

Laurentian Fan: Morphology, Sediments, Processes, and Growth Pattern¹

DORRIK A. V. STOW²

ABSTRACT

Thick sediment accumulations in deep water provide a new target in the search for oil, and require an innovative approach to hydrocarbon exploration. The Laurentian fan is a large, deep-sea (2,000 to 5,000 m) fan in the western North Atlantic, and has been the major depocenter off Nova Scotia since at least the early Tertiary. The main development of the present depositional and erosional fan morphology in the past 2 to 3 m.y. was closely related to onshore glacial history.

The slope above the fan has been the site of rapid sedimentation and consequent slumping. A network of tributaries on the upper fan appears to feed three main channel systems incised up to 800 m between broad asymmetric levees. These channels meander widely across the lower fan, then die out abruptly and pass into a lobate suprafan. Differences between the Laurentian fan and typical fan models result, in part, from the muddy nature of the sediment and the supply system.

The channels contain thick, coarse gravels which probably grade distally into sandy lobes. Both should produce good reservoir bodies with suitable source and trapping mechanisms. Fine-grained sediments were more important in fan construction. Interbedded turbidites, contourites, and hemipelagites are present in the late Quaternary-Holocene sequence. The distribution of these sediments and, in particular, the recognition of structural sequences, textural trends, and

fabric types in the fine-grained turbidites can be used to characterize particular parts of the fan environment. The development of this approach should prove useful in future hydrocarbon exploration.

INTRODUCTION

Continental slope, rise, and deep-sea fan sediment forms an important part of the present ocean basins and past stratigraphic record (Nelson and Kulm, 1973; Mutti, 1974; Nelson and Nilsen, 1974; Whitaker, 1974; Stanley and Kelling, 1978). The petroleum industry is beginning to take an increasing interest in the geology of modern deep-water margins (Yarborough et al, 1977; Walker, 1978; Wilde et al, 1978) with a view to the potential economic recovery of oil and gas. A new approach to old problems and a critical assessment of earlier sedimentologic models is required.

Parts of the eastern North American divergent margin have been comparatively well studied in terms of magnetic, gravity, and sedimentary framework (Emery and Uchupi, 1972; Keen et al, 1975; King and Young, 1977; Haworth and Keen, 1979). The Nova Scotian continental margin (Fig. 1), including the Scotian Shelf, Gulf of St. Lawrence, Laurentian Channel, and Grand Banks (inner Scotian margin) and the adjacent slope and rise (outer Scotian margin), has accumulated 10 to 12 km of sediment since the opening of the Atlantic in the Early Jurassic (McIver, 1972; Jansa and Wade, 1975). King

(1975) referred to the margin as a miogeocline (central and outer shelf)-eugeocline (slope and rise) couplet. The Laurentian fan, lying in deep water (2,000 to 5,000 m) at the base of the slope off the Laurentian Channel, has been the major depocenter on this margin since at least the early Tertiary (Parsons, 1975; Uchupi and Austin, 1979).

Previous work on the late Quaternary stratigraphy and sedimentation of the outer Scotian margin has been at the reconnaissance level (Heezen et al, 1964; Stanley et al, 1972; Piper, 1975; Stow, 1976; Piper and Slatt, 1977). More detailed studies of the adjacent continental shelves include: the Scotian Shelf (Marlowe, 1967; Cok, 1970); the Gulf of St. Lawrence and Laurentian Channel (Conolly et al, 1967; Loring and Nota, 1973); and the Grand Banks Shelf (Slatt, 1974, 1977; Alam, 1976; Alam and Piper, 1976). Stow (1978) has compiled a more extensive regional review of the outer Scotian margin geology.

The present study of the Laurentian fan is based on piston and gravity cores collected during Bedford Institute of Oceanography and Dalhousie University cruises on CSS *Hudson* and CSS *Dawson* during the past 5 years (Fig. 1). Additional sediment samples were taken from the Lamont-Doherty Geological Observatory core collection. Laboratory analyses, for the most part, followed standard sedimentologic techniques (Bouma, 1969; Carver, 1971). Seismic reflection profiles over the fan (Fig. 2) were

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²Grant Institute of Geology, University of Edinburgh, Edinburgh EH9 3JW, Scotland.

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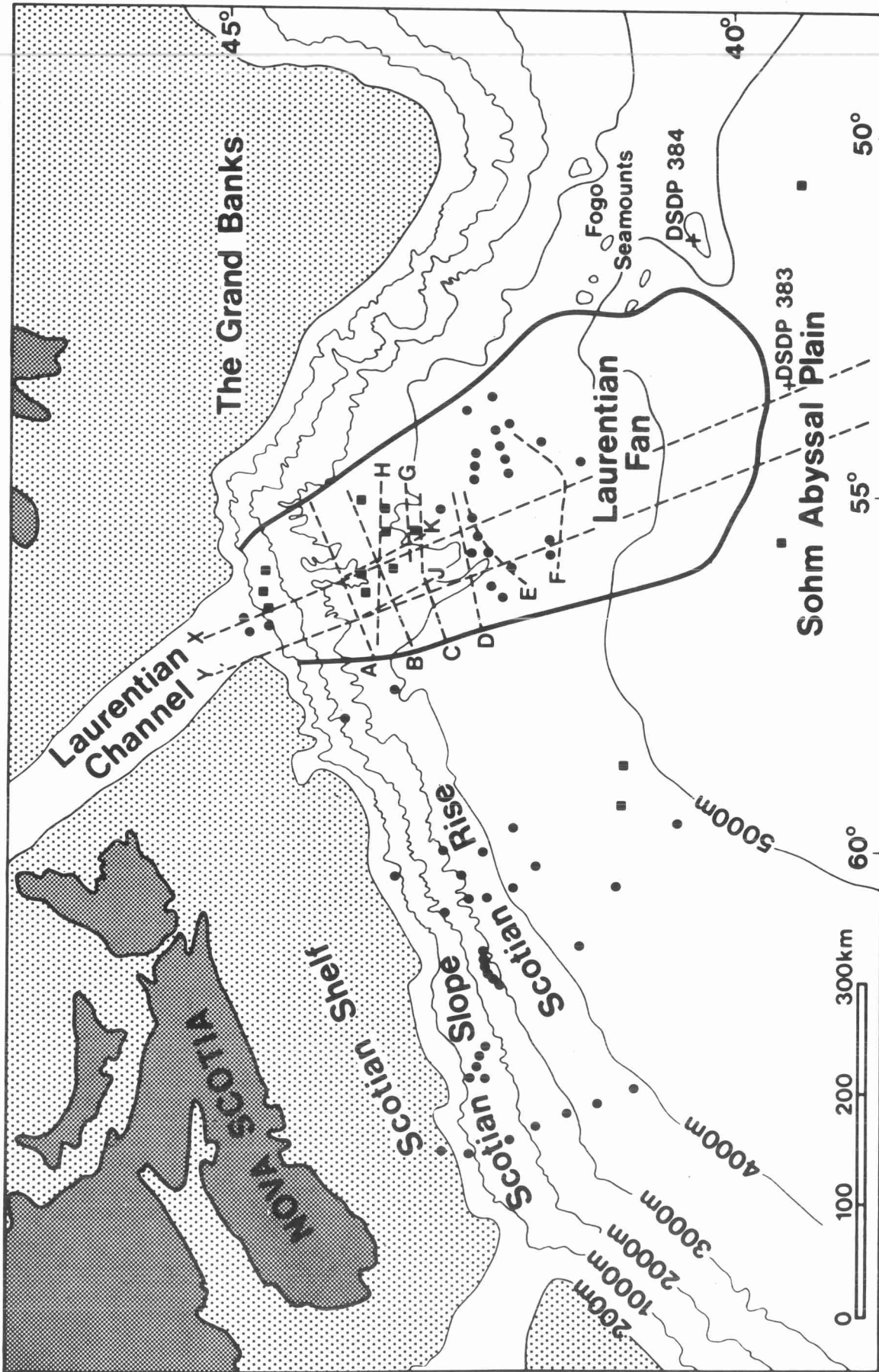


FIG. 1—Laurentian fan and adjacent east Canadian continental margin. Core locations: solid circles, Dalhousie University cores; solid squares, Lamont-Doherty Geological Observatory cores. Western North Atlantic DSDP Sites 383 and 384,

crosses. Seismic lines A, B, D, J, and K are reproduced in Figures 4 and 7; transverse bathymetric profiles in Figure 6; longitudinal profiles in Figure 3.

provided by Imperial Oil Ltd., Calgary (24 fold, common depth point), and Woods Hole Oceanographic Institute (*Chain 70* and *73* cruises, Emery et al, 1970).

FAN MORPHOLOGY

Shape and Morphologic Divisions

The Laurentian fan is elongate and extends southeastward over 600

km from the base of the slope off the Laurentian Channel to merge with the Sohm Abyssal Plain at a depth of 5,200 m. It has a maximum width of 250 to 300 km and pro-

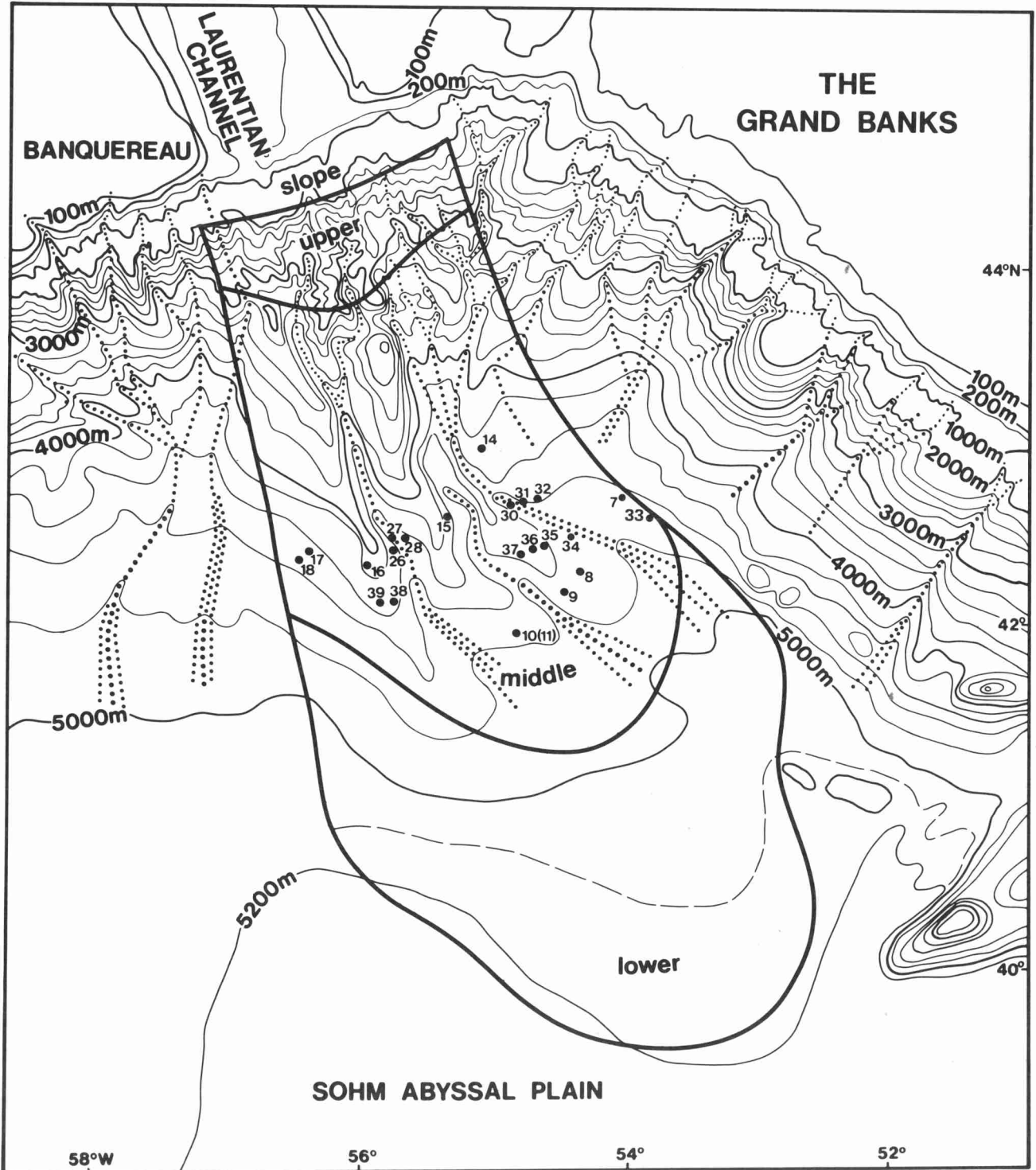


FIG. 2—Bathymetric map of Laurentian fan modified from Canadian Hydrographic Service charts 801 and 802; Stow (1977, 1978); Uchupi and Austin (1979). Contours are in corrected meters, using Matthews (1939) tables. Canyons and channels are stippled.

trudes 80 to 100 km beyond the adjacent Scotian Rise (Fig. 2). The average gradient changes from 5° (1:12) on the slope to less than $1/4^\circ$ (1:300) on the lower fan.

Three morphologic divisions can be distinguished in longitudinal profile (Fig. 3): an upper fan with a rugged concave-upward surface, a middle fan with a convex-upward surface and prominent levees bounding deep channels, and a lower fan with a smooth, slightly concave-upward surface. These divisions are analogous to the threefold profile characteristic of many deep-sea fans (Nelson et al, 1970; Normark, 1970, 1974; Damuth and Kumar, 1975), but with some differences. The upper fan does not have a prominent, leveed, central channel, but a complex network of small and large tributary valleys. A "suprafan" is developed with small distributary channels at the distal end of the main channels on the lowest middle fan (Uchupi and Austin, 1979; unpub. data). Both channel and interchannel areas on the middle and lower fan show smooth or slightly undulating surfaces (Fig. 4). Channel margins, as well as the upper fan and slope, show a more irregular morphology characteristic of slumping.

The elongate shape of the Laurentian fan is different from many 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 may be a function of the amount and type of sediment supplied (Piper, 1975). Large quantities of clayey sediment will be transported farther seaward 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.

Channel Development

The complex network of tributary valleys between slump blocks on the upper fan coalesce to form three

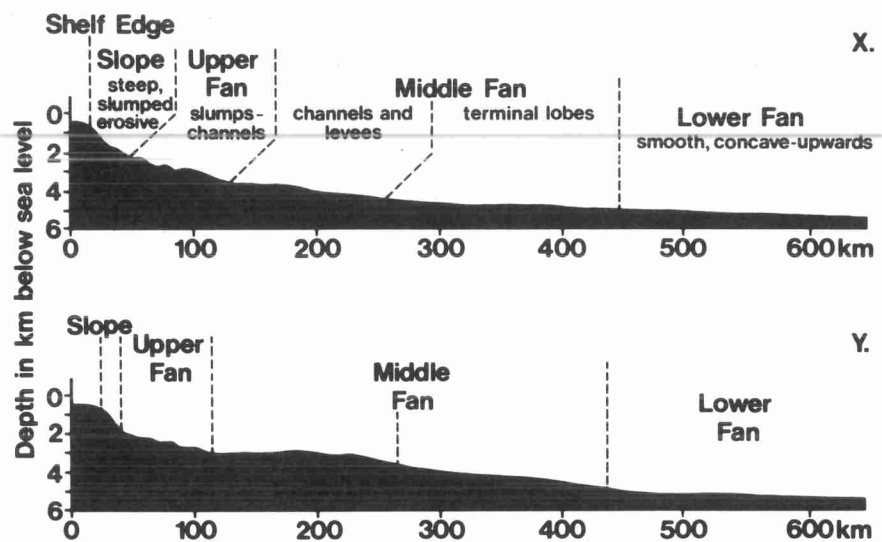


FIG. 3—Longitudinal bathymetric profiles across Laurentian fan showing upper, middle, and lower fan divisions (see Fig. 1 for locations).

large meandering channels on the middle fan that make a sharp "left hook" between 43° and 42° S (Fig. 2). The channels increase regularly in depth to a maximum (about 850 m for the largest) at about 240 km from the shelf break, and then decrease fairly rapidly with increasing distance (Fig. 5). On the lowest middle fan they die out into shallow distributary channels between sediment lobes. This systematic change in channel dimensions (Fig. 5) has been noted by Menard (1964) and others, and interpreted in terms of increasing flow thickness to maintain continuity of discharge over a decreasing bottom slope (Komar, 1973, for the Cascadia Channel).

The channels range from V-shaped (base width 2 km) on the upper fan to U-shaped (base width > 10 km) on the middle fan. They are commonly asymmetric, with the eastern sides having a lower relief and gentler slope (Uchupi and Austin, 1979; Fig. 6). They generally show a sharp surface reflector, probably from a sand or gravel floor, and then a mushy, indistinct "fill" below (Fig. 7). For much of its passage across the middle fan the central channel complex forms a broad, troughlike feature up to 26 km wide and with several distinct thalwegs. Two different terrace levels can be distinguished in channels on the lower middle fan, and

most channel margins are highly slumped. These large channels are deeply erosional (and partly depositional), commonly cutting through more than 500 m of truncated sediments. Smaller transverse, tributary (and distributary?) channels cross the interchannel areas. Shallow, buried channels are evidence of earlier and different fan morphologies.

Interchannel and Levee Construction

On the upper fan the interchannel areas are very irregular, with many hyperbolic reflections and an obscure or discontinuous internal structure (Fig. 7). They generally have an irregular surface morphology, but sometime show the asymmetric development common on the middle fan. Distances between channels are mostly less than 10 km. The channel-levee systems show various combinations of the erosional-depositional forms described by Normark (1970, 1974).

On the middle fan the interchannel areas are wider (up to 40 km), smoother, and have a marked asymmetry (Fig. 7). They have a steep (about 8°), deeply eroded and often slumped, channel side, and a gently dipping (about 2°), smooth or slightly wavy, backside. Near the lower part of the middle fan the interchannel surface shows some areas

of large, antidunal sediment waves characteristic of turbidity current overflow (Embley and Langseth, 1977; Normark et al, 1980).

The internal structure of the interchannel areas comprises, for the most part, strong, flat, closely spaced reflectors that are continuous over several tens of kilometers and gradually decrease in number away from the channel axes. One curious feature of many of these turbidite-constructed interchannel areas is a marked "hinge line" across which the reflectors are either discontinuous or bent (Fig. 7). This may be an indication of interchannel construction by the infilling of back-levee depressions or channels during sheet overflow.

The lower fan has been very

sparingly surveyed and sampled. Most of the channels subdivide into broad, low-relief (< 50 m) distributaries between terminal sediment lobes on the lowest middle fan. Only two of these distributaries continue across the lower fan to the Sohm Abyssal Plain (Uchupi and Austin, 1979). The rest of the lower fan appears to be smooth and flat and has thin, closely spaced, continuous reflectors.

SEDIMENTS

Facies Distribution

Three main sediment facies can be identified in Laurentian fan cores; olive-gray muds, red-brown muds, and thick sands and gravels (Fig. 8).

Olive-gray muds (GSA color code 10YR 4/2 - 5Y 3/1 - 5Y 4/1)—Olive-gray muds are present as a surface layer 0.5 to 2.0 m thick in interchannel areas. They are thinner or absent close to or within channels or may comprise thin upper and lower layers separated by about 0.3 m of red-brown mud. The facies is also developed at one or more deeper horizons within most cores, in beds from 0.02 to 0.2 m thick, where it is darker and less biogenic-rich than the surface mud. Typically, the olive-gray muds are thoroughly bioturbated, with rare irregular sandy layers. They are biogenic-rich (mainly coccoliths and diatoms) and have a small foraminiferal sand content.

Red-brown muds (5YR 4/4 - 10R 4/2)—Red-brown muds are the

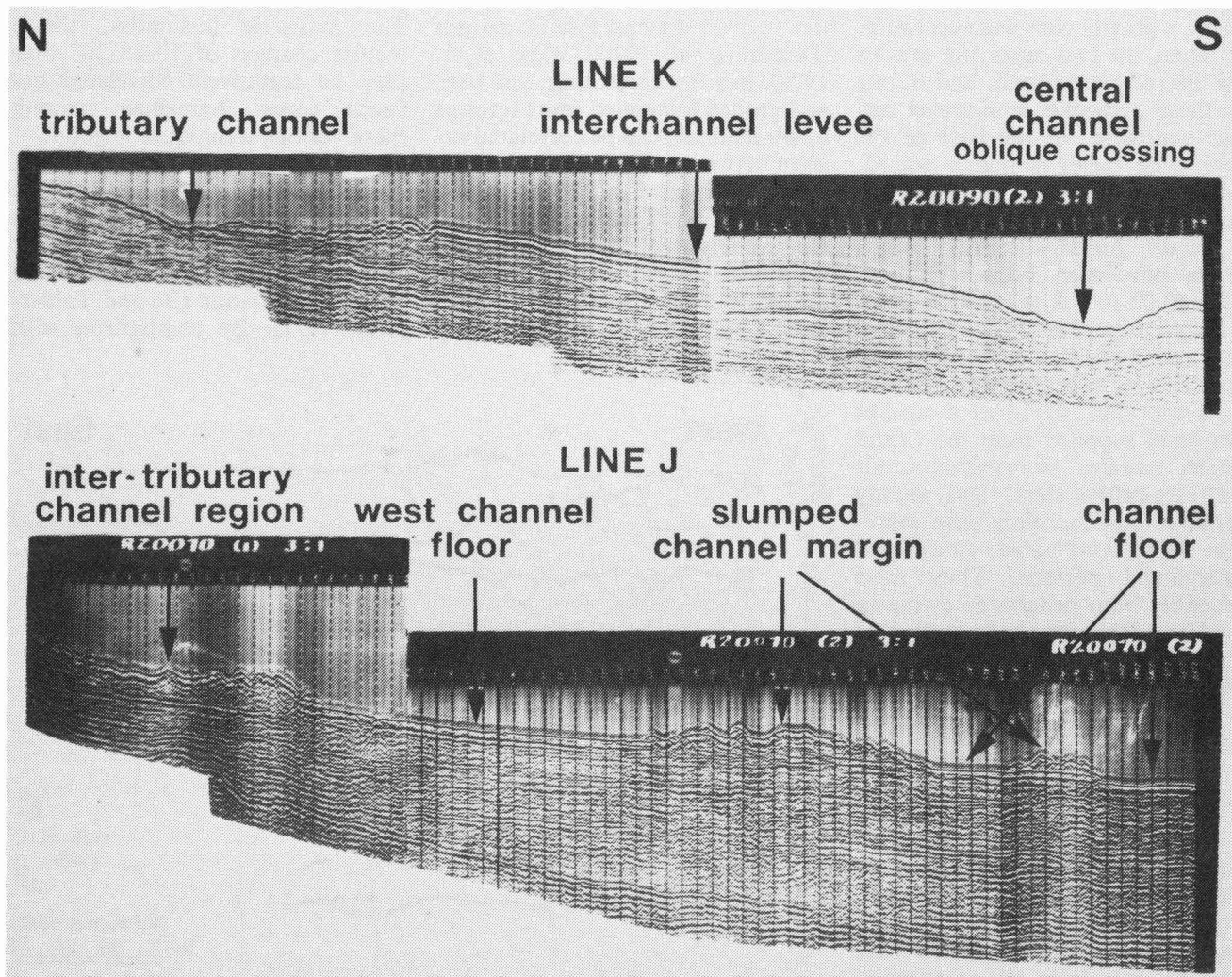


FIG. 4—Longitudinal seismic profiles over interchannel and channel axes (see Fig. 1 for locations).

dominant lithology in the lower parts of most cores to at least 10 m depth (the maximum penetration achieved in this study), and are interbedded with one or more thin horizons of olive-gray mud. For the most part the muds contain abundant thin silt laminae (0.5 to 8.0 mm thick); less commonly they are unlaminated. The laminae decrease in thickness and frequency away from the channel axes (Stow, 1976). There is almost no bioturbation and very little biogenic or sand-sized material.

Thick sands and gravels—These are confined to the channel floors. In one core, up to 7 m of coarse gravel was recovered, although the lower part may be sucked-in material (Stow and Aksu, 1978). The upper 1 to 2 m is generally graded from gravel to fine sand and even to silty mud in the one example where a gravity core was successfully taken. In two cores the gravels overlie red-brown mud, and in one of these a second sand-gravel bed was penetrated at the base of the core. The facies is poorly sorted, mineralogically immature, and has a polygenic clast composition.

Minor facies—Several minor facies have also been identified. Thin (0.02 to 0.2 m) graded sands are present in cores close to channel axes and in one core east of the main fan. This latter is probably from the sand suprafan region of a smaller fan body supplied from the Grand Banks margin. Brown-gray muds with ice-rafted clasts and muddy foraminifer-coccolith ooze represent deposits of earlier glacial and interglacial periods. They have probably been penetrated owing to the loss of the uppermost section of this core during the coring operation (Stow and Aksu, 1978).

Correlation, Age, and Sedimentation Rates

There is a standard vertical sequence of facies in most cores from interchannel areas: olive-gray mud overlying red-brown mud, which is interbedded with one to three horizons of dark olive-gray mud (Fig. 8). Variation in the relative abundances of foraminifers, coc-

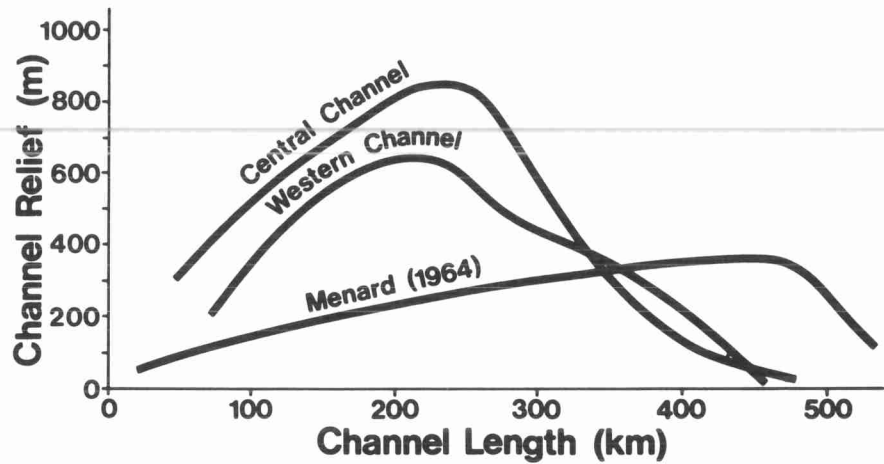


FIG. 5—Variations of channel relief with channel length for central and western channels of Laurentian fan. Data from Pacific Ocean channels (Menard, 1964) are given for comparison.

coliths, and diatoms can be used to correlate different olive-gray layers. Biogenic ratios have been used in this way on the east Pacific margin (Duncan et al, 1970; Griggs et al, 1970). In a few cores, thin sand beds and graded laminated units (groups of silt laminae) can be correlated exactly between adjacent interchannel cores by matching X-radiographs (Stow, 1979a). Textural and mineralogic analyses of these beds show a consistent pattern of variation in a direction away from the channel axes. Detailed paleomagnetic study

was made of several cores from the fan using the methods of Thompson (1975, 1977) and Creer et al (1976). The magnetic inclination shows secular changes of 10 to 30° that may be tentatively correlated between cores. Agreement among these various techniques is good.

Climatic curves have been drawn for each core on the basis of the relative abundance of planktonic foraminifers from the different faunal assemblages recognized in the North Atlantic (Be and Tolderlund, 1971). By comparison with

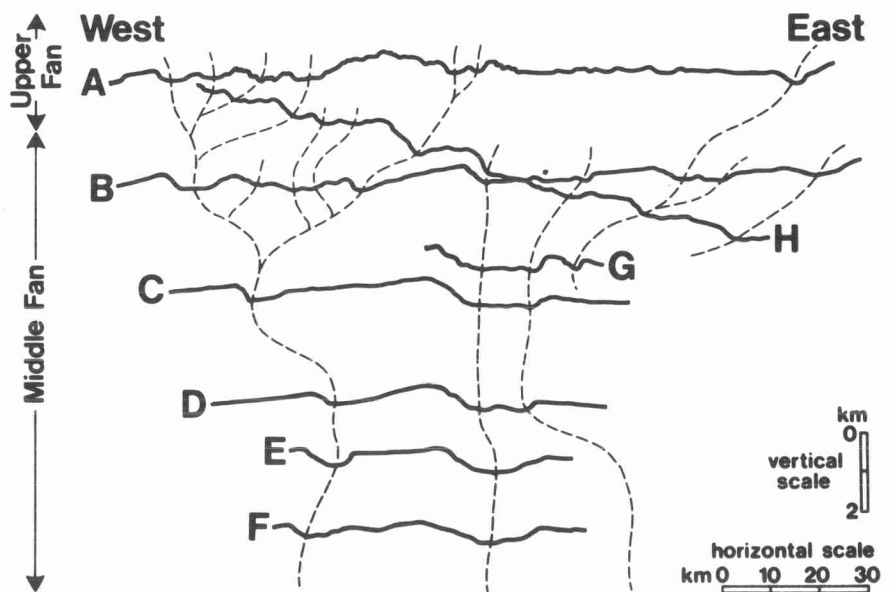


FIG. 6—Transverse bathymetric profiles across Laurentian fan showing channel development (see Fig. 1 for locations).

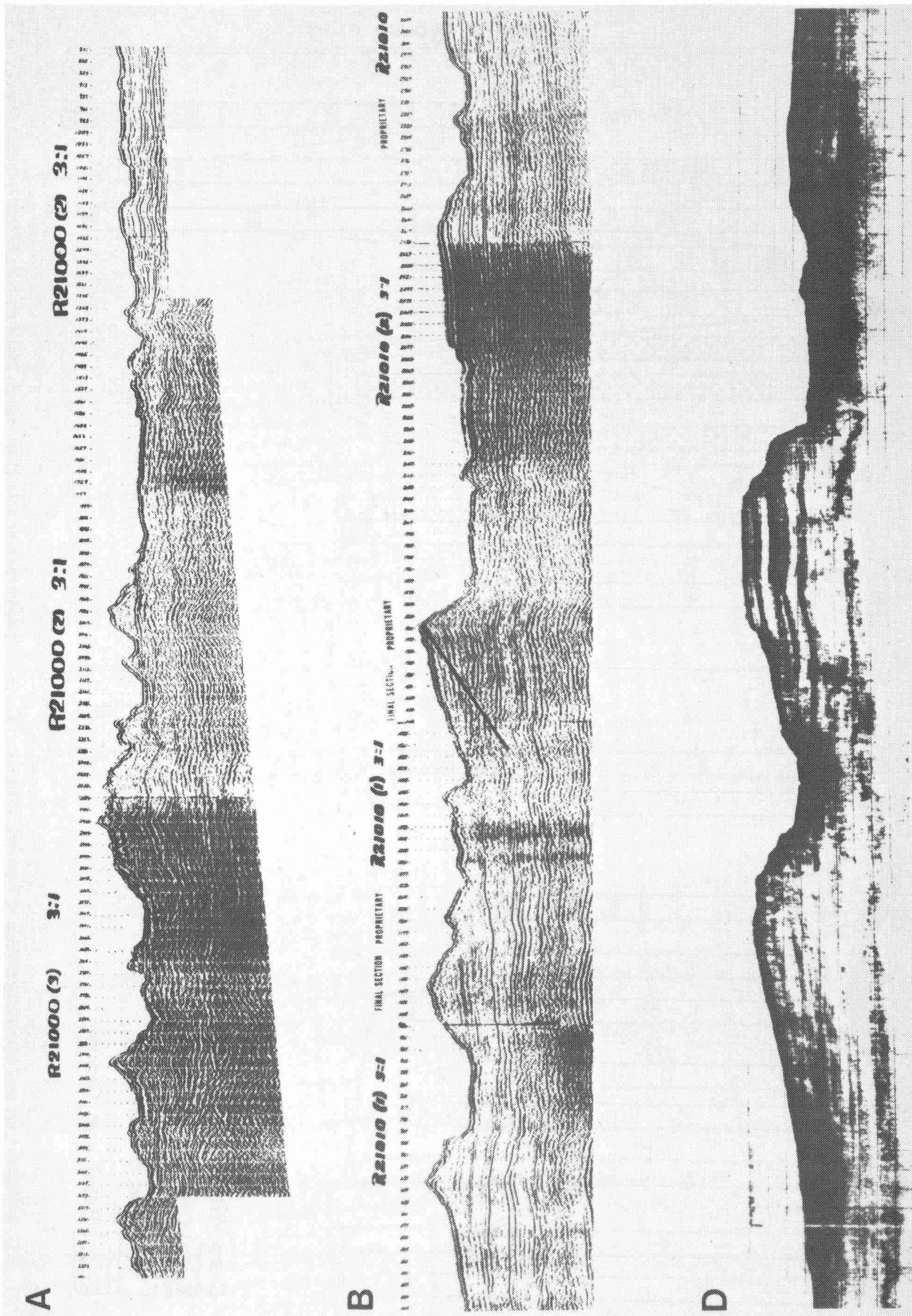


FIG. 7—Transverse seismic profiles across Laurentian fan showing characteristics of channel and interchannel areas and “hinge line” development of interchannel and levee areas (see Fig. 1 for locations).

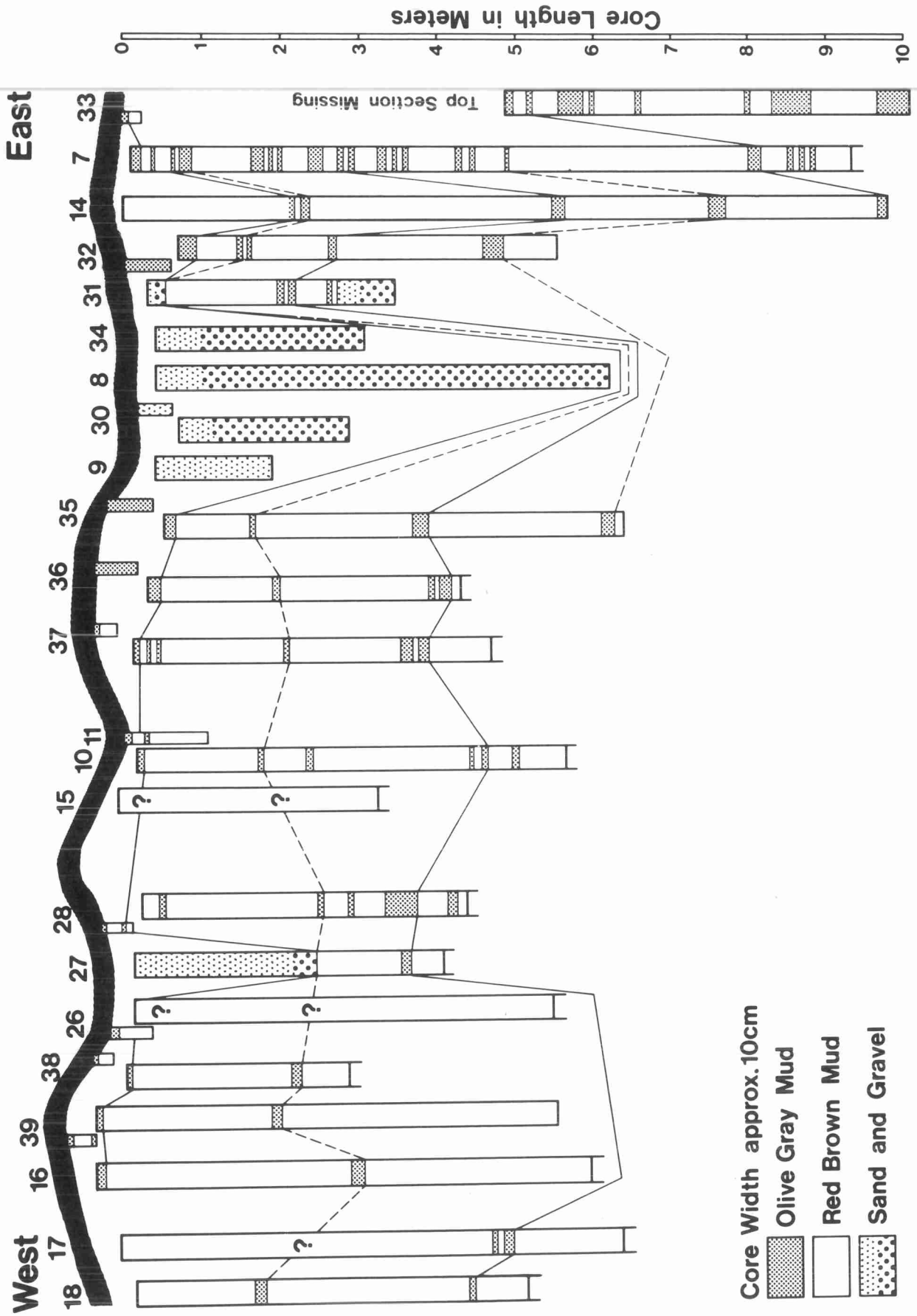


FIG. 8—Facies types and general correlation of Laurentian fan cores. Cores projected onto schematic cross section. Numbers refer to core locations (Fig. 2).

similar oceanic and terrestrial data (Wollin et al, 1971; Alam, 1976, Alam and Piper, 1976) these curves have been interpreted in terms of late Quaternary stratigraphy (Stow, 1977).

The Holocene-Pleistocene boundary, in most fan cores, is somewhere below the base of the upper olive-gray mud layer. In one fan core and in cores from the Scotian Slope and Rise, this marked faunal change occurs at a depth of 50 to 100 cm within the upper olive-gray unit. This corresponds with the Holocene-Pleistocene boundary proposed, from similar evidence, by Ericson et al (1961) and Stanley et al (1972), and shows that the change from "red" to "gray" sedimentation was time-transgressive on the Scotian margin. The greater faunal numbers in the lower olive-gray units (in comparison with the red-brown muds), and the influx of warmer water species at some horizons, suggest that these facies indicate a return to warmer water conditions. They would therefore represent sedimentation during interstadial periods within the Wisconsin. A carbon-14 date from the base of the top olive-gray layer in one core gives an age of $8,955 \pm 280$ years B.P. (9X4,779), which would confirm the position of the Holocene-Pleistocene boundary.

Sedimentation rates can therefore be estimated for the late Wisconsin and Holocene periods. Assuming two-thirds compaction for the thin gravity cores in interchannel areas of the eastern fan, the rate is about 10 cm/1,000 years for the olive-gray Holocene facies. In the same area the Wisconsin red-brown muds have sedimentation rates of between 10 and 20 cm/1,000 years. On the western fan the rate was probably greater (up to 30 cm/1,000 years), continuing through much of the early Holocene.

Sediment Composition and Source

Detailed study was made of the gravel petrology (20 samples), sand mineralogy (110 samples), clay mineralogy (120 samples), and organic carbon content (75 samples) of sediments from the Laurentian fan and

the adjacent slope and rise. Standard methods were used, including thin-section petrography, heavy-mineral grain mounts of the 63 to 90- μ size fraction (Carver, 1971), X-ray diffraction of the < 2- μ fraction (Biscaye, 1964; Carrol, 1970), and oxidation of the organic carbon (Byers et al, 1978).

Gravel-size clasts—Gravel-size clasts from ice-rafted facies at the end of the Laurentian Channel and from thick channel gravels are made up of nearly 70% red and gray sandstones, limestones, and dolomites, and 30% crystalline igneous or metamorphic rocks. The sedimentary rocks have been supplied directly from the Gulf of St. Lawrence red beds and Carboniferous and Ordovician limestones. The minor crystalline component has been derived from either Quebec or Newfoundland. Farther west, on the Scotian Slope and Rise, the sedimentary clasts are replaced by a granite-quartzite-slate assemblage that has been derived from the granites and Meguma Formation of Nova Scotia. Gravels have been transported by glaciers, icebergs, and downslope resedimentation by mass gravity flows (Stow, 1978).

Gross mineralogy of sands—The gross mineralogy of sands gives little indication of specific sources but permits general facies characterization. The olive-gray muds have a small (2 to 5%) biogenic sand content; the red-brown muds generally contain < 1% sand which is dominantly quartzose with minor feldspar, mica, heavy minerals, and shallow-water benthonic foraminifers. Mineralogy of the thin sands and gravel-sands is more varied although no regular variation is apparent. Heavy minerals, however, are more useful in distinguishing sediment sources. The dominant types include amphiboles—mainly hornblende (10 to 40%), garnets (2 to 20%), and opaques (3 to 58%); of secondary importance are orthopyroxenes and clinopyroxenes (1 to 16%) and a resitstate assemblage—zircon, sphene, tourmaline, and apatite. Various accessory minerals, altered grains, and rock fragments are also present.

There is a clear distinction be-

tween sands of the fan and slope-rise provinces. The fan has higher percentages of hornblende and apatite whereas the slope and rise are higher in opaques and tourmaline (Fig. 9A, B). Six samples of slope-rise sands from the olive-gray facies have a mineralogy closer to that of the fan. Limited data suggest that the western margin of the Grand Banks forms a separate mineral province and that the slope-rise can be subdivided into three sub-provinces.

Three heavy mineral assemblages can be identified as possible sources for the outer margin sediments: the Scotian Shelf—high in opaques and accessory zircon, tourmaline, and rutile; the Gulf of St. Lawrence and Laurentian Channel—high in hornblende, pyroxene, and accessory apatite; and the Grand Banks Shelf—high in opaques and accessory zircon, sphene, and epidote (McCleod, 1959; Hubert and Neal, 1967; Loring and Nota, 1969; Emery and Uchupi, 1972; Stanley et al, 1972; Stow, 1978). The close correspondence of source-area assemblages with outer-margin provinces suggests that the dominant dispersal of sands and silts has been perpendicular to the shelf break. The six exceptions noted may indicate limited along-slope mixing or local anomalies in the Scotian Shelf assemblages.

Clay mineralogy—The clay mineralogy shows a general uniformity over the whole Scotian margin (Fig. 9C). Certain facies differences are present, the main one being a greater amount of montmorillonite in the olive-gray facies (Fig. 9D). Only slight regional differences can be detected, in particular a higher kaolinite/chlorite ratio in the Scotian Slope and Rise samples (0.76) than on the fan (0.62). The kaolinite/chlorite ratio in both areas shows an increase with water depth, and a still clearer increase with distance from the shelf break (Fig. 10A, B). The illite/kaolinite + chlorite ratio shows a less distinct decrease with distance from the shelf break (Fig. 10C). Montmorillonite is moderately well-crystallized and increases in percentage offshore within the olive-gray muds.

Stanley et al (1972) and Piper and Slatt (1977) have identified the following sources for the different clay minerals:

1. Illite and chlorite are common high-latitude minerals throughout eastern Canada. The Grand Banks margin and Newfoundland tills are rich in chlorite.

2. Kaolinite may be derived from the Lower Carboniferous and Trias-

sic red beds of the Maritimes, or from offshore Lower Cretaceous and younger strata.

3. Four possible sources have been suggested for montmorillonite: the Triassic red beds of the Maritimes; offshore Upper Cretaceous and Cenozoic strata; the Gulf Stream (Pastouret et al, 1975); and the Western Boundary Undercurrent (Zimmerman, 1972).

The first-order uniformity of the clay mineralogy of different facies, ages, and regions on the outer Scotian margin, suggests a common provenance for these minerals. It suggests also that any clay-mineral variability is largely obscured by the time the material reaches the outer margin.

The secondary distinction between the Laurentian fan and Sco-

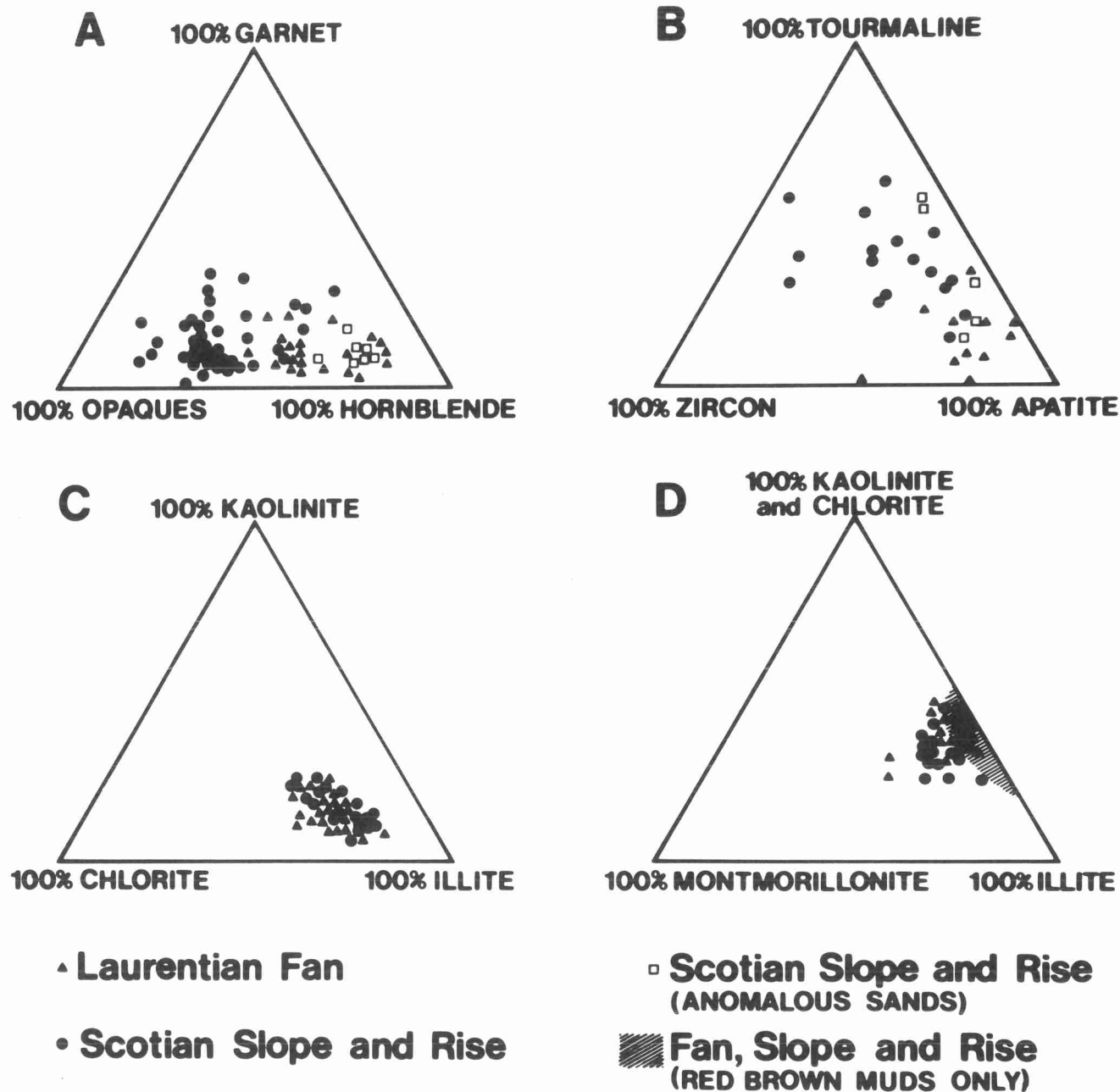


FIG. 9—A, triangular plot of dominant heavy-mineral species in Laurentian fan and Scotian margin sands and silts (63 to 90- μ size fraction). B, triangular plot of resistate heavy-mineral species in Laurentian fan and Scotian margin sands and silts (63 to 90- μ size fraction). C, clay minerals of Laurentian fan and Scotian margin: triangular plot of kaolinite-chlorite-illite recalculated to 100% (< 2- μ size fraction). D, clay minerals of Laurentian fan and Scotian margin: triangular plot of kaolinite and chlorite-montmorillonite-illite recalculated to 100% (< 2- μ size fraction).

tian Slope and Rise on the basis of kaolinite/chlorite ratios is probably 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. These and other mineral differences, as well as the offshore trends noted, favor an offshore dispersal pattern perpendicular to the shelf break.

The appearance of significant montmorillonite only in the olive-gray facies suggests the tapping of another source for this mineral and a reduction in supply of the illite-kaolinite-chlorite suite. This increase in montmorillonite occurs with a warming climate, recession of the ice limits, and a rise in sea level. The reduced supply of other clays results from the decreased erosion of eastern Canada and trapping on the shelf as the sea level rises, whereas the increased input is presumably from the Western Boundary Undercurrent or Gulf Stream. The generally good crystallinity of the montmorillonite is more representative of a northern source (Biscaye, 1964) which lends some support to its derivation from the Western Boundary Undercurrent.

Organic carbon content—The organic carbon content of the olive-gray muds is between 0.5 and 0.8%. This is at least twice that of the red-brown muds and is presumably due to the greater biogenic contribution to the former. The average for 30 Laurentian fan red-brown mud samples is 0.3% carbon, whereas that for 20 slope-rise red-brown muds is 0.42%. This difference may reflect the slower sedimentation rates on the slope and rise and the correspondingly greater biogenic contents of the sediments. No clear variation was seen with depth in the cores.

Textural Trends

More than 150 grain-size analyses have been made of individual sand and silt layers from the outer Scotian margin, using conventional sieve and pipette techniques as well as a Model T Coulter Counter (Sheldon and Parsons, 1967). The dominant mean size of the fan samples is coarse to medium silt, whereas that

of the slope and rise is very fine sand. This difference is believed to be an indication of proximity (i.e., distance from a source on the upper slope; Stow, 1976).

Size analysis of silt laminae from the red-brown mud facies on the Scotian margin and Sohm Abyssal Plain reveals distinctive trends in fining and sorting over distances of more than 1,000 km (Fig. 11). The silts become both finer and more poorly sorted downslope; the inter-

laminated muds also show a very clear downslope fining trend (Stow, 1979a). These downslope textural trends are mirrored, to some extent, by grading through individual depositional units, by across-levee trends in interchannel areas on the fan, and by compositional grading. There is a decrease in frequency and thickness of silt laminae away from channel axes, concomitant with the grain-size decrease and mineralogic changes.

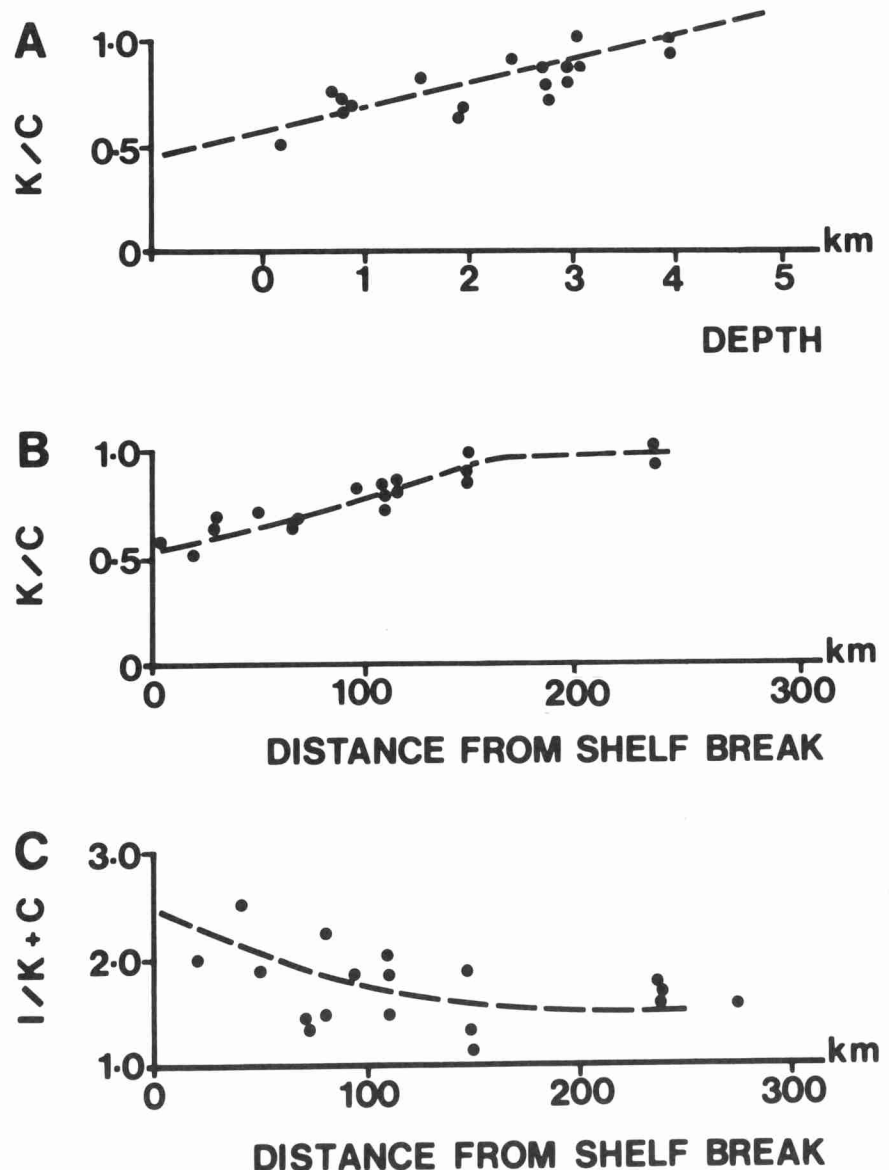


FIG. 10—A, kaolinite/chlorite percentage ratio versus depth. B, kaolinite/chlorite percentage ratio versus distance from shelf break (note still more marked offshore trend than in A). C, illite/kaolinite + chlorite percentage ratio versus distance from shelf break.

Sediment Structure and Fabric

The detailed, small-scale sedimentary structures in the fine-grained facies have been documented elsewhere (Stow and Shanmugam, 1980). The olive-gray muds are mostly thoroughly mottled by bioturbation. They also have black iron sulfide mottles, thin straight mycelia (Bouma, 1968), and helical *Zoophycos* burrows. Rarely, irregular coarse laminae are preserved as possible lag concentrations of foraminifers and sand grains.

The red-brown muds, mostly well laminated and not bioturbated, show a variety of small-scale structures including parallel, lenticular and wispy lamination, micro cross-lamination, low-amplitude climbing ripples, "fading ripples," convolute lamination, loading, scouring, mud

injection, and micrograding. The silt laminae are grouped into graded depositional units (averaging 2 to 4 cm thick) that display a standard vertical structural sequence. Examination of the silt fabric with a scanning electron microscope (Stow, 1979b) shows, for the majority of silt laminae, a single preferred mean orientation. These orientations are almost identical in direction to the current lineation visible on the surfaces of some laminae, and indicate an approximately north-south or downslope current direction when the cores have been reoriented to geographic north using the mean paleomagnetic declination (Ellwood and Ledbetter, 1976, 1977). By contrast, widely bimodal (E-W, N-S) or random orientations are present in the coarse layers of the olive-gray facies.

The thick sands and gravels and the thin sands in or near the channels are typical of coarse, reworked sandstones and conglomerates in ancient flysch sequences. They show both continuous-distribution grading and coarse-tail grading, and partial Bouma (1962) sequences. The gravels are very poorly sorted with clasts 3 to 40 mm long, some sand fraction but, apparently, very little clay-size material. The degree and direction of dip of long A axes were measured for more than 100 clasts in one bed. Clasts from the bottom 16-cm section had widely scattered orientations but were consistently imbricated in one direction. Clasts from the upper parts of the bed had scattered orientations and low dips about the horizontal. Although limited, these data would tentatively place the

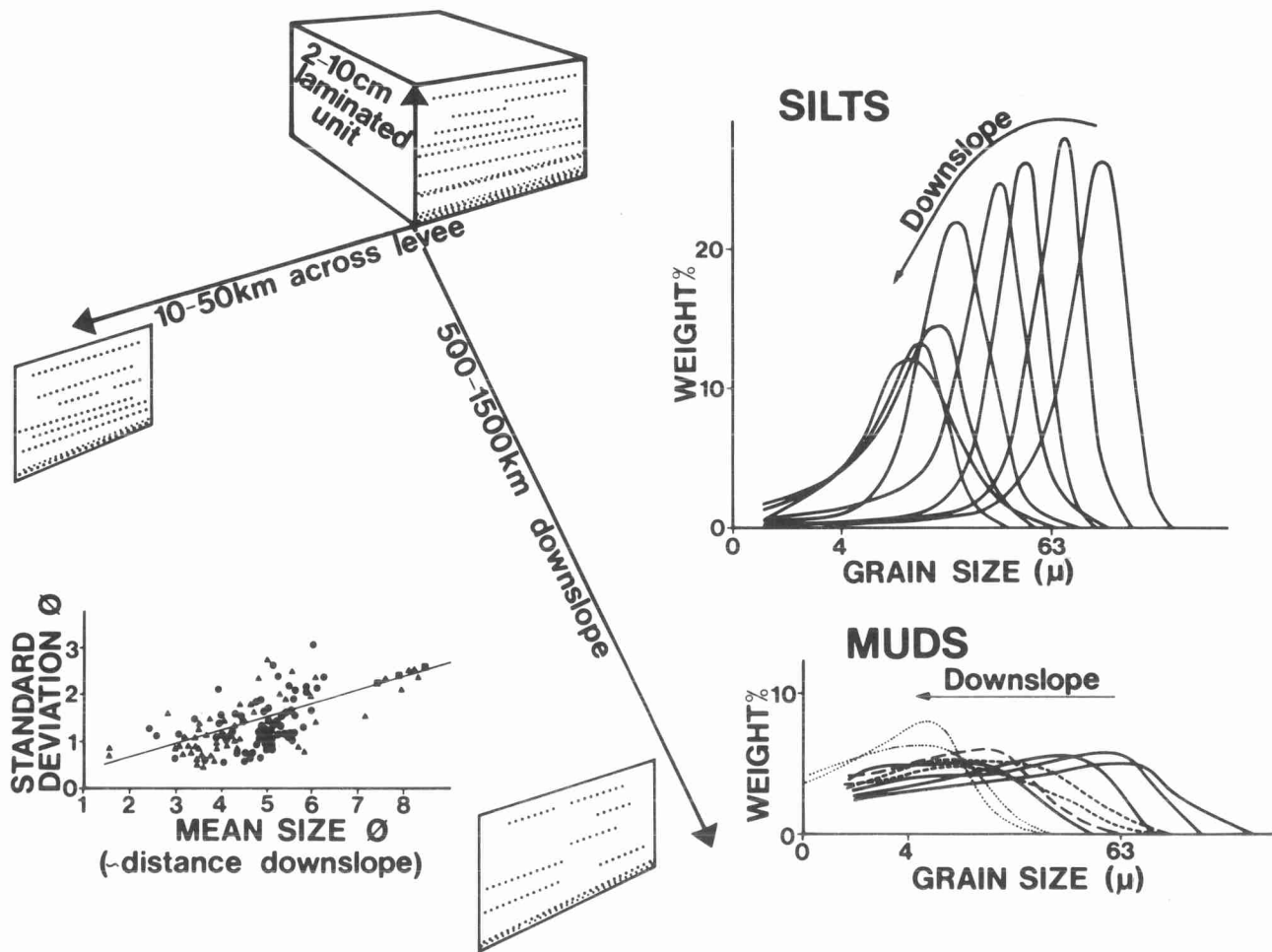


FIG. 11—Schematic model of three-way sorting and grading in fine-grained turbidites. Silt and mud laminae become finer and more poorly sorted downslope, across levees, and upward through graded laminated units. Actual samples of smoothed weight-percent histograms are shown for silts and muds from Laurentian fan—Sohm Abyssal Plain. A plot of standard deviation versus mean size for silts and sands shows approximately linear relation between sorting and downslope distance.

Laurentian fan gravels in Walker's (1976, 1978) normally "graded facies model," in that an apparent basal imbrication dies out toward the top of a normally graded bed, and stratification is not present.

DEPOSITIONAL PROCESSES

Olive-Gray Muds-Contourites

The high percentage of biogenic material, bioturbational mottling, and burrows in this facies suggests relatively low rates of hemipelagic sedimentation. The deeper olive-gray units have higher sand and gravel contents owing to increased ice rafting. There are several lines of evidence which favor the influence of bottom currents during the deposition of this facies (Stow, 1979a): (1) the montmorillonite-rich clay fraction indicates an offshore and more northerly source; (2) the heavy mineralogy of some of the sandy layers indicates limited along-slope mixing; (3) lag deposits at the tops of some cores and some sandy layers indicate reworking; (4) the very fine clay fraction may indicate a long transport distance, whereas an overall coarse mode suggests either bottom-current winnowing of fines or increased sand input from ice rafting or turbidity currents; (5) grain fabrics are consistent with primary downslope sediment supply and secondary along-slope reworking; and (6) photographs and current measurements (Hollister and Heezen, 1972) favor the modification of the present-day sediment surface by the Western Boundary Undercurrent.

The pattern of sedimentation on the fan during the deposition of the olive-gray facies involved several processes. Hemipelagic sedimentation was augmented by ice rafting and rare turbidity currents. Local redistribution of this sediment, as well as the introduction of different source materials, was by the Western Boundary Undercurrent.

Red-Brown Muds-Turbidites

This lithology has previously been described from the eastern North American margin (Conolly et al,

1967; Hollister and Heezen, 1972; Zimmerman, 1972; Piper, 1975) and has been variously interpreted as turbidite or contourite. The absence of bioturbation, biogenic material, or ice-rafted clasts suggests fairly high rates of sedimentation. Several points support a turbidite origin; (1) the fan location, morphology, and the derivation of the red-brown sediment from the Gulf of St. Lawrence; (2) the decrease in frequency and thickness of silt laminae away from channel axes; (3) the regional patterns of mineralogy and downslope textural trends favor an offshore dispersal pattern; (4) the standard sequence of sedimentary structures through graded laminated units and indications of relatively rapid deposition; and (5) the consistent downslope current indications from silt fabric study.

The turbidity currents responsible for the deposition of this facies are thought to have been very thick (up to 1,000 m), very dilute (about 2,500 mg/l), low-velocity (10 to 15 cm/sec) flows (Stow and Bowen, 1978, 1980). They were probably derived mainly from the slumping of unstable sediments on the upper slope. An alternative mechanism involves the direct discharge of large amounts of fine-grained sediment from the front of a floating ice tongue and its concentration into thick, cold, bottom flows.

Sands and Gravels

Thick channel sands and gravels have been noted previously by Piper (1975) from the Laurentian fan, and Stanley et al (1972) from the Gully Submarine Canyon on the west. Their thickness, grading, partial Bouma (1962) sequences, and restriction to channel axes make a turbidity-current (or other mass flow) origin most likely.

FAN GROWTH

Early Growth

The major Mesozoic depocenter on the Scotian margin was the slope and rise south of Sable Island (Parsons, 1975, Uchupi and Austin, 1979). The sediments comprised

Lower Jurassic evaporites, Middle Jurassic to Lower Cretaceous limestones and mudstones, and perhaps Lower Cretaceous black shales.

In latest Cretaceous-Cenozoic time the depocenter shifted to the Laurentian fan region. Large canyons were cut into an Eocene-Oligocene paleoslope (Parsons, 1975; King and Young, 1977) north of the present slope. This Paleogene horizon is a prominent seismic marker which Uchupi and Austin (1979) regarded as coeval to horizon "A" off the eastern United States. Above horizon "A" they have identified three regressive sequences that accumulated as thick (0.5 to 2.0 km) sediment wedges of early-middle Miocene to Holocene age. The major controls on fan sedimentation during this period were the continental glaciations and consequent sea-level variations. Sedimentation rate increases considerably owing to the proximity of the ice margin and meltwater streams eroding an exposed shelf. The fan built upward and outward. The channels were continually filled and eroded, but the aggradation in interchannel areas and the possible backward erosion of the shelf break were such that the valleys became overdeepened and acted as sediment funnels to the outer fan.

It is difficult to assess how the fan morphology has changed in detail. Some of the Paleogene channels appear to have remained active in fan construction through most of the Neogene; others have been filled and abandoned. The more severe glaciations (e.g., the Illinoian) probably had most effect on morphologic changes. For this reason it is believed that sediments of the Wisconsin glaciation were deposited as a relatively thin veneer over an Illinoian surface.

Wisconsin (Fig. 12A)

The dominant Wisconsin facies in most cores is red-brown, silt-laminated mud derived from the Carboniferous and Triassic red beds of eastern Canada and transported to the upper slope by glaciers and proglacial streams. Redistribution of this sediment to the outer margin

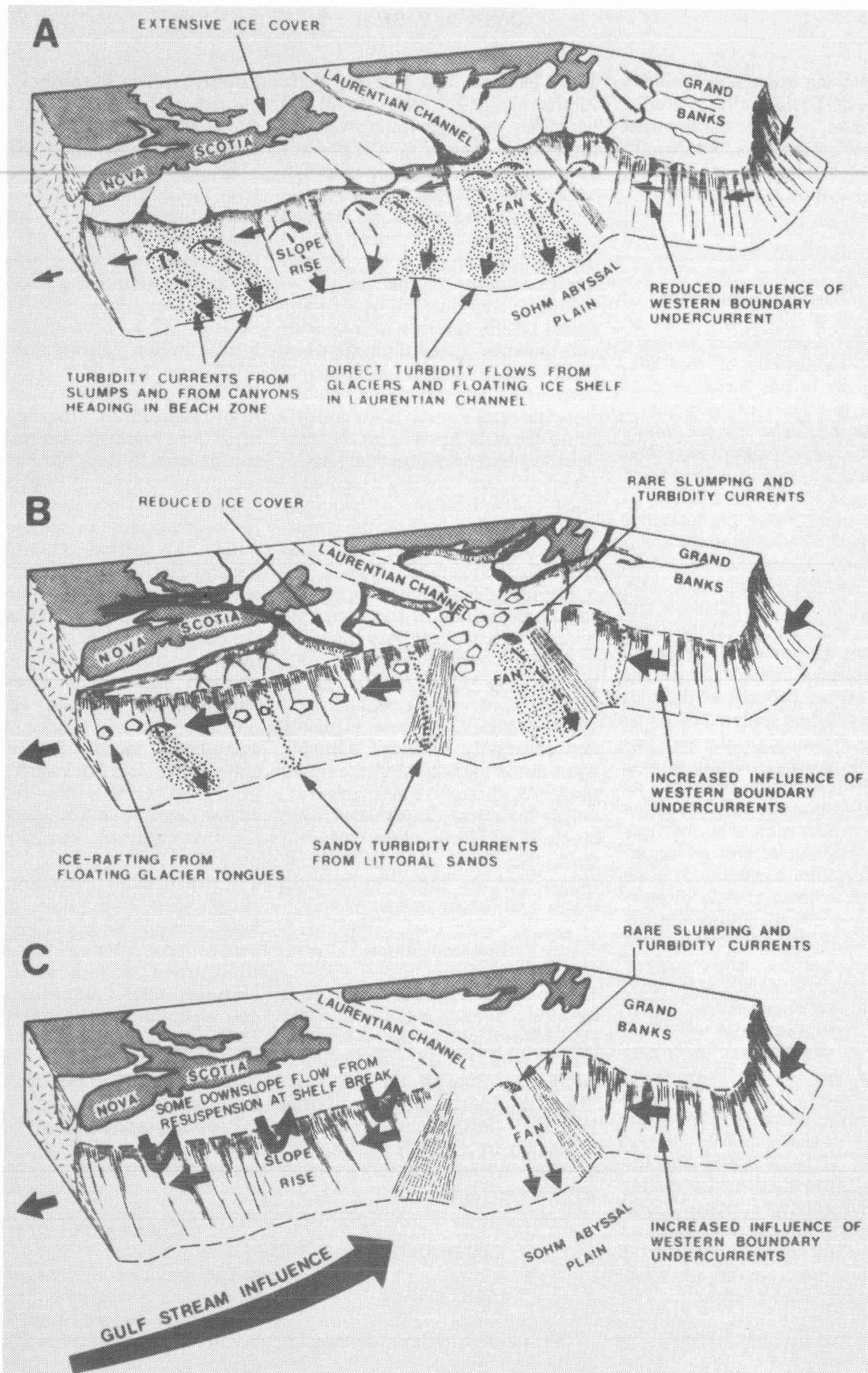


FIG. 12—Interpretation of late Quaternary sedimentation history over Laurentian fan and outer Scotian margin. **A**, glacial: early and mid-Wisconsin stades; sediment supply direct to upper slope and redistribution by turbidity currents; red-brown sediment and channel sands and gravels. **B**, interstades: Wisconsin interstades at ~65,000 and 45,000 years B.P.; late Wisconsin warming from ~28,000 to 15,000 years B.P.; dark olive-gray sediment, thin sands and ice-rafted sediments. **C**, postglacial: rapid rise in sea level in late Wisconsin (~16,000 years B.P.); influence of Gulf Stream on sedimentation during Holocene (from ~11,000 years B.P.); olive-gray sediment dominant.

was mainly by turbidity currents. The frequency of major slumps that developed into turbidity currents was about 1 per 100 to 300 years (assuming a sedimentation rate of 10 to 30 cm/1,000 years, and an average depositional unit 3 cm thick). Direct sediment discharge from floating glaciers and meltwater surface plumes (Alam, 1976) may have also contributed to sedimentation.

There were 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 (Fig. 12B). The planktonic foraminifers 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 (Hughes et al, 1977; Latouche and Parra, 1979). 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,

Conolly et al (1967) suggested 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 color 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 are substantially time transgressive.

Holocene (Fig. 12C)

The early Holocene was a period of ice rafting over the slope and rise and continued red-brown sedimentation on the fan. 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 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 foraminifers, diatoms, and coccoliths) through the water column. These materials were deposited under the intermittent influence of the Western Boundary Undercurrent, which has also introduced limited material from more northerly sources.

Deposition has been sufficiently slow (< 10 cm/1,000 years) and bottom conditions favorable for sediments to have been thoroughly bioturbated, and reduced to a gray color at the sediment-water interface (Hinze and Meischner, 1968; Stanley et al, 1972). There has been some sand spillover of palimpsest sediment onto the Scotian Slope (Stanley et al, 1972). Occasional slumping on the upper slope above the fan, such as that following the 1929 Grand Banks earthquake, has initiated further downslope movement in turbidity currents and helped to flush out the fan channels.

FAN MODELS

Submarine fans are widespread base-of-slope sediment accumulations that have particular horizontal and vertical facies associations controlled by such factors as the rate and type of sediment supply, the tectonic setting and sea-level variations. Fans are important targets for hydrocarbon exploration. The sand or gravel canyons, channels, and suprafan lobes provide good reservoir rocks. The fine-grained slope, interchannel, and basin-plain facies provide potential sealing and source rocks. The interdigitation of these facies due, for example, to fan progradation, may result in stratigraphic traps or, with subsequent tectonism, structural traps. Several large hydrocarbon discoveries have been made in probable fan sediments (Fowler, 1975; Parker, 1975; summary, Walker, 1978) and several authors have emphasized the possibility of substantial petroleum reserves in canyons and fans (Moore and Fulham, 1973; Caughey and Stuart, 1976). Wilde (1978) pointed out that even deep-water continental margin fans should become exploration targets in the near future.

Many different fan models have been developed over the past 15 years in an attempt to understand fan growth and the pattern of facies distribution. The Normark (1970, 1974, 1978) model involves a tripartite morphologic division below the feeder canyon into an upper fan with main leveed channel, a middle fan with active and abandoned suprafan regions, and a smooth lower fan grading into basin plain. The model was originally developed from California continental-margin fans and perhaps best describes a small, deep-water fan type. The Mutti and Ricci Lucchi model (Mutti and Ricci Lucchi, 1972; Mutti, 1977) comprises distributary channels and interchannel areas on the inner fan, a channel-mouth bar and bypass zone, detached sandstone lobes and interlobe areas on the outer fan, and a fan-fringe to basin-plain region. This has been reconstructed from Tertiary flysch deposits of the Italian Apennines and may best represent a large, med-

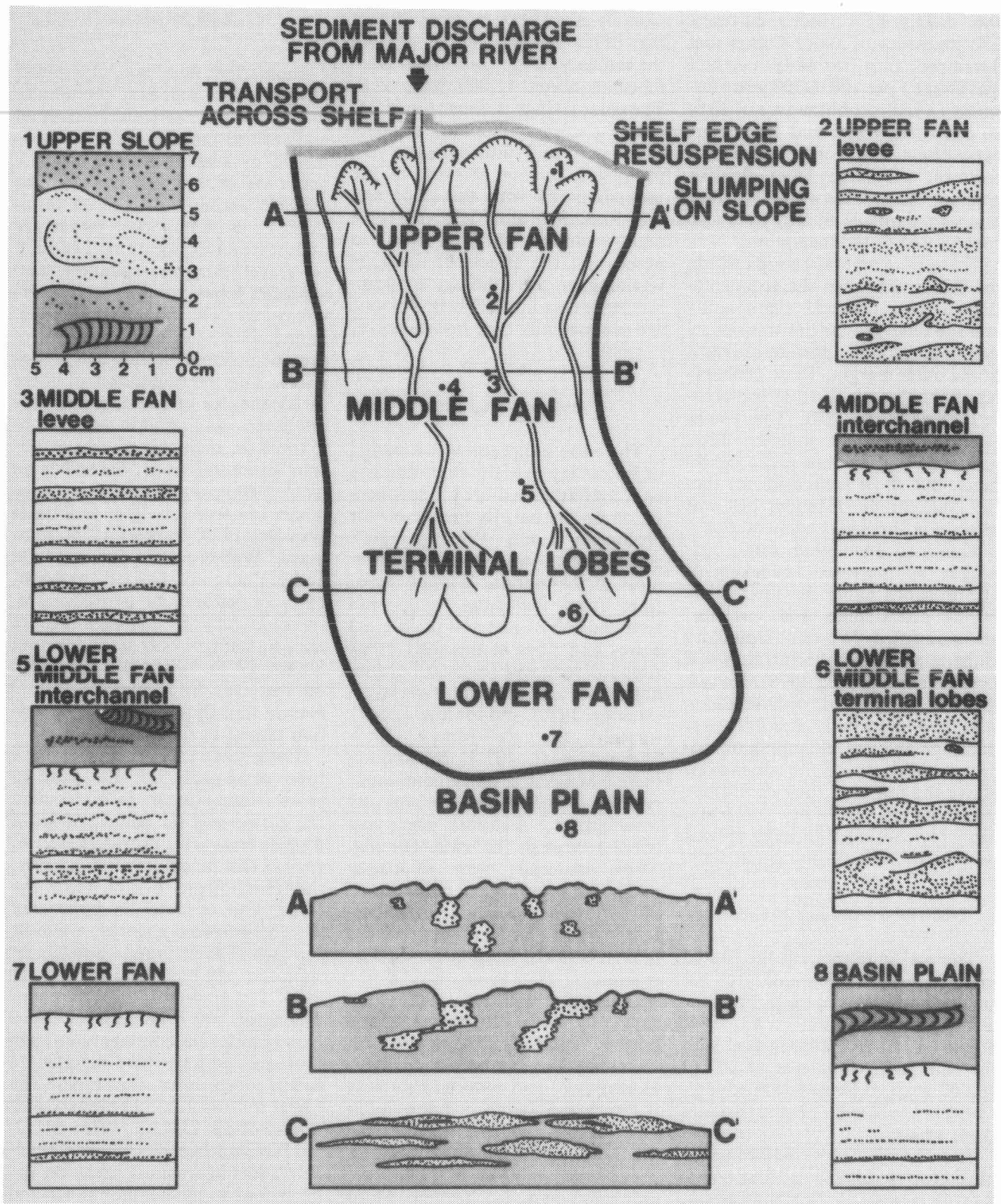


FIG. 13—Proposed fan model for large deep-water fans, showing observed distribution of fine-grained sediment facies and their relations to fan subenvironments. Silts and sands stippled, muds and clays blank. Bioturbation shown as small irregular lines and larger *Spretites* pattern. Dimensions: fan radius, 250 to 2,500 km; channel width, 5 to 25 km; examples, Bengal, Indus, Amazon, Congo, Laurentian; references, Curray and Moore (1971); Stow (1975, 1976, 1977).

ium to deep-water fan type. The Walker (1967, 1976, 1978) model to some extent combines elements of both the other main models. In its latest version it allows for a period of rejuvenation during fan growth that results in channel incision through the middle fan and construction of a new lobe on the lower fan. The model has been developed from several ancient channel-fan systems, concentrating particularly on the nature and distribution of re-sedimented conglomerate and sandstone facies. It may be the closest model for a small to medium, shallow-water fan type.

These models are undoubtedly very useful for predicting facies distribution and prospective sandstone reservoirs for hydrocarbon exploration, but there remains much room for refinement and development:

1. The characterization and distribution of fine-grained sediment facies are not known in detail, although several recent contributions have been made (Nelson et al, 1976, 1978; Mutti, 1977; Piper, 1978).

2. The fan models do not adequately represent either the very large, deep-water fans such as the Bengal (Curry and Moore, 1971), Indus (Jipa and Kidd, 1974), Mississippi (Huang and Goodell, 1970), and others; or the shallow-water fans and slope-apron deposits such as those of the North Sea and similar small basins (Bartolini et al, 1975).

3. We do not have sufficient data on vertical facies development in present-day fans.

4. We have not yet adequately related fan types to the wide range of factors which control their development—basin geometry, margin nature, sediment supply, feeder system, etc.

As the Laurentian fan is large, constructed in deep water, and composed dominantly of fine-grained sediments, the present study can help toward answering parts of 1 and 2 in the foregoing. When compared with other large, deep-water fans the following model (Fig. 13) can be derived for active fan growth. A major river with high sediment/water discharge ratio, or

an actively eroding glacier supplies sediment of all grain sizes to the coast. Cross-shelf transport occurs through a canyon, delta distributary system, or other shelf processes such that the shelf edge and slope are built up. Longshore supply to and mass sediment movement within the canyon head, resuspension at the shelf edge, suspended flood loads, and slumping are among the main processes initiating sediment redistribution downslope by mass flows and turbidity currents.

The slope and upper fan are irregular, slump scarred, crossed by one or more main canyons or channels and by minor channels and tributaries between slump blocks. Erosion with limited deposition is the dominant process. Several main channels are generally developed across the middle fan, piling up large amounts of fine sediment on the levees and interchannel areas. The channel floors may be built up above the fan surface or deeply incised following a period of rejuvenation. The channels funnel sediment downslope, producing an elongate fan shape, then die out on the lower middle fan where they construct large terminal lobes. Provided that the receiving basin is sufficiently large, a smooth lower fan can be built out a long way and merge with the basin abyssal plain.

Coarse-grained sediments are mostly confined to the channels and terminal lobes. Their character and downslope evolution has been discussed by Walker (1978) and others. The fine-grained sediments show a separate and distinctive three-way evolution of textural and mineralogical grading and sorting. The silt laminae become finer and more poorly sorted over hundreds of kilometers downslope, tens of kilometers across interchannel areas, and a few centimeters upward through a single depositional unit. Repetition of different parts of the standard sedimentary structure sequence (Stow and Shanmugam, 1980) is characteristic of different fan environments (Fig. 13). On the upper fan, near-channel levees, and parts of the terminal lobes, the silt-sand layers are thickest, irregular, lenticular, cross-laminated, and

flaser-bedded. Further downslope (middle fan) and away from channel axes are the regular, thinly silt-laminated muds. On the lower fan an alternation of silt-laminated and graded-mud units is common; abyssal-plain turbidite muds are graded to ungraded with few thin, wispy silt laminae.

Slumped and structureless silty sandy muds are deposited on the upper slope as fallout of suspended river and shelf sediment. Hemipelagic muds may be interbedded with turbidite units in interchannel, lower fan, and basin-plain areas, increasing as a proportion of the total sediment in the lower energy environments. Muddy contourites may also be intercalated with fan turbidites. They are similar in appearance to the monotonous, structureless hemipelagic muds but with irregular sandy layers indicating winnowing by bottom currents.

The distribution of characteristic fine-grained sediment facies over different fan types and other margin settings is an important new tool in hydrocarbon exploration.

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