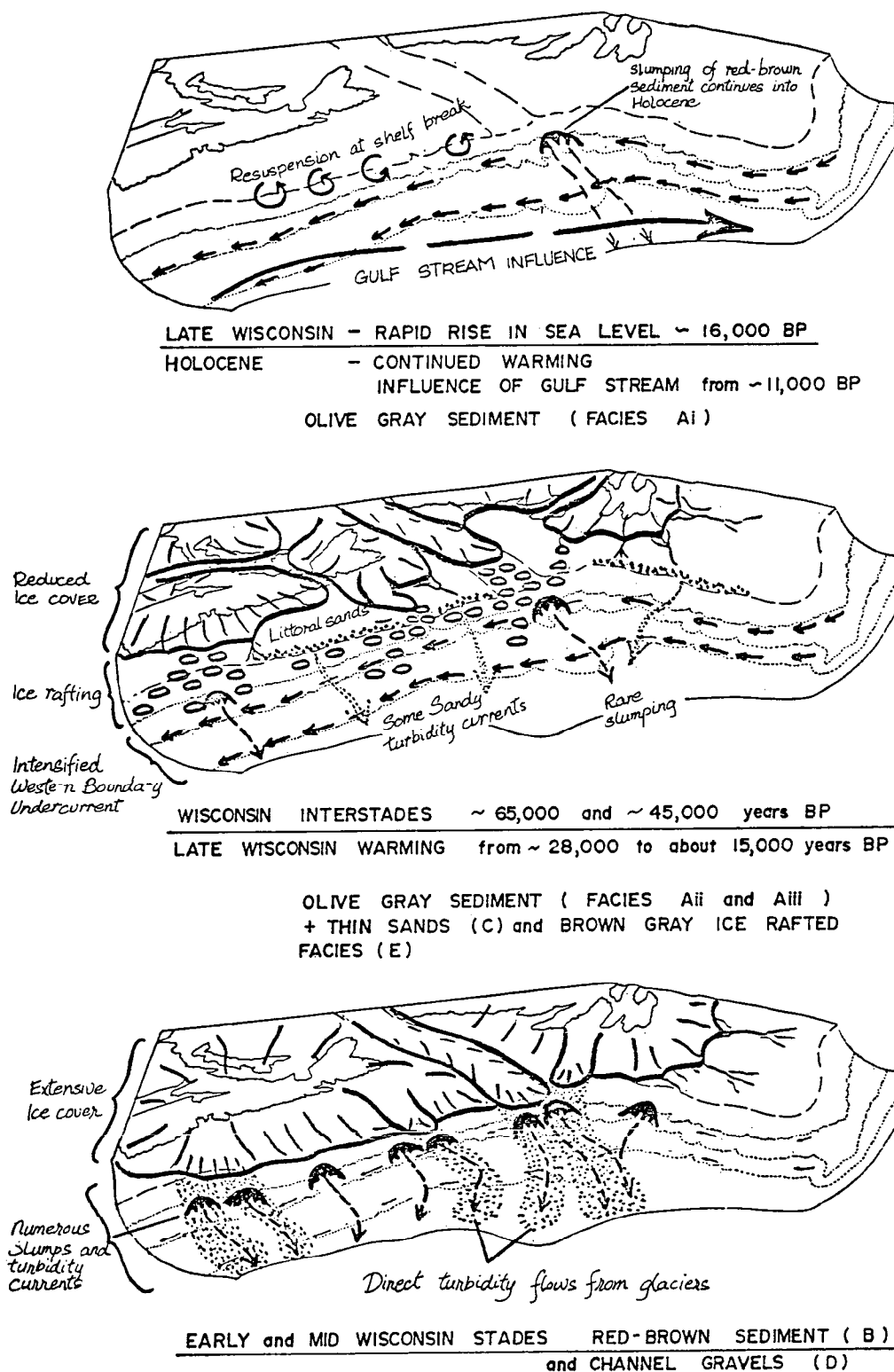


FIG. 8 Interpretation of late Quaternary sedimentation history on the outer Scotian margin.

sedimentation, which is probably more applicable to olive-gray sediment times. Alam (1976) estimates rates of about 2 cm/1000 years for the tops of sea-mounts southwest of the Grand Banks which, if correct, could mean that 6 to 20% of the Fan sediments were deposited in this way.

Ice rafting was apparently not a significant contributor of sediment to the Rise or Fan during the red-brown sediment time, although its importance on the upper slope was probably greater. Through the late Wisconsin (from about 28,000 years B.P.) and early Holocene it has been more evident over most of the Slope and Rise, with coarse sand and gravel scattered throughout the sequence. Ice rafting, meltwater plumes, as well as slumping and turbidity currents may all have been important. The two thin, "brick-red" granular mud horizons deposited between about 22,000 and 28,000 years B.P. are evidently ice-rafted deposits, although the reason for their presence and distribution remains enigmatic.

There are several periods within the Wisconsin when the sedimentation pattern changed significantly and the olive gray facies was deposited in correlative units across most of the outer margin. These probably represent climatic fluctuations or interstadials. The planktonic foraminifera indicate cool temperate rather than arctic conditions, but show little evidence that the Gulf Stream meander belt was directly influencing sedimentation.

The associated thin sand beds suggest an increased reworking of littoral sands along the shelf break during interstadials and, perhaps, an intensified Western Boundary Undercurrent. Ice rafting and hemipelagic sedimentation were also important, especially over the Slope and Rise. Slumping of red-brown sediments on the upper slope above the Fan, and their downslope transport in turbidity currents, probably continued through at least parts of the Wisconsin interstadials.

Holocene-Pleistocene Boundary

The major faunal change, noted in these cores at a depth of 50 to 100 cm and at similar depths by previous investigators (Ericson *et al* 1961, Stanley *et al* 1972), is equated with the change in climate at 11,000 to 10,000 years B.P., as recorded elsewhere in the North Atlantic (Ericson *et al* 1964).

The change from red-brown to olive-gray sediment is time transgressive across the Scotian margin. It occurs below the Holocene-Pleistocene boundary on the Slope and Rise, where it may mark the onset of rapid warming and corresponding rise in sea level at about 16,000 years B.P. (Stanley *et al* 1972). In the Laurentian Channel, Connolly *et al* (1967) suggest that it may be due to the retreat of ice from the red beds in the Gulf of St. Lawrence at about 11,000 years B.P. The colour change is above the Holocene-Pleistocene boundary in many Fan cores, and thus indicates the prolonged activity of parts of the Fan compared with the Slope and Rise. Ruddiman and McIntyre (1973) and Needham *et al* (1976) have also noted that the effects of deglacial warming on the lithology of deep-sea sediments in the North Atlantic has been substantially time transgressive.

Holocene (Fig. 8)

The early Holocene was a period of ice rafting over the Slope and Rise and continued red-brown sedimentation on the Fan. However, by middle or late Holocene time "hemipelagic" accumulation was dominant over most of the margin. Winnowing of fines from the outer banks and resuspension of material by internal waves and tides at the shelf break have supplied sediment for near-bottom nepheloid or suspension-rich layers (Stanley 1970), and for low velocity turbidity currents (Moore 1969, Shepard *et al* 1977). In addition there has been a fairly continuous rain of biogenic remains (mostly foraminifera, diatoms and coccoliths) through the water column. These materials have been subjected to redistribution by the Western Boundary Undercurrent, which has also introduced limited material from more northerly sources.

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