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THE MORPHOLOGY OF TWO TRANSVERSE CHANNELS ON THE NORTHEAST NEWFOUNDLAND SHELF

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INTRODUCTION

During the past decade, many geological and geophysical studies have been undertaken in the Labrador Sea. Grant (1971) presented a comprehensive regional study of the geology of the Canadian margin of the Labrador Sea. Van der Linden (1975) summarized the history of the formation of the bedrock beneath the Labrador Sea.

A bathymetric compilation was made covering an extensive portion of the continental shelf off northeast Newfoundland (Figs. 1 and 2). Two small areas indicated in the figures were selected for detailed study of their geomorphology. Transverse channels are the dominant geomorphological feature in both areas.

The bathymetric data was collected on detailed multi-disciplinary marine surveys, conducted jointly by the Canadian Hydrographic Service (Atlantic Region), and by the Atlantic Geoscience Centre of the Bedford Institute of Oceanography, Dartmouth, Nova Scotia, during 1973 and 1975. These two surveys form part of a detailed geophysical program to map Canada's continental shelf. Additional data collected during previous studies has been used where relevant.

REGIONAL SETTING

A. Bathymetry and Physiography

The continental margin off southern Labrador and northeastern Newfoundland forms part of the western flank of the Labrador Sea. This study is confined to the area off northeast Newfoundland, which can be physiographically subdivided on the basis of water depth (Fig. 2):

1. The Inner Shelf fringes the coasts of Labrador and Newfoundland and generally has a water depth less than 200 m.
2. The Outer Shelf consists of large bank areas (Belle Isle Bank, and Funk Island Bank) which have water depths ranging between 200 m and 400 m.
3. The Marginal Channel separates the Inner Shelf from the Bank areas: this feature has a variable water depth, generally between 200 and 400 m.
4. Transverse Channels (Hawke Saddle, and Notre Dame Channel) cross the Outer Shelf from the Marginal Channel to the shelf break at around 400 m.

All names of features used in this study were taken from existing charts, except North Arm, South Arm, North Ridge, and South Ridge, which are new names applied to the complex relief within Notre Dame Channel.

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B. Geology

The Precambrian Shield and the Appalachian System are the two major geological provinces which affect the study area. The area has been affected by orogenies in Ordovician, Devonian, and Caroniferous times. Sediment accumulation within the study area is a result of the subsidence of a rifted continental margin, caused by the opening of the Labrador Sea (van der Linden 1975). The Labrador Sea was formed by sea-floor spreading about a mid-ocean ridge (Laughton 1971), as shown by magnetic stripes on the seafloor. The Labrador Sea began to open during the Cretaceous period (82 mybp), and continued to open until the Eocene (47 mybp). During the Eocene, Labrador and Greenland ceased to separate; however, the Norwegian Sea and the North Atlantic ocean continued to open and spreading continues in these two areas.

C. Previous Investigations of Geomorphology

Holtedahl (1950, 1970) studied marginal channels off glaciated coasts and suggested that they were formed mainly by faulting at the contact between offshore sediments and continental 'shield' rocks. Grant (1971) examined the marginal channel off the Labrador coast and found no evidence of recent faulting. Grant suggested that preferential erosion by glaciation together with a tectonic 'hinge' zone near the contact of Palaeozoic strata with the Precambrian crystalline rocks, were the reasons for the formation of narrow marginal channels off glaciated coasts. Glaciation was considered mainly responsible for over-deepening of transverse channels.

The Outer Shelf is underlain by Cenozoic strata (Grant 1971) on which Pleistocene ice sheets deposited a thin veneer of sediments during their retreat (van der Linden *et al* 1975).

On Hamilton Bank van der Linden *et al* (1975) recognized end moraines, ground moraine, and kame and kettle morphology in a detailed survey using side scan sonar, seismic reflection profiles, and bottom photographs.

Slatt *et al* (1972) sampled surficial sediments of Funk Island Bank, Belle Isle Bank, and Hamilton Bank. The results suggested that Cretaceous or Tertiary bedrock underlies the surficial sediments, in agreement with inferred data obtained by seismic reflection and seismic refraction data.

DATA PROCESSING

A. Navigation

In 1973, navigation was controlled mainly by Decca 12f in the range-range mode (Eaton 1975). The baseline between the two shore-based slave stations was relatively short so that Loran-C in the rho-rho mode and satellite navigation

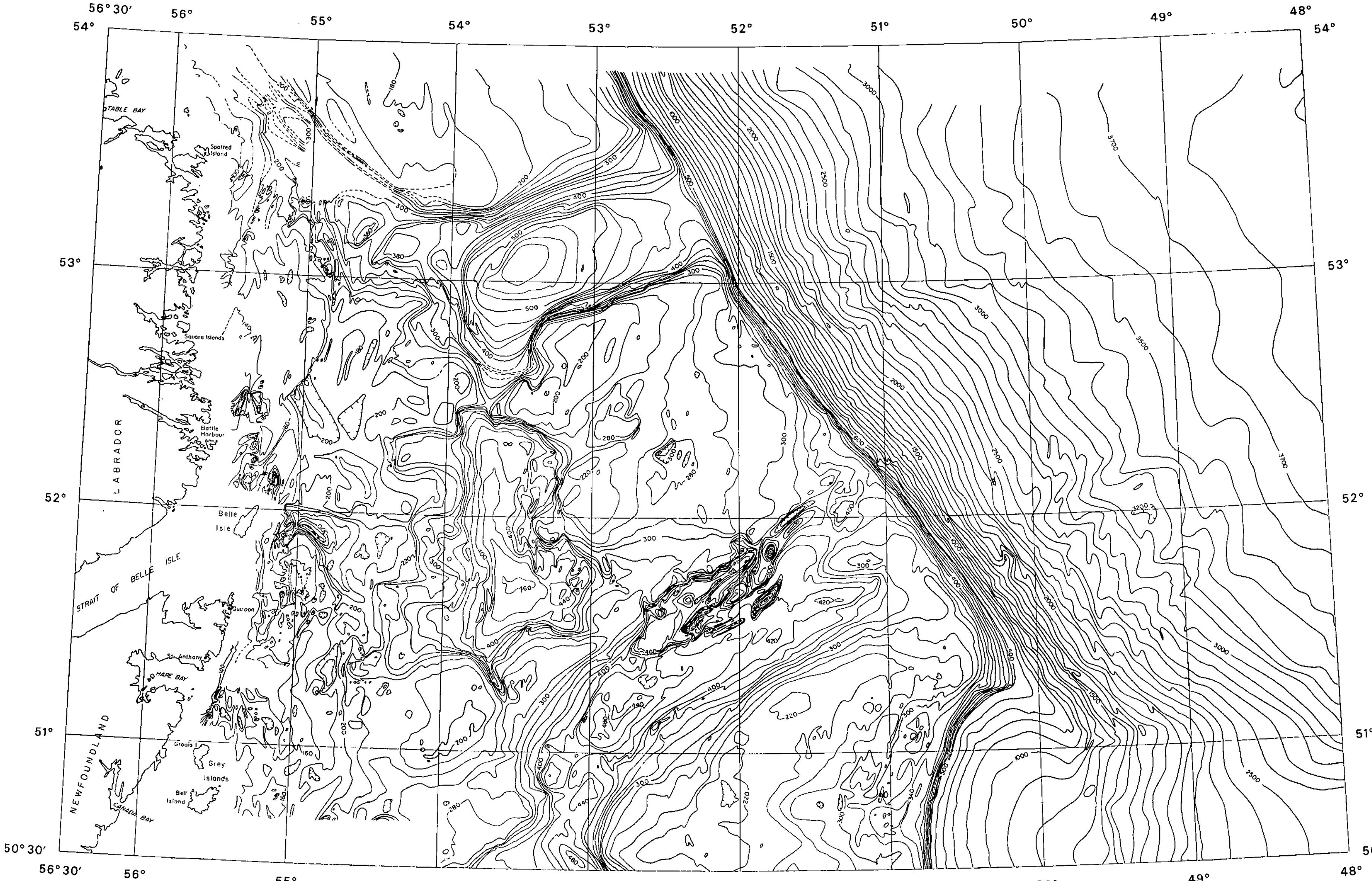


FIG. 1 Bathymetry of Northeast Newfoundland Shelf.

(Grant 1973) were used to overcome the short operating range offshore, which was imposed by the Decca geometry.

In 1975 Loran-C, supported by satellite navigation, was used as a primary navigation device. A hybrid Decca 12f system (a rho-rho system) was used while operating near the Loran-C baseline, in order to improve navigation in a longitudinal sense.

Reference buoys were used in both surveys to monitor clock drifts of the cesium beam time standards.

Post-survey analysis of 70 navigational satellite and Loran-C comparison fixes show a standard deviation of 157 m in latitude, and 225 m in longitude.

Survey lines in 1973 and 1975 were run in an east-west direction with a line spacing of about 4 km. Cross lines run at oblique angles to the regular line network help to check on equipment, and navigation performance. Cross-line checks were within four m, where bathymetry indicated considerable bottom roughness.

B. Bathymetry

Bathymetric data in 1973 were collected using a combined Raytheon Transceiver and Gifft recorder system. Calibration for sound in sea water was done by lowering a metal cone to specific depths by means of a calibrated wire. Data were collected and recorded at a fixed velocity of sound in sea water of 800 fathoms per second (m/s) and were reduced, according to corrections published by Matthews (1939), for variations in the velocity of sound in seawater. The resulting reduced depths were converted to metres and portrayed in the form of soundings on field sheets (scale 1: 150000; Polyconic projection).

In 1975, bathymetric data were collected using a Raytheon Transceiver and Recorder system. This system was employed in a similar fashion to the one used in 1973, with regards to collection and portrayal.

The resulting field sheets from these two surveys, although incomplete in the north, were contoured at an interval of 20 m out to the continental slope (500 m). The slope and rise were contoured at an interval of 100 m. Figure 1 was produced from these field sheets.

C. Seismic Reflection Profiles

Seismic reflection profiles were collected using Bolt airguns driven by air compressors, with chamber sizes of 32 cm^3, 102 cm^3, and 760 cm^3. The larger airguns were used in deeper water, while the 32 cm^3 airgun was used in shallow water. Data were recorded on magnetic tape and displayed on 48-cm paper.

Seismic reflection profiles were spaced approximately 37 km apart (Fig. 3). Grant (1971) also obtained seismic reflection profiles which were used to provide additional coverage.

D. Bottom Roughness

Monahan and MacNab (1974), and van der Linden *et al* (1975) used a technique of 'meso and micro-relief' mapping on Flemish Cap and Hamilton Bank, respectively. This technique consists of expressing meso and micro-reliefs in terms of their half wavelengths and amplitudes. Confidence in the results, and the interpretation of the roughnesses observed, is enhanced when independent checks are made with devices such as underwater photography, side-scan sonar, and bottom samples. A 'calibration' of sea floor roughness can be obtained by employing other independent observations.

This study relies on seismic reflection and echo-sounder profiles for mapping the sea-floor roughness. The bottom roughness types recognized by van der Linden *et al* (1975) on Hamilton Bank, have been used to compile Figure 4.

RESULTS

Hawke Saddle Detailed Area

The Labrador Marginal Channel separates the Inner Shelf from Hamilton Bank and parallels the southeast Labrador coast. The channel widens as it merges with the northeastern corner of Hawke Saddle. The Marginal Channel continues (?) southward from the southwest corner of Hawke Saddle, where the channel widens and deepens again to form an isolated basin (St. Anthony Basin) which separates Belle Isle Bank from the Inner Shelf. St. Anthony Basin has a deeply indented margin compared with Hawke Saddle.

Hawke Saddle is a transverse channel separating Hamilton Bank from Belle Isle Bank, and is approximately 130 km long and 65 km wide. It has a variable longitudinal profile, due to a deep basinal region at the western end of Hawke Saddle (water depth greater than 560 m), and a relatively shallow region near the shelf edge (water depth less than 440 m). Hawke Saddle has steep sides and is U-shaped in cross section.

Type III relief occurs on the north flank of Hawke Saddle. This relief is associated with ground-moraine on Hamilton Bank (van der Linden *et al* 1975), and is also observed on the saddle area near the shelf edge. The southern slope of Hawke Saddle has a Type IV roughness which may be indicative of a thin glacial sediment cover;however, the relief portrayed may be due to a hyperbolic reflection effect sometimes observed on slopes.

Pre-Pleistocene bedrock units have been mapped where seismic data from Grant (1971) intersects seismic lines from the present study. North of Hawke Saddle, Mesozoic (?) - Cenozoic (?) strata onlap lower Palaeozoic rocks. To the south a wedge of upper Palaeozoic (?) - Mesozoic (?) folded sediments onlaps the lower Palaeozoic rocks and underlies the Mesozoic (?) - Cenozoic (?) strata. The lower Palaeozoic rocks unconformably overlie Pre Cambrian rocks near shore (Grant 1971). There is an unconformity upon which upper Palaeozoic strata were deposited. Evidence from the Grand Banks (Grant 1975) suggests that this unit may be

Jurassic, as the folding may be a result of salt tectonics. The Jurassic folded strata are truncated, indicating a period of erosion prior to the deposition of Mesozoic (?) - Cenozoic (?) strata. Seismic reflection profiles indicate that this unit has numerous reflective horizons that are parallel to the lower Cretaceous unconformity (Grant 1975) which truncated the Jurassic beds. The lower Cretaceous unconformity and the overlying strata dip gently seaward, probably due to uplift in Tertiary time (Grant 1971) or subsidence since the period of the Labrador Sea opening.

Notre Dame Channel Detailed Area

Notre Dame channel is a depressional feature extending from the confluence of three tributary channels, south of the study area, acorss the Outer Shelf to the Shelf Edge.

Between Belle Isle Bank, and Funk Island Bank, Notre Dame Channel separates into 'finger-like' extensions (North and South Arms). North Arm is about 80 m deeper than South Arm. Three depressions within North Arm exceed 500 m water depth. Small peaks occur on the north wall of North Arm, and an isolated peak occurs near the centre of North Arm.

North Ridge and South Ridge separate North and South Arms. The long axis of the ridges roughly parallels the direction of Notre Dame Channel. North Ridge is dominated by four peaks, all of which have least depths of less than 280 m. The largest peak has a water depth less than 160 m. A depression deeper than 480 m water depth separates North and South Ridge. South Ridge consists of two separate peaks that are aligned parallel with North Ridge. The northernmost peak has a water depth less than 280 m, and the other peak is about 20 m deeper.

The saddles that exists near the Shelf Edge seaward from Notre Dame Channel is more complex in morphology than is the saddle within Hawke Saddle. A ridge associated with Funk Island Bank trends northwesterly to truncate South Arm. The large peak on the North Ridge merges with Belle Isle Bank to constrict the North Arm.

Type V bottom roughness occurs on the floors of North Arm and Notre Dame Channel. Type II roughness is observed on the floor of South Arm, and on most of Funk Island Bank. Hodge (1972) found gravelly mud, sandy mud and muddy sands within a portion of the Funk Island-South Arm zone mapped as Type II, which may have a real or apparent relationship with bottom roughness in this area. Type III bottom roughness occurs between St. Anthony Basin and North Arm, on the North and South Ridge, and on the saddle area adjacent to the shelf edge.

DISCUSSION

The following distinctive relief features seen within Notre Dame Channel (Fig. 6) require an explanation: (1) the local highs, represented by North and South Ridges; (2) the general broad depression, on which North and South Ridge are superimposed; (3) the local depressions, represented by North and South Arms; (4) a fan-like feature north of section AA' in Figure 6; and (5) the 'terraces' or 'benches' seen on the flanks of the depressions, and their possible concordance.

These features could be a result of one or more of the following processes: (A) sub-aerial erosion, (B) sub-glacial erosion and (C) glacial deposition.

A. Sub-Aerial Erosion

Van der Linden *et al* (1975) suggest that glaciation probably began on the Labrador Shelf during the Illinoian glàcial period (0.5 mybp), because this glaciation was more extensive than the Wisconsinan glaciation. Sedimentation of 300 to 400 m of deltaic sands by an ancestral Churchill River during the Late Pliocene-Early Pleistocene suggested to van der Linden *et al* (1975) a subsidence rate of 90 m in 0.5 my.

A 5-km accumulation of Cretaceous and younger sediments at the shelf edge is depicted by van der Linden (1975), based on seismic refraction data. 80 my of subsidence is implicit in the history of the opening of the Labrador Sea. The basal Cretaceous sediments are terrestrial in origin (G. Williams, personal communication) and can be considered to have been deposited above or near sea level. Sediment thickness at the shelf edge is roughly equivalent to continental subsidence. If subsidence was a linear function with time, a 5-km. subsidence in 80 my is equivalent to 60 m/my. A theoretical exponential function of relative subsidence (Sleep 1971) suggests an approximate subsidence rate of about 40 m/my during the last my. These figures do not agree with van der Linden *et al's* suggested rate of van der Linden *et al (op cit)*.

Although fluvial downcutting may have originally formed Marginal Channel, Hawke Saddle, and Notre Dame Channel these depressions have distinctive U-shapes in cross section, indicative of glacial modification (Shepard 1931).

The ridges have not been emergent since their formation, if the unconsolidated cover is Pleistocene. Therefore, sub-aerial erosion was not a factor, except to provide a small degree of relief on which glacial debris was deposited. The 'benches' or 'terraces' are not likely to be erosional features but may be syn-depositional in origin.

Sub-Glacial Erosion

Grounded ice within the study area is implied when glacial overdeepening of the depressions is considered. Glacial erosion is suggested in the formation of the basinal depressions and the deposition which resulted in the formation of the saddles (van der Linden *et al* 1975). The occurrence of glacial drift on the bank areas implies glacial deposition as well as erosion.

Sub-glacial streams (or 'rinnentaler') (Flint 1971), provide a mechanism for localized erosion (as opposed to a regional erosion caused by the 'glacial mill') as the ice sheet excavated the underlying bedrock. Large hydrostatic heads develop (due to the pressure of the overlying ice)

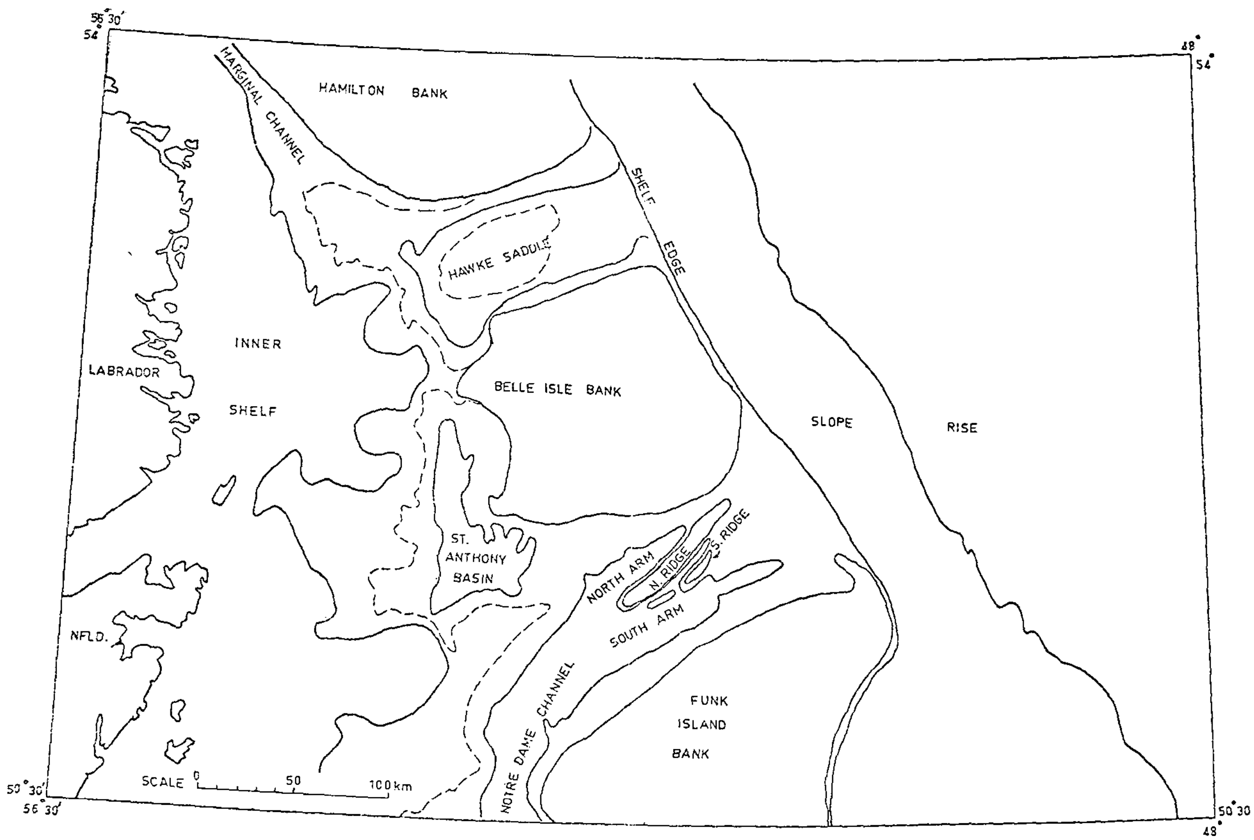


FIG. 2 Physiography and names on Northeast Newfoundland Shelf.

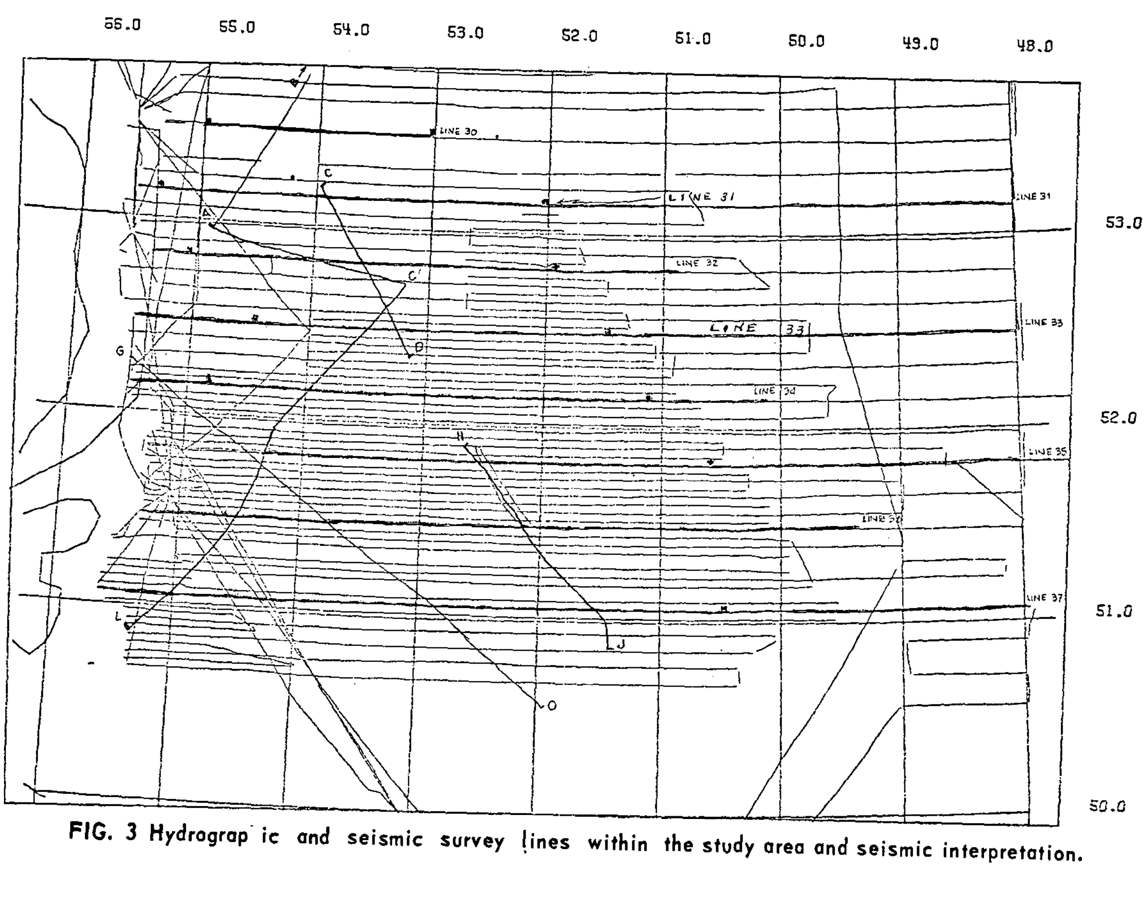


FIG. 3 Hydrograp ic and seismic survey lines within the study area and seismic interpretation.

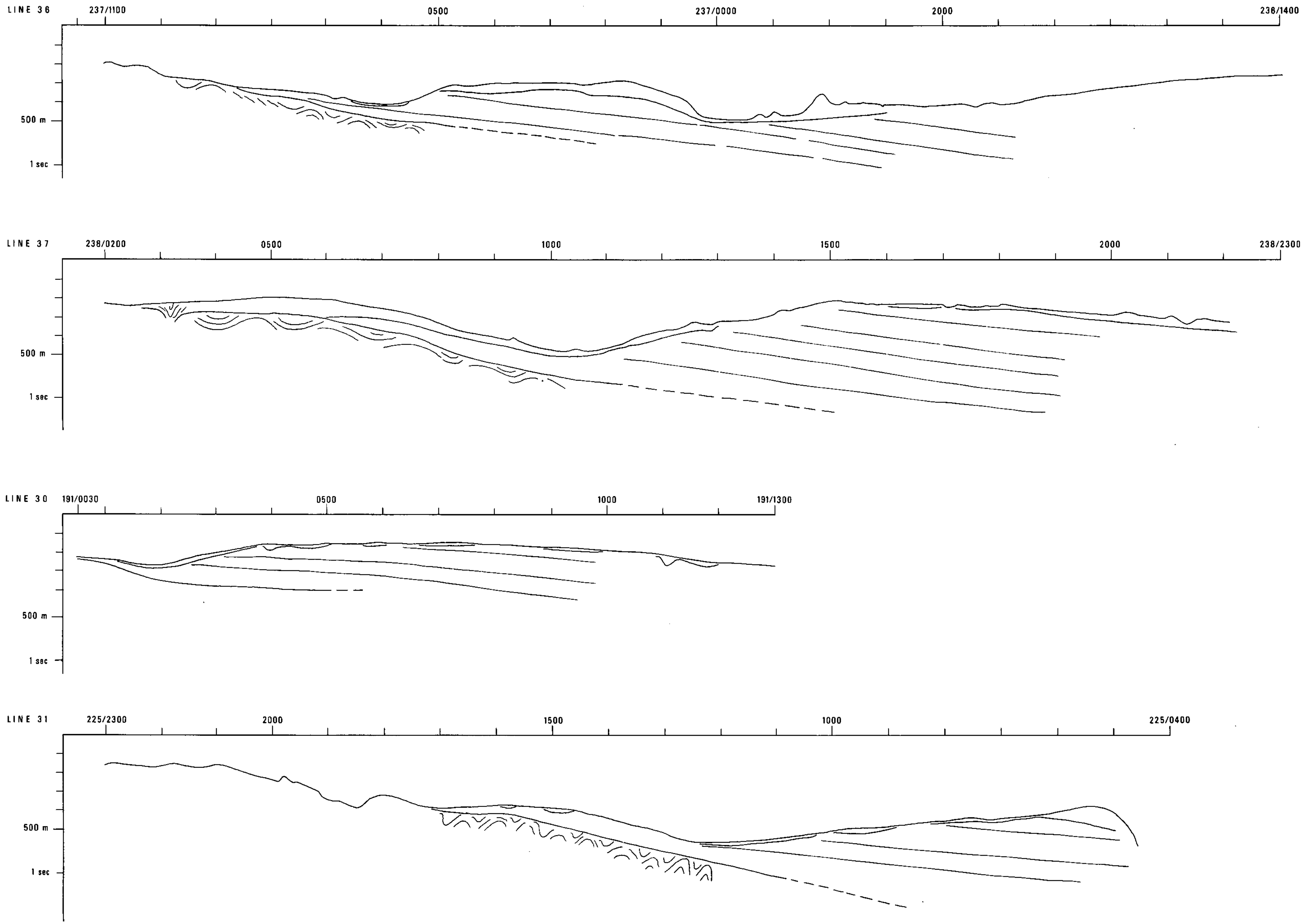


FIG. 3 Continued

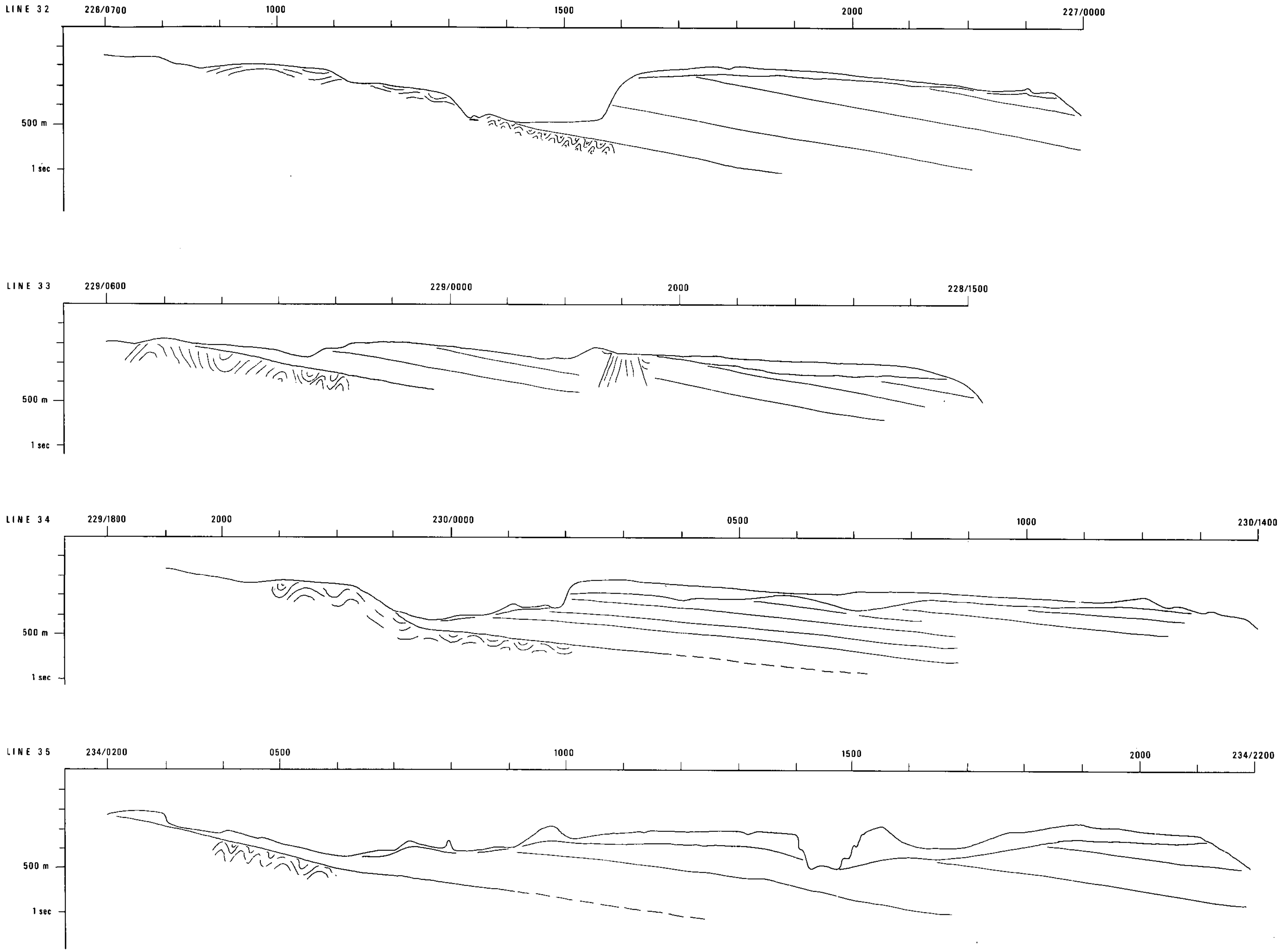


FIG. 3 Continued

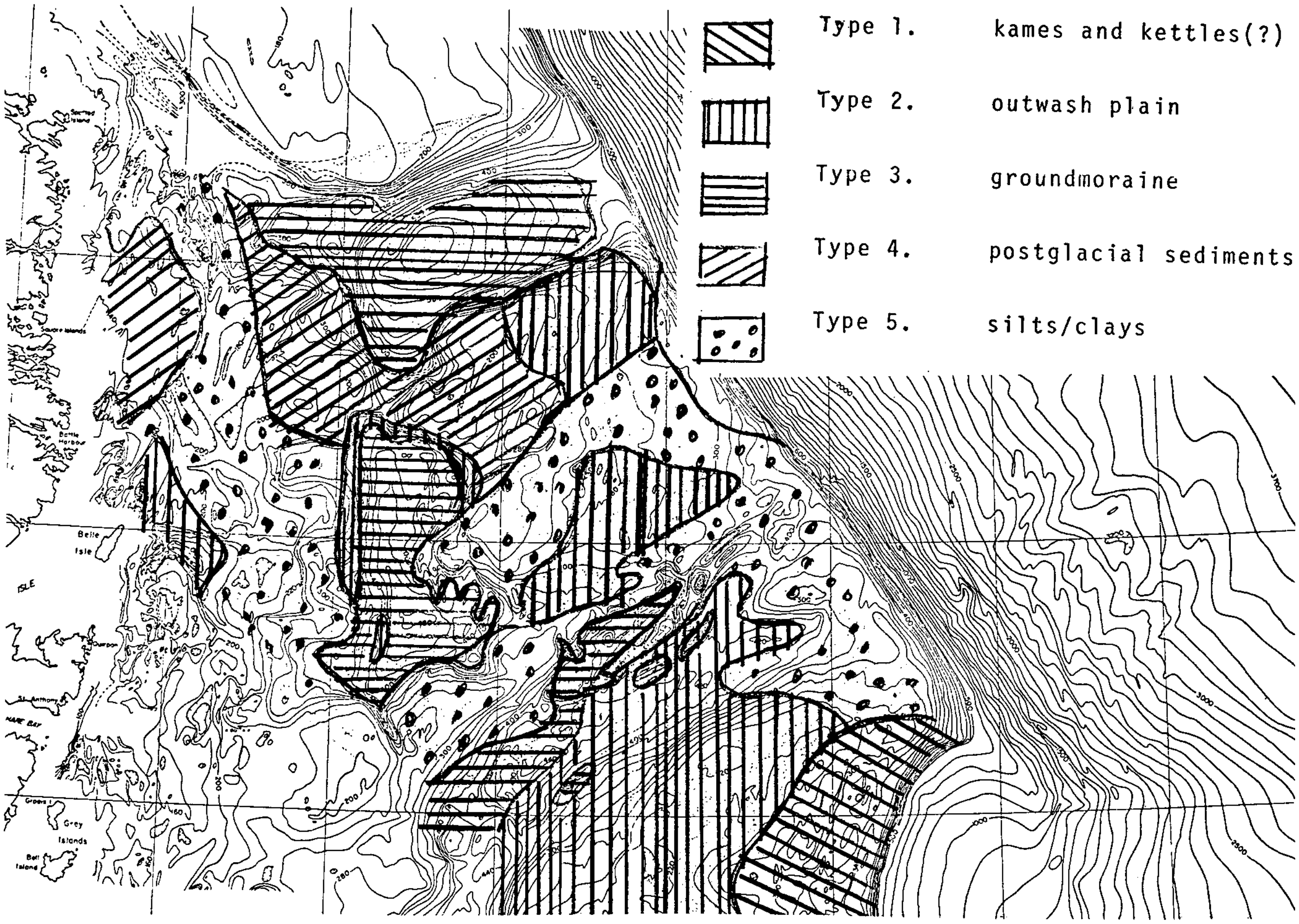


FIG. 4 Bottom roughness categories

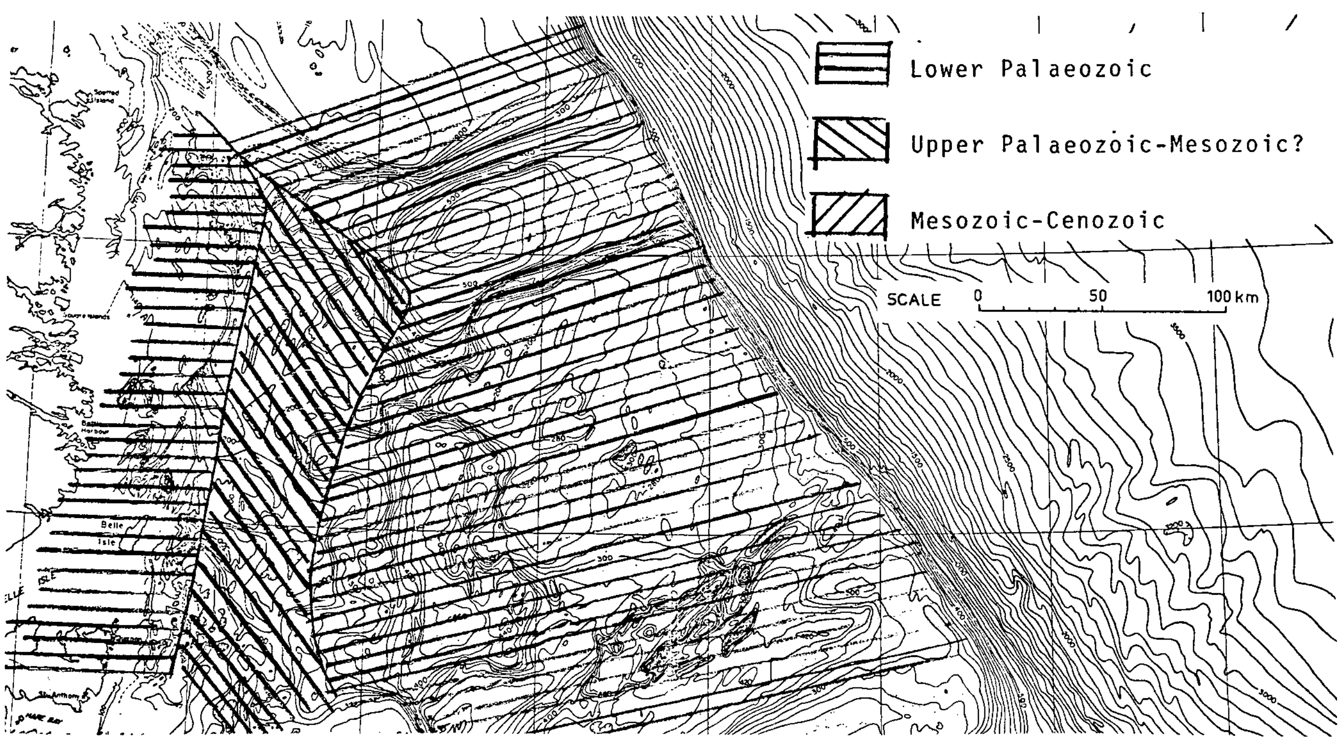
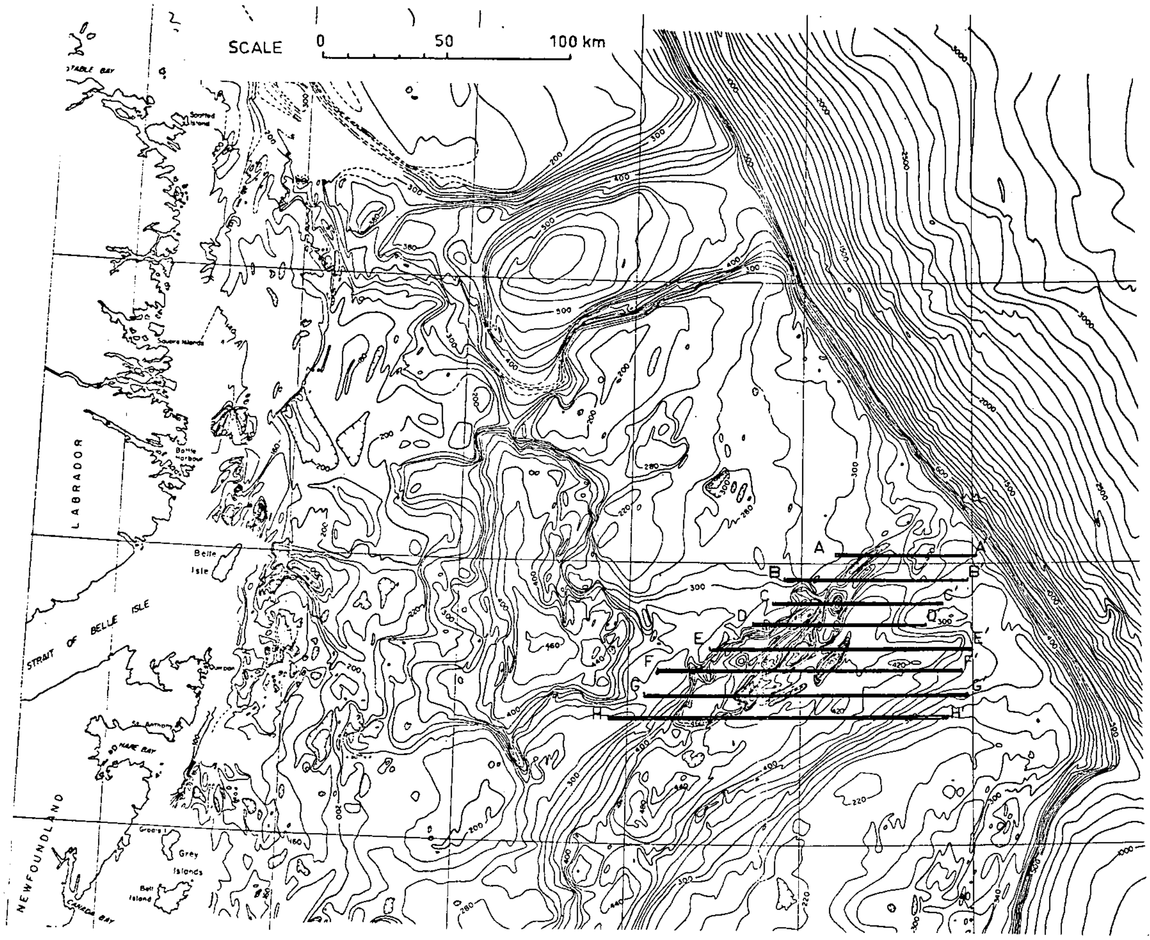


FIG. 5 Distribution of bedrock units



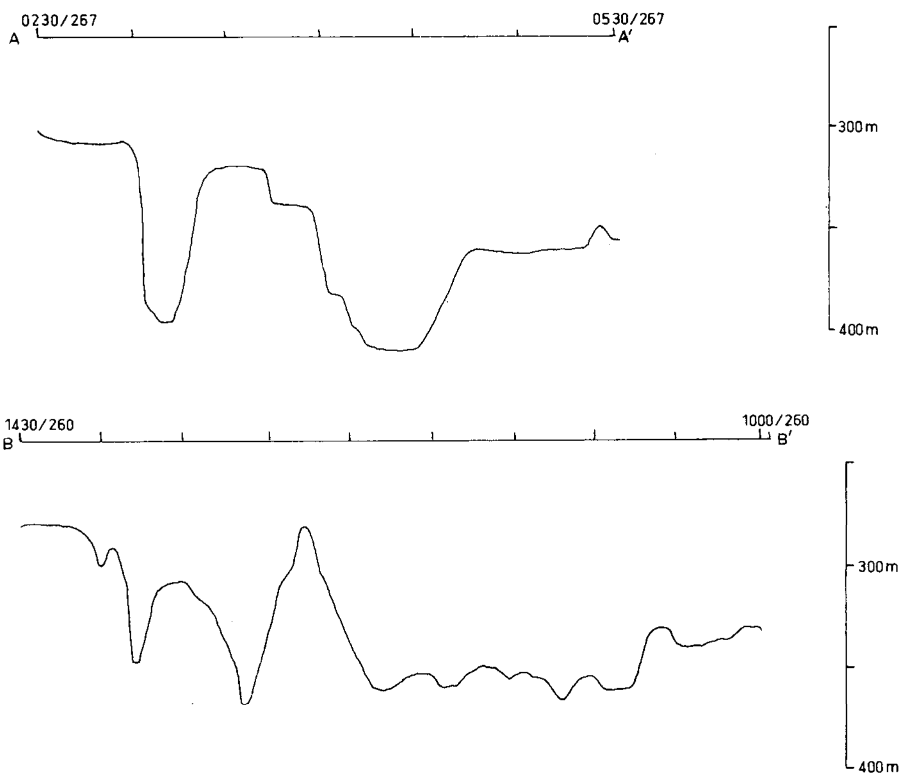


FIG. 6 Location and display of eight bathymetric profiles across Notre Dame channel

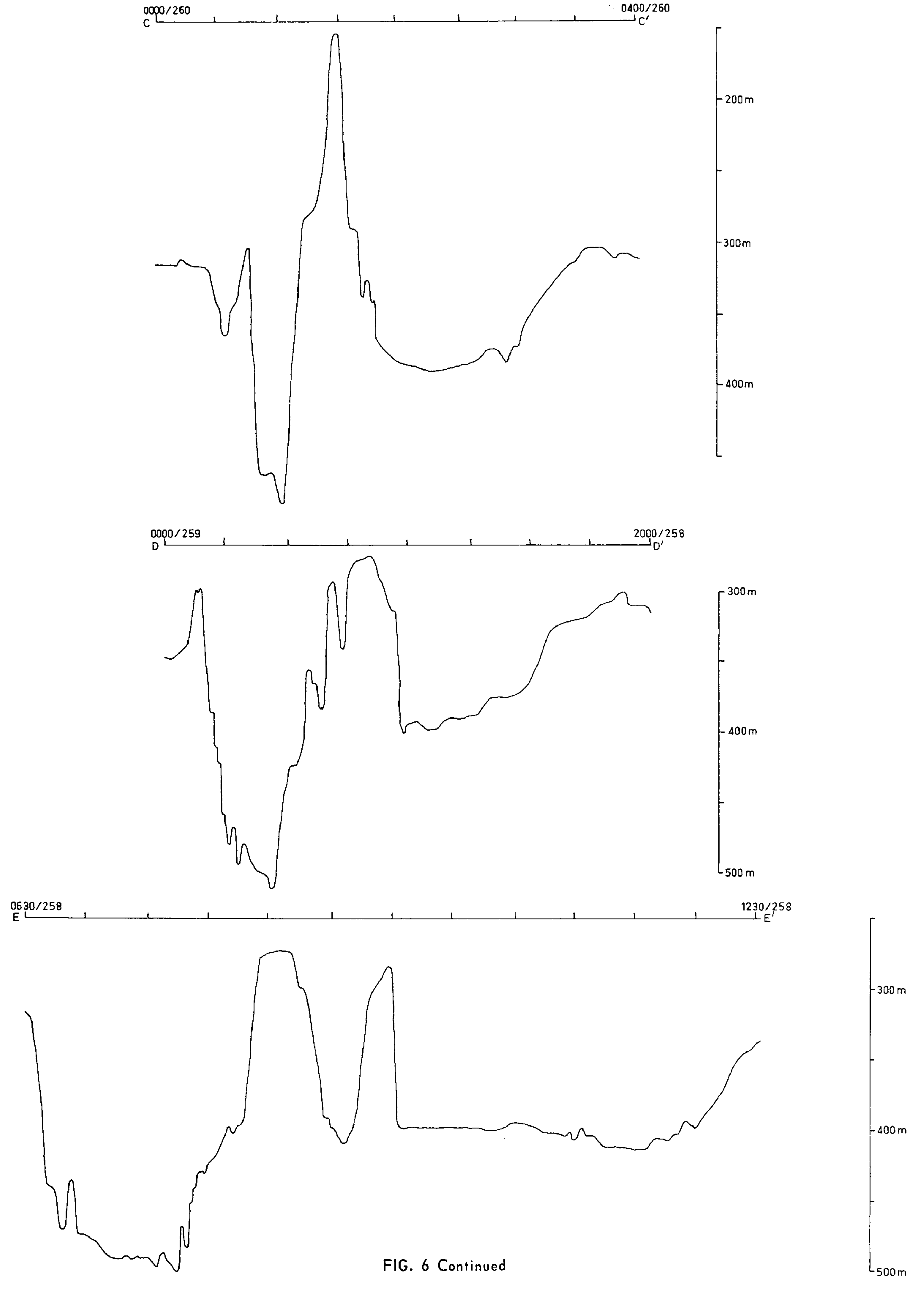


FIG. 6 Continued

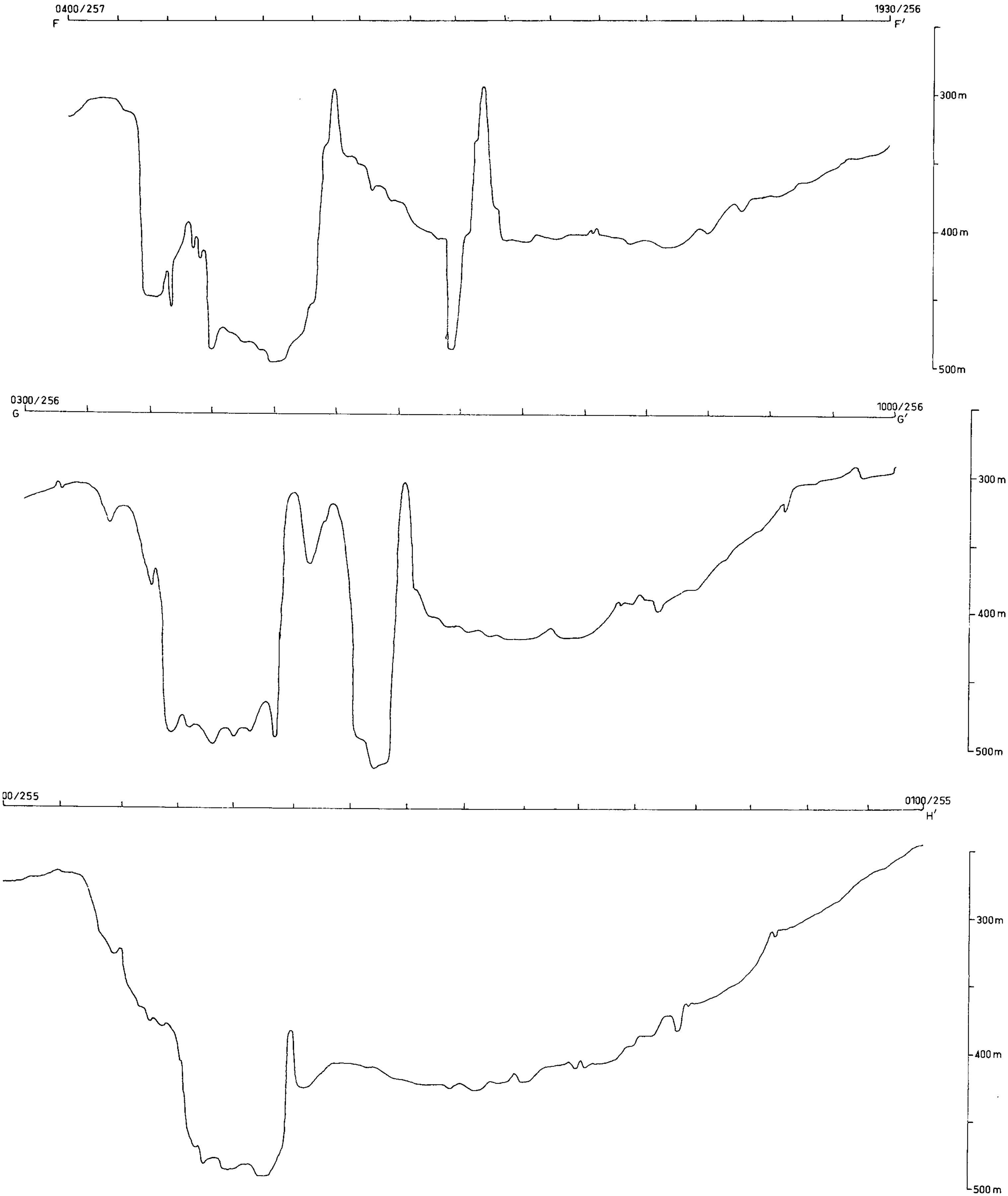


FIG. 6 Completed

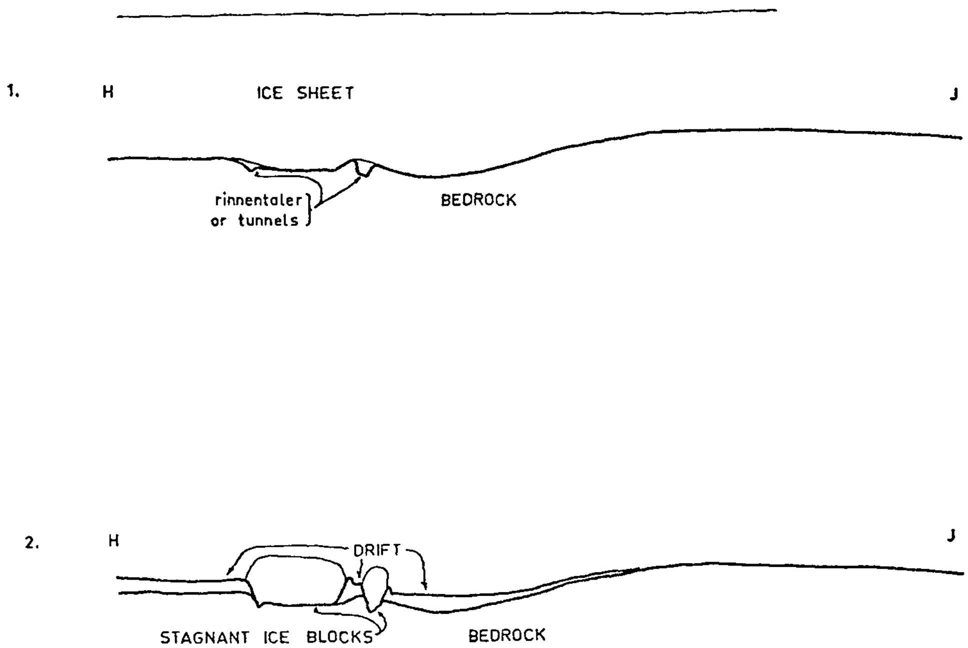


FIG. 7 Hypothesis of glacial debris distribution.
1. Ice sheet grounded at sub- Pleistocene/Pleistocene unconformity (base on seismic profile HJ-Fig. 3).
2. Stagnant ice prevents accumulation of glacial debris in depression areas.

at the base of the ice sheet, so that meltwater that seeps to the base of the ice sheet can down-cut the underlying bedrock, and the sub-glacial stream may flow over topographic barriers. Outwash fans are associated with sub-glacial streams and occur at the margin of the ice sheet, where the hydrostatic pressure is released. Preservation of features such as rinnental, and small outwash fans requires that post-glacial erosion is minimal, as glacial deposits are generally unconsolidated and are, therefore, subject to eradication by re-advances of ice sheets.

A rinnental may have modified the North Arm. Minor depressions are observed to be superimposed on the general relief of the floor of North Arm. A small fan-like feature is seen north of section AA' (Fig. 6) and is located near the mouth of North Arm.

C. Glacial Deposition

Post-glacial deposition is inferred from bottom roughness, and from seismic reflection data, where unconsolidated sediments are believed to have been deposited when the ice sheet retreated. Pleistocene to present submergence of the outer shelf has preserved the features formed by retreat of the last ice sheet to have covered the area.

The ridges are composed partly of glacial debris and partly of a small core of Mesozoic-Cenozoic bedrock. The ridges could be either drumlins, eskers, or kames.

Drumlins are formed while the ice sheet is in a dynamic state, so that their orientation is an indicator of ice sheet movement. Drumlins usually occur in groups, and many drumlins may occur over a wide area. Seldom do drumlins exceed 200 m in height. A bathymetric profile spacing of 4.5 km does not provide sufficient information on the shape of the peaks on North Ridge and South Ridge to analyze the morphology of these peaks with respect to an ideal drumlin shape.

Eskers are a type of ice-contact stratified drift. Their formation is believed to be caused by ice-channel filling. The sides of eskers are generally steep, approaching the angle of repose of the esker sediments. Eskers generally follow the trend of valley floors, except where the valley tends to diverge from the direction of ice movement. The slopes of the sides of North and South Ridge (parallel with the long axis) are not very steep, about 4 degrees. This angle cannot be considered steep enough to be angle of repose of the esker sediments. The ridges may be stratified, but this is hard to observe, on seismic profiles because of a low-velocity contrast between the Pleistocene sediments and older bedrock, and because of the distortion of any layering present due to 'edge effects' on the seismic records.

A kame is a mound like hill of stratified glacial drift deposited when stagnant ice melts. Kames can be formed by crevasse deposition or by surface sediments on stagnant ice, left behind when the ice melts. Usually, kames are associated with kettles, and both features record stagnant disintegrating ice.

The kame-and-kettle roughness mapped by van der Linden *et al* (1975) has a relief of less than 30 m (Type I). Relief on North Ridge and South Ridge implies glacial deposition of about 150 m.

A speculative model of glaciation is portrayed in Figure 7. Individual ice lobes followed the river valleys, overdeepened them, and terminated near the shelf edge. The main ice sheet continued to expand by progressing offshore. The individual lobes expanded in extent, progressively covering more of the shelf, until most of the shelf was covered at the maximum of glaciation. Ice shelves probably existed beyond the shelf edge, but the steep continental slope must have prevented grounding of the ice beyond the 500-m isobath. Figure 11 shows a hypothetical sequence of ice advance.

The ice was thicker in the depressions, as the ice probably maintained a uniform surface elevation over the entire region, except near the margin. Two small depressions could be either the location of rinnentaler which downcut into the bedrock, or natural tunnels which were unaffected by the overlying ice sheet.

Stagnant blocks of ice may have remained grounded in the depression area while the ice melted on the higher bank areas. Glacial debris was unloaded wherever melting took place, but the depression areas remained choked with ice. Sea level began to rise in response to the release of water within the ice sheet. This, and continued ablation, may have caused the grounded ice to float, thereby removing the source of glacial debris from the depression areas. As a result of this action, a thick cover of glacial drift occurs mainly on the bathymetric highs, and the depression areas remain relatively free of unconsolidated sediments.

CONCLUSIONS

The continental shelf off northeastern Newfoundland is an area of contrasting relief. The whole region of the outer-shelf is underlain by coastal-plain type sediments. However, the bank areas are regions of very little relief, and the depressions are areas of high relief. It is difficult to envisage sub-aerial erosion to be the only landscape-forming mechanism. Sediments within the depressions are fine-grained, which suggests that there is little sediment movement at the present time.

Sub-aerial erosion likely occurred prior to Pleistocene glaciation, during which time the valleys and channels were formed as river downcutting took place. Pleistocene ice sheets have modified the relief to the extent of over-deepening in the depressions and increasing the relief by deposition during glacial retreat. The preservation of glacially deposited features suggests that their formation took place when the ice sheet was in the last stages prior to retreat.

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