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SURFICIAL GEOLOGY OF HECATE STRAIT, BRITISH COLUMBIA CONTINENTAL SHELF

J. Vaughn Barrie

Centre for Cold Ocean Resources Engineering (C-CORE) and
Department of Earth Sciences, Memorial University of
Newfoundland, St. John's, Newfoundland, A1B 3X5

Canada

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SUMMARY

Four surficial geological units are defined for Hecate Strait of the northern British Columbia continental shelf. They consist of underlying Tertiary bedrock (Unit 1) that is unconformably overlain in much of the Strait by glacial till (Unit 2) which are, in turn, overlain below 200 m water depth by thick Holocene silts (Unit 4), and above 200 m by Quaternary sands and gravels (Unit 3), except in areas where till or Tertiary bedrock are at or near surface.

Glacial ice has covered most of the Strait during some period of the Pleistocene but the late Wisconsinan advance appears to have been limited to the principal troughs within the Strait. Sea level has been as low as the present day 180 m isobath during the Quaternary and possibly as low as 100 m at the end of the Pleistocene, based on the presence of drainage channels, wave cut terraces and a drowned barrier island system with oblique-connected sand ridges. Presently, seabed sediment erosion and transport, and extensive areas of shallow gas (biogenic and thermogenic), could present engineering difficulties for any potential hydrocarbon or other seabed development of the area.

INTRODUCTION

The northern British Columbia continental shelf, influenced by long period Pacific waves entering from the western regions, moderate tides, and seismicity is an excellent area in which to study sedimentary processes in a active high latitude shelf environment. It also has a potential for hydrocarbons, increased fishing and offshore placer minerals.

Hecate Strait lies between the Queen Charlotte Islands and the British Columbia mainland and covers an area of over 23,000 km^2 (Fig. 1). Since 1968 six petroleum exploration wells have been drilled in the Strait and offshore placers have been predicted for the area (Hale and McLaren, 1984). Indeed, Barrie et al. (1987) show from a mineralogical analysis of bottom grab samples that high concentrations of ilmenite in conjuction with zircon and magnetite occur, particularly in the inner northwest part of the Strait.

The following discussion will describe the surficial geology and distribution of each unit for the Hecate Strait region from which a preliminary interpretation of the late Quaternary development is presented. Potential engineering hazards that may constrain offshore development, such as shallow gas and sediment transport, become apparent in light of the geological history.

FIELD INVESTIGATIONS AND METHODS

Regional acoustic geophysical surveys have been carried out over the last six years in Hecate Strait (Fig. 2). These include 50 kHz sidescan sonar, Huntec DTS high resolution seismic profiling (Hutchins et al., 1976), 12 kHz echo sounder, and a limited network of 5 cubic inch airgun lines. Sampling consists almost entirely of bottom grab samples using a Shipek grab sampler (Conway, 1986). Photographic data were obtained in the southwestern portion of the Strait (12 stations (Fig. 3)) during a cruise of CSS VECTOR in 1981 and submersible dives (4) using PISCES IV in 1982.

The initial geophysical coverage of the southern half of the Strait was carried out from CSS HUDSON in 1981 and the northern portion was completed in 1984 using the CSS VECTOR. Additional sidescan sonar coverage was undertaken on Laskeek Bank in 1981 during a cruise of CSS VECTOR and in 1982 from PANDORA II. The airgun lines, other than two completed during the HUDSON 1981 cruise, were obtained as part of the Regional Resource Mapping program (Currie et al. 1983).

Grab samples were collected by the Pacific Biological Station using the G.B. REED in 1979 and from 1983 to 1986. The samples are concentrated in small grid blocks, with a 1 or 7 km sample spacing (Fig. 3), primarily on northern Laskeek Bank and at the northern entrance to the Strait. The most comprehensive sample coverage (4 km grid) is on Laskeek Bank, based on cruises of the Pacific Biological Station and the CSS VECTOR in 1981 (Bornhold and Collins, 1984) (Fig. 3). Further samples have been collected on cruises of CSS PARIZEAU in 1983 and 1984, particularly on Dogfish Bank.

Samples collected were washed, dried, split and prepared for textural analysis by separating the gravel fraction (>2.0 mm). The remainder of the sample was split into a sand fraction for analysis using the Pacific Geoscience Centre settling tube, and the a mud fraction for analysis using a Sedigraph 5000D. Of the 940 grabs analysed, 36 were selected for further mineralogical analysis (Barrie et al., 1987). Elemental analysis (Mn, Au, Pt, Pd, Ti, V, Cr, Zr) was carried out on 9 of these samples (Barrie et al., 1987). Aliquots of 59 samples from the G.B. REED 1979 collection, were also geochemically analysed for 18 trace elements (Sneddon and Holman, 1982).

GEOLOGICAL SETTING

Hecate Strait and Queen Charlotte Sound combine to form a continuous physiographic province known as the Hecate Depression (Holland, 1964). This depression marks the northern part of the Coastal Trough which separates the Coast Mountains of the mainland from the Insular Mountains of the Queen Charlotte Islands and Vancouver Island. Hecate Strait itself is a shallow strongly asymmetric channel lying between the Queen Charlotte

Islands and the British Columbia mainland (Fig. 1). In the eastern portion of the Strait a "U" shaped trough opens southward leaving a broad shallow (<20 m) shelf (outwash plain) in the northwestern portion (Dogfish Bank) and a 30-40 m deep bank (Laskeek Bank) in central Hecate Strait (Fig. 1).

Hecate Strait originated about 6 Ma ago (Miocene) when underthrusting along the the margin and associated lithosphere flexure uplifted the western part of the Queen Charlotte Islands and depressed the crust to the east, forming the Strait (Yorath and Hyndman, 1983). To the east, the Coast Range is comprised of Mesozoic and Cenozoic granites as well as Palaeozoic and Mesozoic metamorphic volcanic and sedimentary rocks. The Insular Belt to the west of the Strait is characterized by sedimentary and volcanic rocks of Mesozoic and Tertiary age. Hecate Strait itself is underlain by a thick sequence of primarily non-marine Tertiary sediments (Skonum Formation (Shouldice, 1973; Young, 1981)).

The thickness of the overlying Quaternary sediments is variable, but exceeds 100 m in places. Glaciation during the Late Wisconsinan (Fraser Glaciation) appears to have been relatively short-lived and not extensive in the offshore regions (Luternauer and Murray, 1983; Conway and Luternauer, 1985; Luternauer et al., 1985).

On eastern Graham Island of the Queen Charlottes, a thick sequence of exposed Quaternary sediments has been examined by

Clague et al. (1982a). Two thin tills were found, underlain by glaciomarine silts, outwash sands and gravels, and laminated to massive silt and sand. The upper till is of Late Wisconsinan age and the older was probably deposited during a separate glaciation. Clague et al. (1982a) and Warner et al. (1982) infer from their data that the late Wisconsinan glaciation of the coastal lowlands off Graham Island was weak and of short duration and that part of the Queen Charlotte Islands was ice-free.

The timing of the last glacial maximum differed markedly between the northern and southern coasts of British Columbia. Glaciation on northern Graham Island ended about 16,000 years BP (Clague et al., 1982a) and fossil fauna suggests that any grounding of late Wisconsinan ice in Queen Charlotte Sound probably occurred before 15,000 years BP (Luternauer et al., 1985). Ice appears to have retreated from the outermost mainland coast (but not necessarily from the fiords) by about 12,000 - 13,000 years BP (Clague et al. 1982b; Clague, personal communication, 1986). No data, until this study, have been reported from Hecate Strait.

Postglacial sedimentation has been strongly controlled by sea level fluctuations. Late Wisconsinan glacial/postglacial relative sea level history was complex and varied sharply both across the shelf and from north to south, as glacial ice appeared to have thinned abruptly from the mainland coast towards the Queen Charlotte Islands and western Vancouver Island (Clague, 1975; Howes, 1981; Clague et al, 1982b). Upon deglaciation (10,000 - 13,000 years B.P.), the mainland coast was submerged with sea levels up to 200 m higher relative to land than at present (Clague et al., 1982b) and on eastern Vancouver Island 175 m of submergence may have occurred (Howes, 1981). Regression followed along the coast with relative sea level falling just below the present sea level between 6,000 - 9,000 years ago. In contrast sea levels were lower than present levels (possibly up to 35 m) in western Hecate Strait at 13,000 to 9,500 years BP (Clague et al., 1982b). Subsequent transgression occurred on the eastern coast of the Queen Charlotte Islands, at 7,500 - 8,500 years BP, resulting in sea levels 15 m above present level (Clague et al., 1982b). Western Vancouver Island may have undergone a similar pattern of emergence as the Queen Charlotte Islands. Emergence of these areas may be ongoing presently while the mainland coast is undergoing submergence. Isostatic adjustments along the entire continental margin may have been complicated by the collapse of a subcrustal forebulge during ice retreat and tectonic uplift (Clague et al., 1982b; Riddihough, 1982).

Postglacial sedimentation is minimal from evidence on northeastern Graham Island, where a maximum of 10 m is recorded (Clague et al., 1982a). Offshore in Queen Charlotte Sound, Holocene sedimentation has been minimal (2-3 mm/yr) in the interbank basins only (Luternauer and Murray, 1983; Conway and

Luternauer, 1985). Northwestern Moresby Trough in southern Hecate Strait exhibits similar deposition rates (Luternauer and Murray, 1983; Luternauer and Conway, 1987).

OCEANOGRAPHY

Circulation on the central and northern British Columbia continental shelf is dominated by semi-diurnal tidal streams that are continually modified by wind and run-off (Thomson, 1981). Tidal currents, best developed in Queen Charlotte Sound, consist of clockwise-rotary tidal streams with a 12.5 hour cycle. Principal floods are to the northeast and principal ebbs to the southwest (Thomson, 1981). Tidal streams in Hecate Strait are rectilinear (north-south) due to restrictions imposed by bathymetry (Fig. 1). Maximum surface velocities reach 0.5 m/s.

No bottom current measurements have been made in Hecate Strait but several current meter moorings were placed in the lower water column in 1984 (M. Woodward, personal communication). Near-bottom tidal velocities are characteristically between 0.15 - 0.25 m/s, with a dominant flow to the northwest (IOS Review, 1984, p. 18-19). Near-bottom current velocities in the deeper water of the extreme southern portion of Hecate Strait appear to be quite small (less than 0.10 m/s (Crawford et al., 1985)).

Wave conditions vary depending on fetch and the land sheltering effect of oceanic swell, particularly in Hecate

Strait. Ocean waves entering Queen Charlotte Sound and southern Hecate Strait from the west are unrestricted until they lose energy as the seabottom shoals. Wave conditions are most severe in autumn and winter and mildest in spring and summer (Thomson, 1981). Mean winter wave height (Hsig) for Queen Charlotte Sound was near 4 m, from October 1982 to May 1984 (Seakem, 1985), compared with less than 2 m for Hecate Strait. These correspond to mean peak periods of 12 s and 9 s respectively. Waves in Hecate Strait show alignment with the Strait, the main direction in winter being from the southeast and less frequently from the northwest.

SURFICIAL GEOLOGICAL/ACOUSTIC UNITS

Four surficial geological units have been defined for Hecate Strait based on acoustic geophysical records, the surficial expression as recorded by the sidescan sonar and the surficial sediment textural distribution. The units are bounded on the eastern side of the Strait by Coast Mountain crystalline rocks that extend a short distance offshore (Figs. 5 and 25).

Tertiary Bedrock - Unit 1

Tertiary clastic sediments (lower Miocene to upper Pliocene) underlie most of Hecate Strait and the eastern portion of northern Graham Island, Queen Charlotte Islands. Where the Quaternary sediments that unconformably overlie the Tertiary are thin, the dipping Tertiary strata are acoustically well defined (Fig. 4). In many areas there is no Quaternary section, only a thin mobile veneer, due to the lack of deposition or, most likely, due to a dominance of erosion during the Quaternary.

Generally the Tertiary sediments are either exposed or covered by a thin sand and gravel unit in the western half of Hecate Strait (Fig. 5) above approximately 100m water depth and, in central Hecate Strait, above 200 m water depth. Tertiary volcanic intrusives may also be exposed just off of South Moresby Island (T. Hamilton, personal communication, 1987). The unconformable surface of the Tertiary is very rough and channelised, indicating subaerial exposure possibly several times during the Pleistocene. The overlying sand thickness is variable as it infills the rough morphology, resulting in a flat and smooth seafloor. The sediments at the seabed of these areas are primarily gravel lags (Fig. 6) mixed with a complex distribution of poorly sorted coarse sediments (Bornhold and Collins, 1984).

Glacial Till - Unit 2

An acoustically uniform, non-stratified unit with a strong surface reflector is interpreted to be a till (Fig. 7). The upper surface has a characteristic ringing reflection on the Huntec DTS records in many places. The unit has numerous moraines (Fig. 8), similar to the lift-off moraines of King and Fader (1986). When exposed at the surface, the till has a characteristic hummocky expression made up primarily of poorly sorted gravel, silts and sands (Fig. 6). In water deeper than 100 m the surface of the till is scoured and pitted (Fig. 17), presumably from the action of grounding icebergs calved during glacial retreat. As little airgun data associated with high resolution profile data exists, there is poor definition of till thickness or variabliity. Only one upper till unit could be adequately mapped within Hecate Strait though two distinct tills were observed in areas of the southern Strait.

The till unit is found over much of the Strait (Fig. 5) but is noticeably absent on the western side of the main trough, on Dogfish Bank (though survey coverage is limited) and in the central area of the southern portion of the Strait, where Tertiary bedrock is near surface (Fig. 5). A continuous till tongue appears to have entered Hecate Strait from the trough off Lyell Island and Juan Perez Sound.

In summary, it appears that a till unit(s) of unknown age covers a large portion of Hecate Strait but is not continuous between the Queen Charlotte Islands and the mainland. The significance of this will be discussed later.

Hecate Strait Sand and Gravel - Unit 3

Most of Hecate Strait, above 200 m water depth, is covered by Quaternary sands and gravels, with a minor amount of silt. These stratified sands, up to 50 m in thickness, have a moderate acoustic reflectivity. Prograding crossbeds are seen occasionally, particularly near the terrace breaks. The Hecate Strait sands are primarily medium to fine sands (Fig. 6).

Unit 3 occurs generally above 200 m water depth on the western side of the main trough and within a small basin off Banks Island in the eastern Strait. The sands overlie Tertiary sediments above 100 m water depth, though the Huntec DTS system, from which most of the interpretations are determined, could rarely penetrate through this unit. In waters deeper than 100 m the sands are superimposed on till which in turn overlies the Tertiary bedrock. Until further data are collected it is impossible to date or subdivide the Unit into depositional facies.

In the northward opening trough, at the extreme north end of Hecate Strait, the Hecate Strait Sand and Gravel (Unit 3) can be divided into three sub-units, all overlying a till. Unit 3a is a stratified sand of uniform thickness (10 m) overlying till (Fig. 5). It is only exposed from the centre to the eastern slope of the trough (Fig. 9), resulting in a slight westward dip. Overlying this unit is another very stratified unit (3b) with a similar thickness, dipping slightly to the west (Fig. 9). Unit 3b has only limited exposure on the seafloor at the base of the western terrace slope of the trough (Fig. 9). Superimposed on these two units is a third stratified sand (3c) that drapes over the west side of the trough and forms a distinctive terrace. This same unit may then form the predominate surficial unit as far as the Queen Charlotte Island coastline. It is acoustically similar to the other areas of Unit 3 within the Strait where no acoustic subdivision can be made, at present.

Holocene Silts - Unit 4

In water depths greater than approximately 200m thick (> 60 m) sequences of acoustically semi-transparent to transparent sediments occur, overlying acoustic till and Tertiary sediments (Fig. 5). These sediments resemble silts acoustically (Parrott et al., 1980) and the surface samples are dominantly silt with minor clay and sand (Fig. 6). The Holocene Silts can be divided into two principal sub-units.

Unit 4a

The lower unit (4a) is common in water depths greater than 200 m where till or Tertiary sediments do not occur. The Unit is characterised by stratified draping beds (Fig. 10) similar to the Qeovik Silt found on the Labrador Shelf at similar latitudes (Josenhans et al., 1986). At surface the silts are coarse and few gravels or dropstones are found. The same stratigraphic and acoustic unit continues into Moresby Trough where the top of the unit has been dated at 10,500 - 11,000 years old (Luternauer and Conway, 1987), suggesting an early Holocene to late Pleistocene age.

Unit 4b

Overlying the stratified silts, and in areas till, in the deepest parts of Hecate Strait, is a fine muddy silt unit that is almost acoustically transparent (Figs. 10 and 16). Sometimes stratification can be seen but generally the unit has no distinguishing features. Cores from Moresby Trough, within this unit, suggest a Holocene age, the base of the unit dating from 10,500 - 11,000 years B.P. (Luternauer and Conway, 1987)).

SURFICIAL SEDIMENT DISTRIBUTION

The present surface sediment distribution in Hecate Strait (Fig. 6) is a product of both water depth and surficial geology. The sediments generally fine with increased water depth, with silts found below approximately 200 m and sand and gravel found above this depth. This general distribution is modified particularly in areas where Tertiary bedrock or glacial till are exposed or occur near surface, as described earlier. Sedimentary bedforms also complicate a sediment textural pattern as each bedform has its own surficial sediment distribution. One of the most complex areas of surficial sediment distribution is on Laskeek Bank where Tertiary bedrock, till and sedimentary bedforms occur at the seabed. Bornhold and Collins (1984) have mapped this distribution, based on a 4 km sample grid (Fig. 11).

The sediments themselves are lithic and heavy mineral rich (Suczek, 1983; Barrie et al., 1987). Lithic fragments indicate primary volcanic origin (Suczek, 1983) with likely sources being the Mesozoic tholeiitic basalts and early Tertiary volcanic arc rocks exposed on the Queen Charlotte Islands (Sutherland-Brown, 1968; Suczek, 1983). Heavy minerals are dominated by amphibole (approximately 30%) with lesser amounts of ilmenite and magnetite (Barrie et al., 1987).

SEDIMENTARY BEDFORMS AND SEABED FEATRUES

Terraces

The geophysical records indicate four principal terrace breaks that extend down the entire length of the Strait (Fig. 12). These have been mapped from the Huntec DTS seismic profiles and echo sounding records. Other terrace breaks, at similar water depths, occur on Dogfish Bank (Warner et al., 1982), but were not surveyed during this program.

The terraces of northern Hecate Strait primarily occur at 20-22 m, 30-35 m and at 40-45 m, all measured at the base of the characteristic wave-cut slope. An extensive terrace begins at

110 m in the northern portion of the Strait and extends to Queen Charlotte Sound (Fig. 12). The terrace feature occurs in progressively deeper water down the Strait, with the base of the slope being at 180 m at the southern end. The terrace slopes are as much as 20° with a average bathymetric change of between 20 and 30 m. A unique erosional channel occurs at the base of the slope along the entire length of the continuous terrace (Fig. 13).

Slope Processes

Several slides and small scale debris flows occur mainly in two areas of Hecate Strait (Fig. 12). These are the eastern side of the Strait at the contact with the Coast Mountain crystalline rocks and in Juan Perez Sound and the trough off Lyell Island. Features on the eastern side probably occur as a result of the steep bedrock slopes where thin Quaternary sediments have been deposited (Fig. 14), while those in the area of Juan Perez Sound and off Lyell Island result from an oversteepened trough, likely formed by glacial erosion. Minor faulting of surficial sediments can also be seen in the Juan Perez Sound area (Fig. 15). No evidence exists for sediment instability or slope failure within the main area of the Strait, where terrace slopes and thick unconsolidated sediments on the central trough slopes occur.

Shallow Gas

Extensive areas of shallow gas have been mapped from the geophysical records (Fig. 12), identified as acoustic voids, enhanced reflections and plumes. Similar near-surface gas occurs on the Alaska shelf (Nelson et al., 1978; Hampton et al., 1979). The gas seen can arise from two sources; gases produced during early diagensis from biogenic degradation of organic matter, and gas diffusing upward from the Tertiary bedrock (thermogenic).

Gas is distributed over the entire Strait and occurs in all units except were till is at surface. Within the thick silt deposits of Unit 4 biogenic gas is extensive (Fig. 16). Gaseous sediments also occur along the base of the terraces, the northern portion of the main trough and within the northern trough into Dixon Entrance. The sediments containing gas are generally near the contact of the till with Unit 3 (Hecate Strait Sand and Gravel); the gas appears to migrate along this boundary (Figs 7 and 8). Smaller areas that show the acoustic properties of gas-charged sediments are on the western side of the Strait in the Unit 3 sands and in areas where the sands form a thin cover over Tertiary bedrock (Fig. 12). These latter gas showings may relate to gas migration from the Tertiary (Fig. 26).

Iceberg Scours

When an iceberg keel or an ice ridge keel loads and disturbs the seafloor, it either becomes grounded and ceases to move on producing a pit or, if it has sufficient energy under the influence of swell, currents, wind or pressure from other ice, the keel penetrates the seafloor sediment and excavates a trough or scour. Relict iceberg scours occur on many high latitude shelves. Their longevity is apparent from studies of ancient (Pleistocene) scours found in the Norwegian Trough (Belderson et al., 1973) and shelf (Lien, 1983), in the North Sea (Stoker and Long, 1984) on Chatham Rise off New Zealand at 43°S (Kundrass and Rad, 1984), in the Beaufort Sea from ridge-keel scouring (Lewis, 1978), in the Laurentian Channel and western Grand Banks (King, 1976), on the northwestern Grand Banks (Fader and King, 1981; Lewis and Barrie, 1981) and on the Labrador Shelf (Barrie, 1980).

Iceberg scours and pits occur below 110 m water depth in the main trough of Hecate Strait (Fig. 12). They probably formed at same time as the icebergs that formed the scours in the interbank troughs in Queen Charlotte Sound (Luternauer and Murray, 1983). The area of late Pleistocene iceberg scouring was far more extensive than the presently exposed scours at the seabed. The till surface appears scoured under most of Units 4a and 4b (below 100 m), as seen from the seismic profiles. The exposed scours are linear with scour depths of up to 7 m but mostly less than 3 m (Fig. 17). Generally they are partially to fully infilled with fine-grained sediment (Fig. 17). The icebergs appear to be travelling north to south down the trough into Queen Charlotte Sound possibly from a calving margin in north-central Hecate Strait.

Buried Channels

Almost the entire area of Hecate Strait, above 200 m water depth, must have been subaerialy exposed allowing for the formation of drainage channels (Fig. 12). The characteristic fluvial channels are almost always fully infilled (Fig. 18). They commonly occur at the upper surface of the Tertiary and within the Hecate Strait Sand and Gravel. In northeastern Hecate Strait the orientation of the channels is still uncertain, while those in central and southern Hecate strait show alignment with the axis of the Strait. One principal channel, that occurs at 125 m water depth, can be mapped for over 50 km at the base of Laskeek Bank. The pattern of this channel and the other channels in Figure 12 are interpreted from cross-sectional profiles using the Huntec DTS system.

In the upper reaches of the central trough, along the base of the main terrace slope and in Juan Perez Sound, erosional channels are found that could be initiated and maintained by the modern hydrodynamic regime. Figure 19, for example, shows a deep channel at the mouth of Juan Perez Sound which has been partially infilled with fine-grained sediments and subsequently eroded by strong currents, possibly related to the present seabed dynamics.

Sediment Mounds

Two areas of eastern Hecate Strait (Fig. 12) have unusual features that occur superimposed on a hard substrate of glacial till or crystalline bedrock, which have no known origin. They are mounds, up to 10 m in height (5 m average), of very transparent (fine-grained) sediment with rough irregular surface and chaotic stratigraphy (Fig. 20). In plan they are somewhat linear but confused in orientation. The mounds form essentially in areas of gentle seabed slope, not adjacent to any geological boundary. Nowhere have similar features been reported and as such will remain a mystery until further investigation.

Boulder Fields

Three areas of densely distributed, large boulders occur on the seabed, especially where Tertiary bedrock (Unit 1) or glacial till (Unit 2) are exposed at the seabed. The boulder fields can be seen on the high resolution sidescan sonar records, though there is limited coverage of this kind. Consequently, areas of seabed covered by boulders may be far more extensive than shown in Figure 12.

Sand Ridges

Extensive areas of western Hecate Strait, from Laskeek Bank to Dixon Entrance, have a ridge and swale topography similar to areas of the Middle Atlantic Bight (Swift et al., 1978) along the Delaware and Maryland inner shelf (Field, 1980; Swift and Field, 1981b), the inner and middle New Jersey shelf (Stubblefield and Swift, 1976; Stubblefield et al., 1984) and the eastern Canadian shelf (Amos and King, 1984; Barrie et al., 1984; Fader and Miller, 1986). Both coast-parallel and coast-oblique ridges are found in the Strait.

Three distinct populations of coast-oblique sand ridges are distributed in Hecate Strait. The best mapped ridges occur in 20 - 30 m of water in the northern portion of Hecate Strait, off eastern Graham Island (Fig. 12). These ridges are asymmetric, with wavelengths of 0.6 - 1.2 km, lengths of 3 - 6 km and are oriented northeast-southwest (45° - 225°). They average 4 to 5 m in thickness. A second population of ridges are found at 100m water depth in central Hecate Strait (Fig. 12). They are similar in orientation and have thicknesses from 2 to 5 m (Fig. 21). Finally a few isolated ridges, 6 m thick and similar orientation, occur in 130 - 140 m of water in southern Hecate Strait (Fig. 12).

On the west side of the northern sand ridge facies is a larger coast-parallel ridge, 2.5 km wide in 17 m of water. It is oriented nearly north-south (350° - 170°), at a 55° angle from the sand ridges. In central Hecate Strait on the eastern side of the 100 m sand ridge group and off the mouth of Juan Perez Sound are two other coast-parallel ridge features of similar width, both between 90 and 95 m water depth. The latter two features have prograding beds on the western side of the ridge feature. These features are considered to be drowned barriers formed during lower stands of sea level.

Stubblefield et al. (1984) recognise both transgressive and post-transgressive sand ridges on the New Jersey continental shelf of the United States Atlantic shelf. They propose that one group of ridges formed as regressive barrier islands (Stubblefield et al., 1983) whereas the other group represents post-transgressive features (Swift and Field, 1981a) forming at the base of the shoreface. These two groups of ridges have distinctive orientations, wavelengths, morphology and sediment textures.

It can be argued, based on acoustic data alone, that a barrier beach system with shoreface-connected ridges was drowned upon transgression in the mid-Holocene as seen on the eastern Atlantic shelf. The present ridges can be classified as offshore sand ridges (Swift and Field, 1981a). The Central Hecate Strait sand ridges and barriers possibly relate to earlier times of lowered sea level. Whether these features are contemporary or not is unclear. The deeper water ridges could be tidally formed ridges (Smith, 1969), but more analysis is needed to confirm this suggestion.

Megaripples, Sand Waves, and Sand Ribbons

A full development of sedimentary bedforms exists throughout Hecate Strait, particularly in the north, on the southern edge of Laskeek Bank and at the mouth of Juan Perez Sound where enough sediment exists for transport, particularly on the Hecate Strait Sand and Gravel (Unit 3). They occur as deep as 200 m, but generally are found above 100 m water depth. The flow-transverse bedforms are primarily oriented northeast-southwest or northwest-southeast, showing a general trend for northwestern to northeastern migration, though variability, due to currents and bathymetry, can been seen in Figure 12.

The megaripples usually have amplitudes less than 1.5 m and a mean wavelength of 25 m. Sand waves are more variable in distribution and wavelength; the average bedform height is 1.5 - 5.0 m with wavelengths varing from 50 - 300 m (150 - 200 m average). The sand ribbons are less common, being found in areas where surficial sediments over bedrock are thin. They are oriented north-south to northeast-southwest.

Wave Ripples

Wave ripples are ubiquitous in the western shallow areas of Hecate Strait, as seen in seabottom photographs and from submersible dives on Laskeek Bank. Coarse-grained symmetrical ripples with wavelengths up to 3 m are seen in the northern portion of the Strait and on Laskeek Bank (Fig. 12), oriented northeast-southwest. They occur in patches and in distictive linear bands or ribbons, 30 - 50 m wide (Fig. 22). Similar features have been found off central California (Cacchione et al., 1984), on the inner Nova Scotia shelf and on the Grand Banks of Newfoundland (Fader and Miller, 1986), and are defined as large oscillation ripples. Forbes and Boyd (1987) have defined threshold criteria to develop such ripples in shallow nearshore environments, such as western Hecate Strait.

SEDIMENT TRANSPORT

High bottom current velocities (> 0.30 m/s) at water depths of 150 m and the occurrence of large sand ripples at water depths more than 100 m attest to the significance of sediment transport on the northern British Columbia shelf (Barber, 1957; Yorath et al., 1979; Nelson and Bornhold, 1983; Bornhold and Yorath, 1984; Luternauer et al., 1986; Luternauer, 1987).

Using data from Seakem (1985) for Queen Charlotte Sound and Hecate Strait, and assuming a mean predicted tidal bottom velocity of 0.18 m/s (Thomson, 1981) and a grain size of 0.125 mm, the equivalent wave/current velocities (at 1 m above the seabed, U100) were calculated using yearly wave exceedances and the Bijker (1967) method. The combined wave/current bottom shear velocity (U*wc) is defined by Bijker (1967) as:

$$U*wc = U*c[1 + 0.5(\xi Um/m)^2]^{1/2}$$

where ξ is a function of the wave friction factor (Jonsson, 1966) and the Chezy coefficient of roughness as expressed by Swart (1976), Um is the wave orbital velocity, U is the current speed and U*c is the current shear velocity at the seabed.

The results (Fig. 23) show that wave action with a mean bottom current will result in initial transport down to 100 m, and at 60 m sediment transport will occur about 10% of the time during one year (assuming a critical threshold velocity of 0.25 m/s for 0.125 mm sediment size). Transport would be primarily to the northwest, considering the mean wave and current (tidal and wind driven) direction.

Higher current velocities than 0.18 m/s must occur often, based on the distribution of sedimentary bedforms in the Strait. Megaripples form at unidirectional velocities between 0.5 and 0.7 m/s and are independent of water depth (Dalrymple et al., 1978). Sand waves are generated by unidirectional currents in excess of 0.4 m/s (Dalrymple et al., 1978). Both bedform types form in a few hours under appropriate currents and may migrate several wavelengths after periods of only hours in the case of megaripples and days in the case of sand waves. Megaripples are short-term response features that tend to be erased during quiet periods by the effects of current winnowing, browsing organisms and bioturbation and generally last only a matter of months

(Swift et al., 1979). Sand waves on the other hand are long term response features lasting a period of years (Swift et al., 1979).

Sediment transport, therefore, must occur with current flows greater than 0.5 m/s down to as great a depth as 200 m, based on the distribution of sedimentary bedforms. The migration direction of these bedforms is consistent with the predominant wave and current direction (northwesterly). In areas of bathymetric change where sediment supply is sufficient, such as the upper edge of the terrace and trough slopes, sand waves and megaripples probably mark the enhanced current flow that result because of the change in seabed slope. Migration direction would respond to the direction of these strong flows and would explain some of the variablility from the general northwesterly sediment transport.

DISCUSSION

Several cycles of sea level regression and glaciation, followed by transgression occurred during the Quaternary in Hecate Strait. The Strait has been subaerially exposed to the present 180 m isobath at least once during the Quaternary, based on the presence of buried fluvial channels and wave-cut terraces. Drainage was primarily off the present land masses into the Strait and south, towards Queen Charlotte Sound. The lowest stand of sea level may be related to eustatic lowering combined with tectonic uplift. The continuous terrace does not follow the present day bathymetry suggesting uplift in the north and depression in the south.

The presence of boulders and moraines throughout the Strait suggests that glacial ice covered the entire Strait sometime during the Wisconsinan. Whether a late Wisconsinan ice advance extended offshore covering the area of the Strait is not certain. A continuous till is found in the three principal troughs of the Strait and could represent the extent of the late Wisconsinan ice advance; they are the main central trough, the trough opening to the north at the top of the Strait and Juan Perez Sound trough. If this is correct, the tills formed in the two central troughs would have resulted from ice coming offshore in the northern portion of the Strait from the B.C. mainland. Only in the southern Strait, off Lyell Island, does there appear to be an ice tongue that came from a Queen Charlotte Island ice cap. This indication of limited ice advance offshore supports the hypothesis of Clague et al (1982a) and Warner et al (1982) that the late Wisconsinan glaciation on the Queen Charlotte Islands was weak and did not cover all of Graham Island or the offshore. Luternauer et al. (1985) also suggest a limited late Wisconsinan glacial advance in Queen Charlotte Sound and that ice went into the present offshore area of northern Hecate Strait.

Upon deglaciation the principal ice tongue coming down the central trough of the Strait would have receded and likely became a floating ice shelf resulting in the numerous lift-off moraines (Fig. 8). At the ice margin, large icebergs were being calved which scoured the seabed down the central trough and off the shelf through Moresby Trough (Fig 1). At the same time, the northwestern part of the Strait was undergoing deposition as a large outwash plain (Unit 3). Fines (Unit 4), derived from the outwash deposition in this and adjacent areas of the Strait, were transported offshore and deposited in the deep troughs (Fig. 24), continuing until deglaciation was complete.

During the low sea level stand, at the time of deglaciation, a barrier island formed the shoreface of part or all of the northwestern coastline, with shore-connected sand ridges. The existence of barrier islands and sand ridges in central Hecate Strait suggest that sea level at the end of the Wisconsinan glaciation was possibly lower than the 35 m proposed by Clague et al. (1982b). Sea level may have been as low as the present 90 - 100 m water depth at the beginning of the Holocene. It would be difficult for the deeper water (100 m) sand ridges and barriers to have survived as distinct fully developed features from a lowered sea level, prior to the last glacial advance. The mid-Holocene transgression in western Hecate Strait drowned the barrier(s) and the ridges became offshore sand ridges. A desiccated surface, that is stratigraphically and geotechnically identifiable, may have remained after transgression of the exposed Quaternary, and in places, Tertiary sediments of western Hecate Strait. Sediments on the eastern margin of the Strait were probably eroded during the early Holocene regression, except in a basin off Banks Island. The surficial geology of Hecate Strait, based on this preliminary interpretation, is schematically shown in a cross-section (Fig. 25).

Erosion and sediment transport are significant agents of sediment redeposition in the present day Hecate Strait and can be regarded as engineering hazards. Not only can large-scale sediment transport alter foundation conditions by scour and bedform loading, but continued erosion, in an area where no new sediment is entering the system, can result in oversteepened slopes, a critical factor in submarine slides and debris flows, particularly in an area of high seismicity. In many areas of the Strait where sediment is in sufficient quantity to be transported and redeposited, there is a risk of liquefaction. Wave action or seismic shaking can cause sediment pore pressure buildup that in extreme cases may lead to seabed liquefaction (loss of shear strength) with enhanced grain entrainment by sea-bottom flows or downslope movement under gravitational stress (i.e. transport).

The extensive distribution of shallow marine gas in the sediments of Hecate Strait can be both a potential engineering hazard and a useful exploration aid. Blowouts due to shallow gas have occurred at shallow depths (Bouma, 1981). Near-surface, gas-charged sediments associated with larger subsurface accumulations, may also seriously reduce the bearing capacity for seabottom structures. Alternatively, thermogenic gas derived from deeper sources (Fig. 26) may provide an indication of the source of hydrocarbon by using a sniffing technique (Nelson et al., 1978). Figure 26 shows evidence for sediment instability due to possible thermogenic gas and a potential coring site for hydrocarbon analysis. The source of the gas in some areas is questionnable, and as such the hazard, or potential, is not well defined.

CONCLUSIONS

A chronology of sedimentary development from the late Quaternary through the Holocene is presented for Hecate Strait on the northern British Columbia continental shelf, and the distribution of specific surficial features within the Strait, are described.

Specific conclusions are:

1. Four units (Tertiary Bedrock, Acoustic Glacial Till, Hecate Strait Sand and Gravel and Holocene Silts) have been mapped for Hecate Strait. The majority of the Quaternary section in the Strait is considered to be late Pleistocene to mid-Holocene in age.

2. The late Wisconsinan ice advance appears to have been limited to the principal troughs and was not continuous across the Strait.

3. Sea level may have been as low as the present 100 m water depth at the end of the Pleistocene, as defined by drainage channels, wave cut terraces and the presence of a drowned barrier island system and shore-oblique sand ridges.

4. Sediment erosion and transport, as well as shallow marine gas, could present engineering difficulties for any potential hydrocarbon or other seabed development of the area.

RECOMMENDATIONS

Many of the conclusions of this project are based on stratigraphic inferences from acoustic data and, therefore, can only be considered working hypotheses. The units described are based on acoustic comparisons to other areas with a similar history, such as the Labrador shelf (Josenhans et al., 1986), where coring and sedimentological analyses have been completed. Dates, derived from cores that are obtained from selected sites, will provide for a temporal chronology of sedimentological development, that is lacking at present. For example, Figure 27 is a typical Huntec DTS seismic profile showing an excellent target to obtain data from the base of Unit 4b (Holocene Silts) and the top of the continuous till (Unit 2). A coring program, based on the data used for this report, should then be carried out in the near future. In addition, the surficial grab sampling is only complete for portions of the Strait and many areas have not yet been sampled (Fig. 3).

Certain features seen on the seismic profiles cannot be explained and could potentially represent engineering hazards. The best example are the extensive areas of sediment mounds (Fig. 20) found in the eastern side of the central trough (Fig. 12). Further geophysical seismic survey lines, with high resolution sidescan sonar, are required at different orientations and more closely spaced lines than the original regional coverage.

Finally, the two major hazards in the Strait, sediment transport and shallow gas, need detailed investigation. A prediction of present rates and directions of transport will require a specialized hydrodynamic monitoring program. The mobility of the large sand waves and sand ridges would then be better understood; their genesis can be derived from sediment cores as part of a larger program. Analysis of cores will also give insight into the origin and properties of the shallow marine gas. Additional acoustic data, including simultaneous high resolution profiling (Huntec DTS), single channel seismic reflection (airgun) and high resolution (100 KHz) sidescan sonar, would help to define further the distribution of gas and establish coring sites.

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FIGURE CAPTIONS

Figure 1. Area of study. Bathymetry shown in metres.

Figure 2. Regional geophysical survey coverage including sidescan sonar, high resolution seismic profiling, airgun seismic and echo-sounding.

Figure 3. Distribution of seabed grab samples and bottom photographs.

Figure 4. Airgun seismic line across southwestern Hecate Strait, showing Tertiary bedrock (Unit 1) and Quaternary stratified sediments (Hecate Strait Sand and Gravel (Unit 3)).

Figure 5. Distribution of surficial geological units in Hecate Strait.

Figure 6. Mean grain size distribution for bottom sediments in Hecate Strait, based on the Wentworth Scale.

Figure 7. Huntec DTS seismic profile illustrating the rough upper surface of the till (Unit 2), overlain by

stratified sands (Unit 3). Notice the infilled channel on the right and the presence of shallow gas.

Figure 8. Seismic profile of a till with a lift-off moraine, overlain by stratified sands. Shallow gas occurs commonly in association with the contact of till and Quaternary stratified sediments.

Figure 9. Acoustic profile showing the three sub-units of the Hecate Strait Sand and Gravel (Unit 3) in the northern portion of the Strait.

Figure 10. Huntec DTS high resolution profile of Unit 4 (Holocene Silts) underlain by till, in central Hecate Strait.

Figure 11. Surficial sediment distribution of Laskeek Bank (after Bornhold and Collins, 1984).

Figure 12. Distribution of sedimentary bedforms and seabed surficial features in Hecate Strait.

Figure 13. Wave-cut terrace and characteristic channel at

the base of the slope in central Hecate Strait. Notice that the line was run from east to west.

Figure 14. Small debris flow in eastern Hecate Strait. The substrate is crystalline Coast Mountain bedrock.

Figure 15. Shallow faulting of stratified sediments in Juan Perez Sound.

Figure 16. Shallow gas (biogenic) found in Unit 4b (Holocene Silts) sediments, which overlie till and Tertiary bedrock.

Figure 17. Huntec DTS profile and sidescan sonogram of iceberg scours formed in glacial till in central Hecate Strait.

Figure 18. Typical infilled fluvial channel superimposed on a pre-existing channel.

Figure 19. Deep channel that is partially infilled and subsequently eroded at the entrance to Juan Perez Sound.

Figure 20. Sediment mounds found in eastern Hecate Strait,

sitting on glacial till. Their origin and 3D character is unknown.

Figure 21. Sand ridge at 100 m water depth in central Hecate Strait.

Figure 22. Sidescan sonogram of a wave ripple band (2.5 m ripple wavelength) found on Laskeek Bank.

Figure 23. Predicted annual wave and current velocities, 1 m above the seabed, at various depths in Hecate Strait using the Bijker (1967) method.

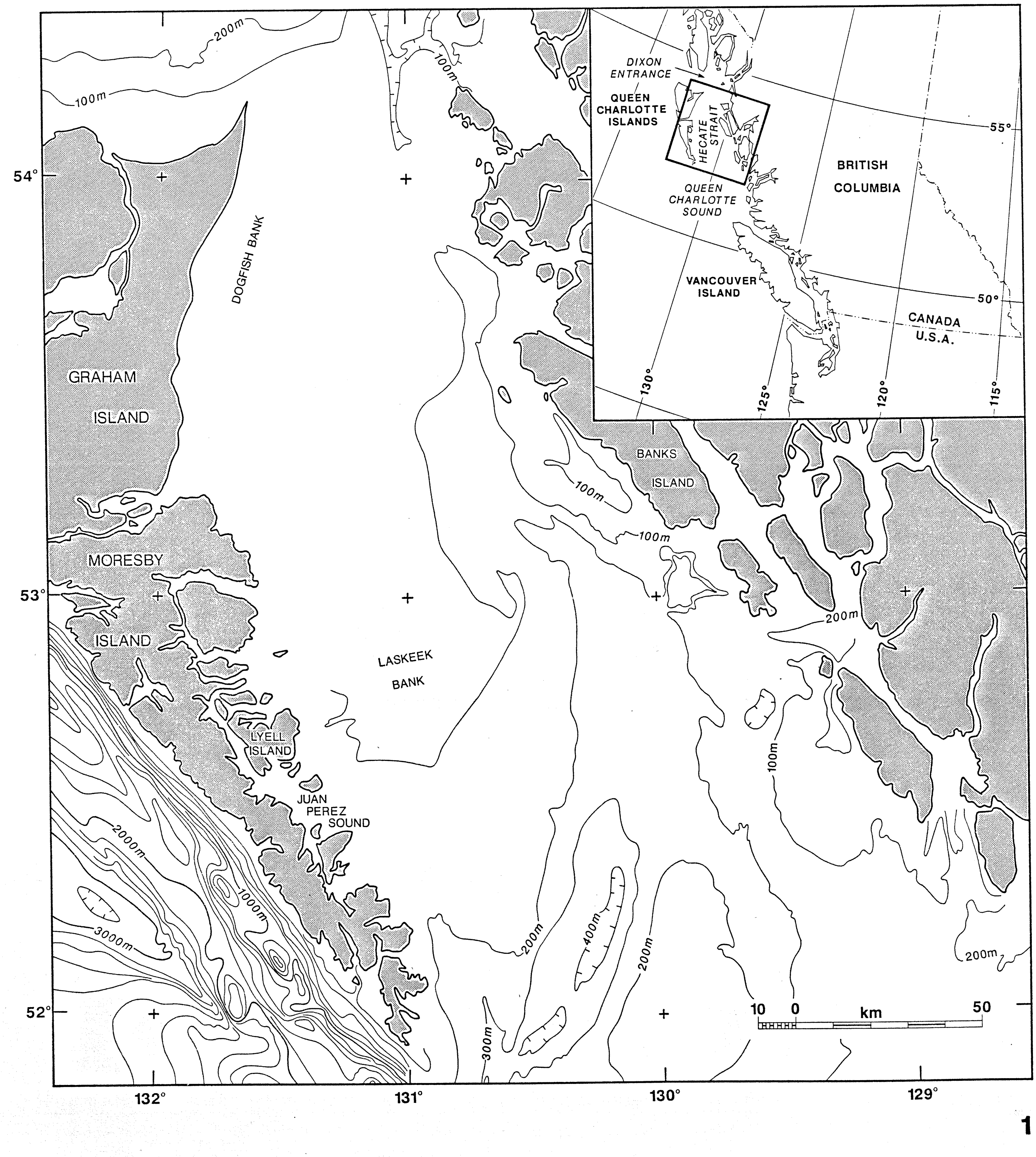
Figure 24. Airgun profile of Holocene Silts (Unit 4) overlying glacial till and Tertiary bedrock in the west, and Coast Mountain crystalline bedrock in the east.

Figure 25. Interpretation of the surficial geology of Hecate Strait, shown by a schematic cross-section (E' - W') across the southern Strait. Location of the section is shown in Figure 5.

Figure 26. High resolution Huntec DTS profile of shallow gas which appears to migrate from the Tertiary

(thermogenic) and cause sediment failure of the overlying Holocene silts.

Figure 27. Profile of Unit 4b silts, over till (Unit 2) and Tertiary bedrock (Unit 1) in central Hecate Strait. The arrows indicate suggested future coring locations.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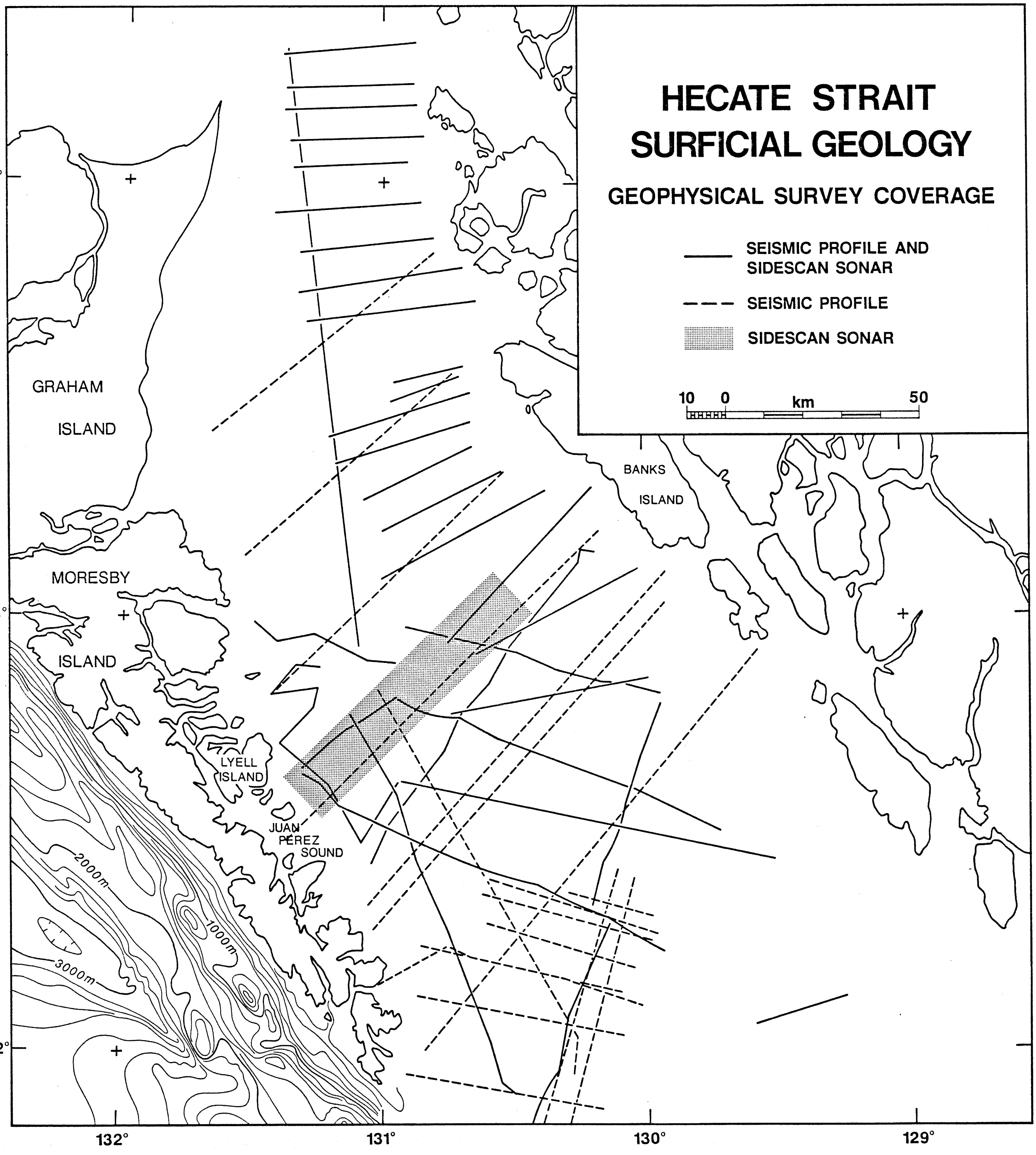
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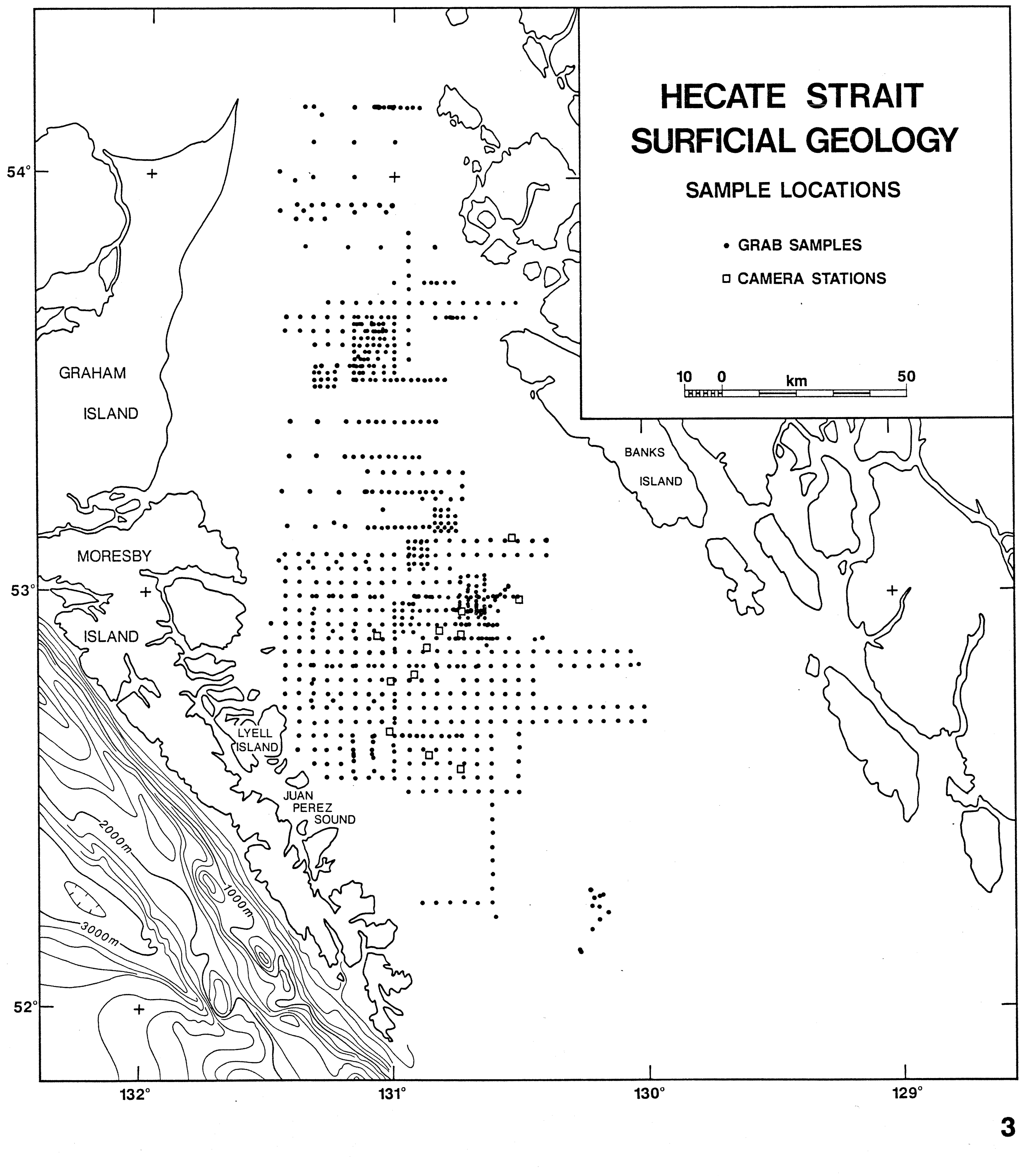
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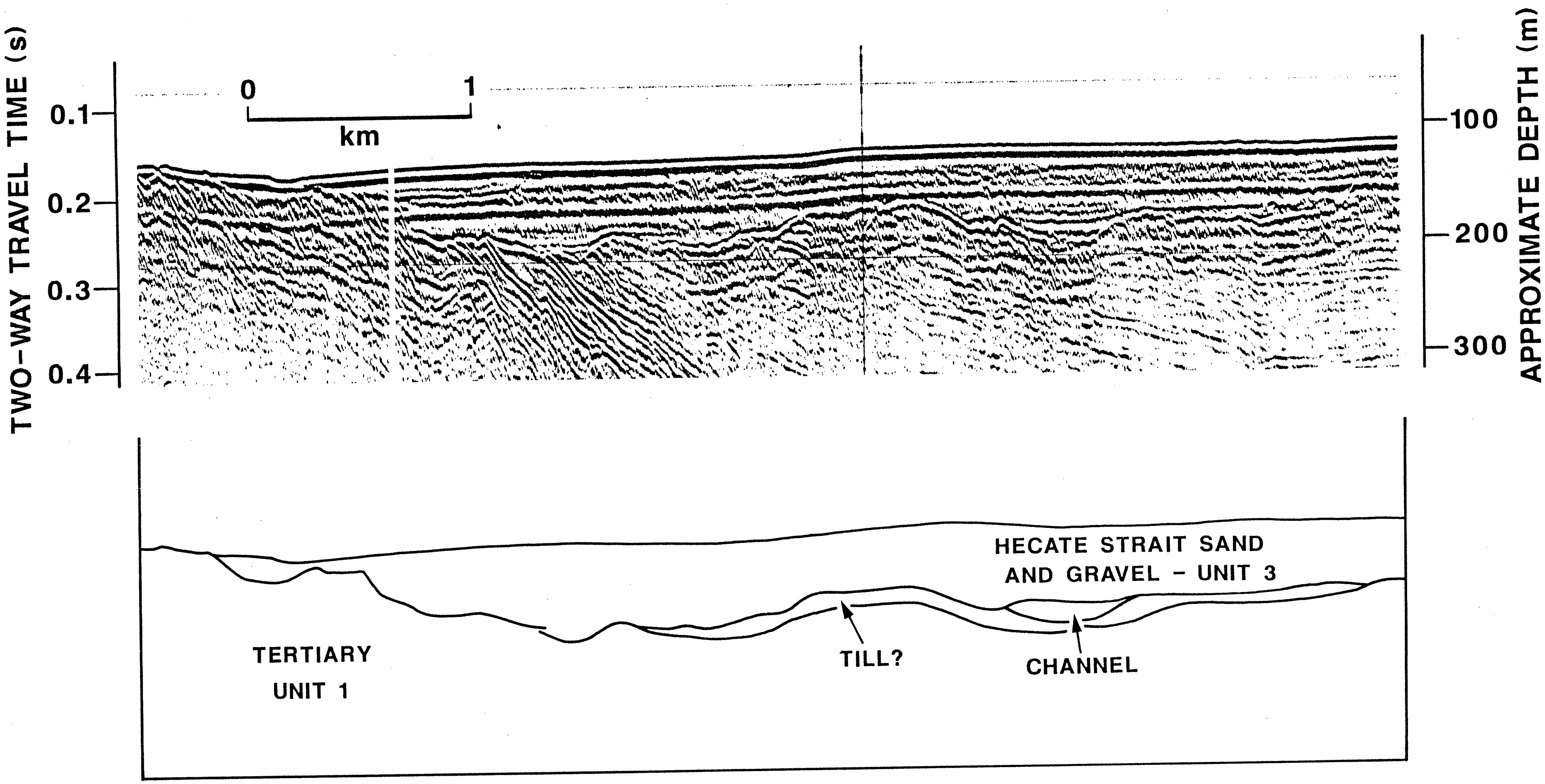
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HECATE STRAIT SAND
AND GRAVEL - UNIT 3
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TILL?
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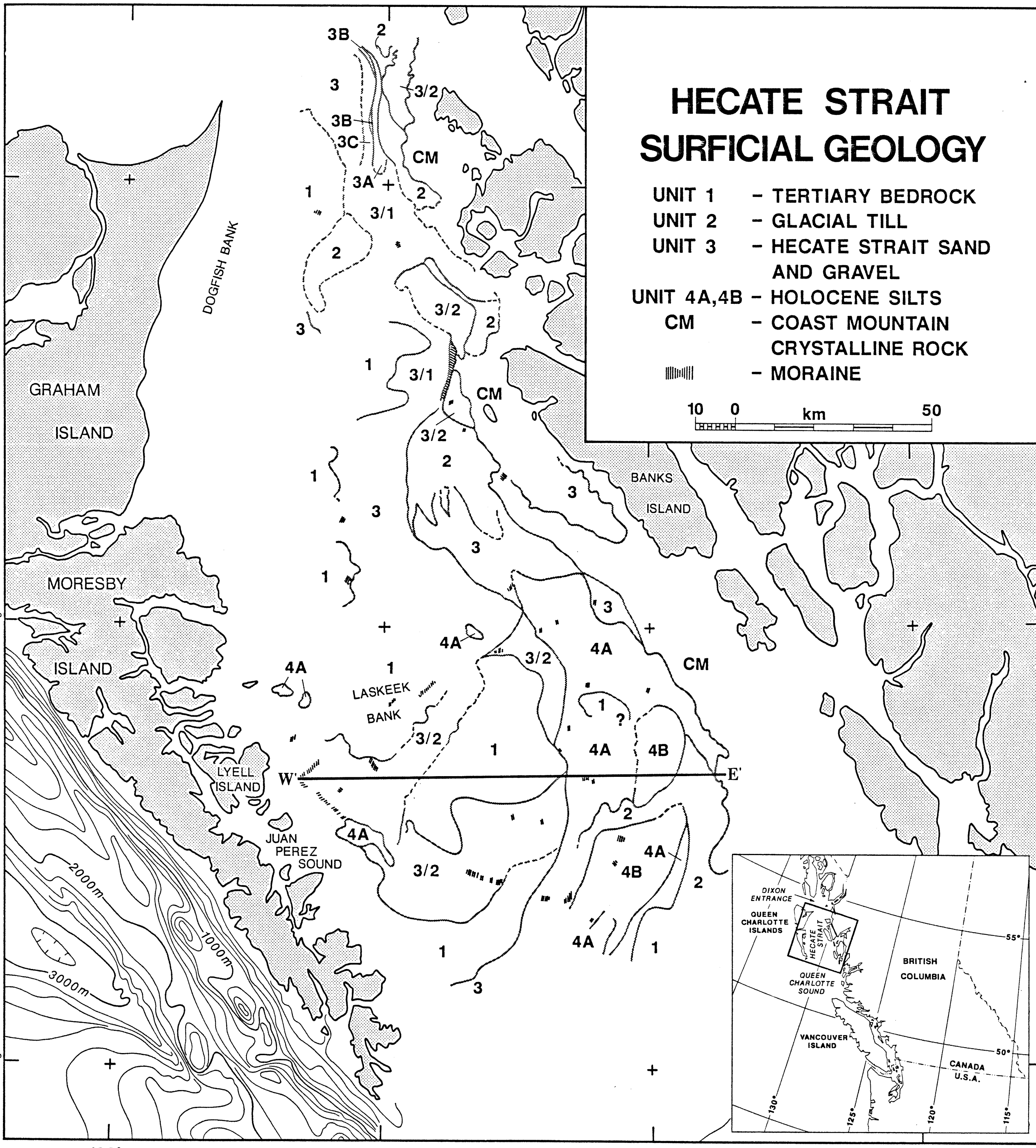
HECATE STRAIT
SURFICIAL GEOLOGY
UNIT 1 - TERTIARY BEDROCK
UNIT 2 - GLACIAL TILL
UNIT 3 - HECATE STRAIT SAND AND GRAVEL
UNIT 4A,4B - HOLOCENE SILTS
CM - COAST MOUNTAIN CRYSTALLINE ROCK
- MORAINE
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MORESBY ISLAND
DOGFISH BANK
LASKEEK BANK
LYELL ISLAND
JUAN PEREZ SOUND
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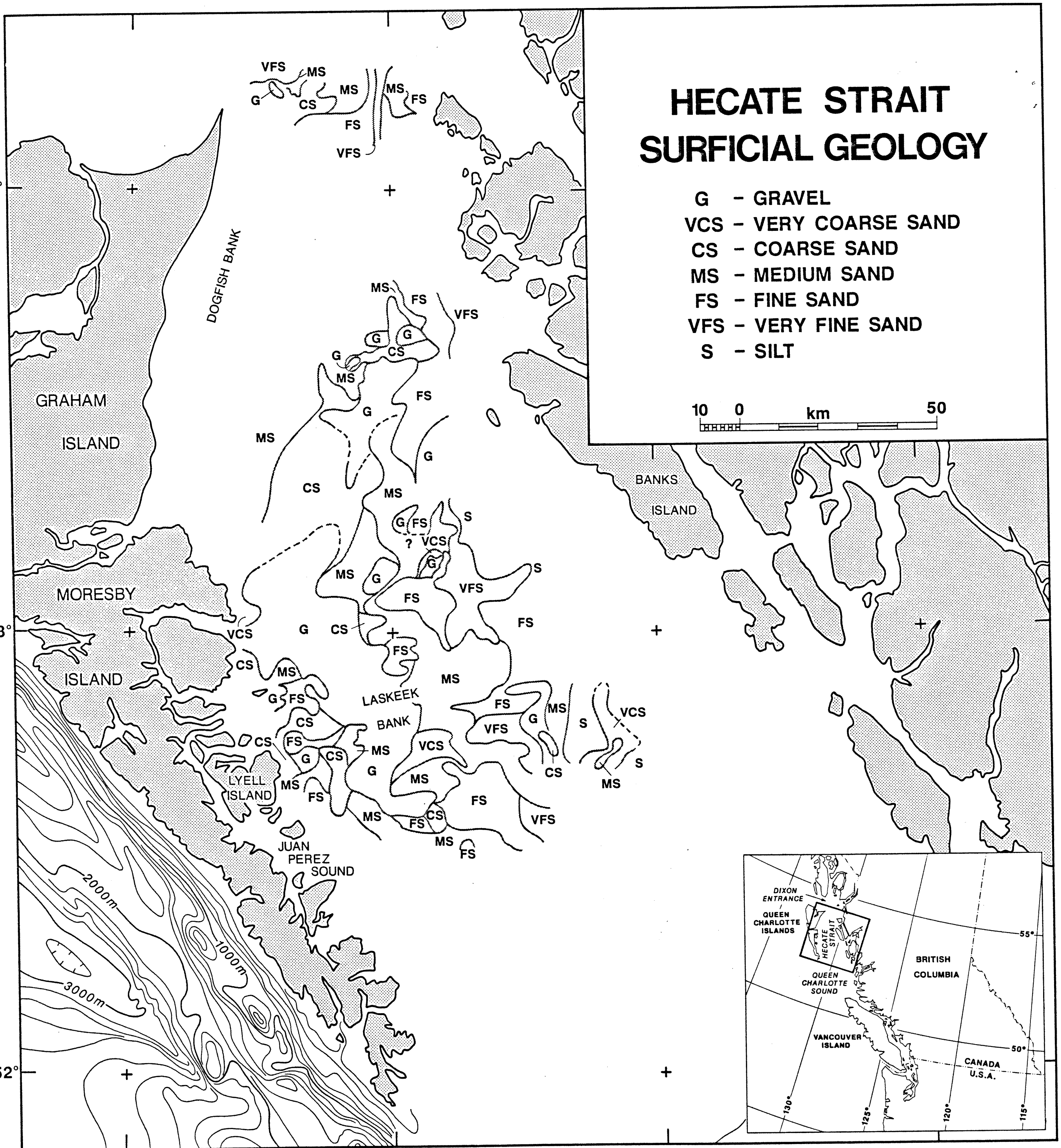
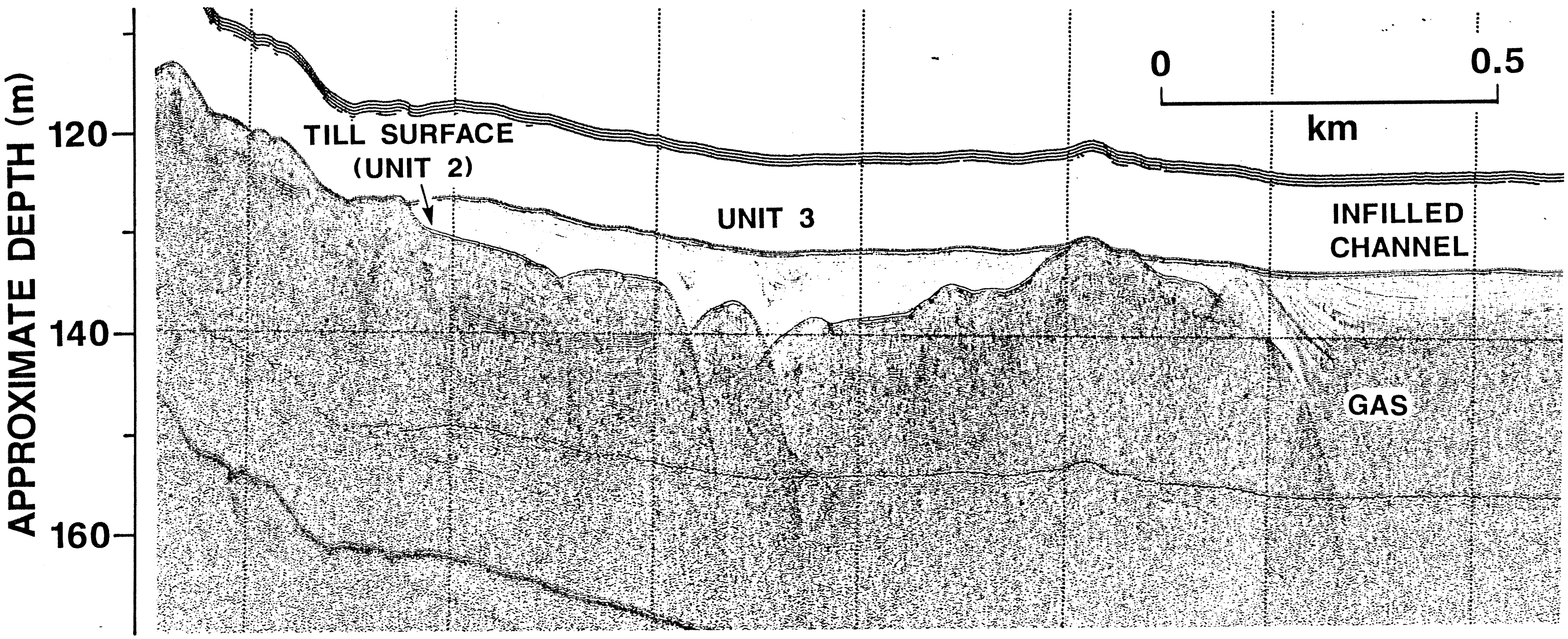
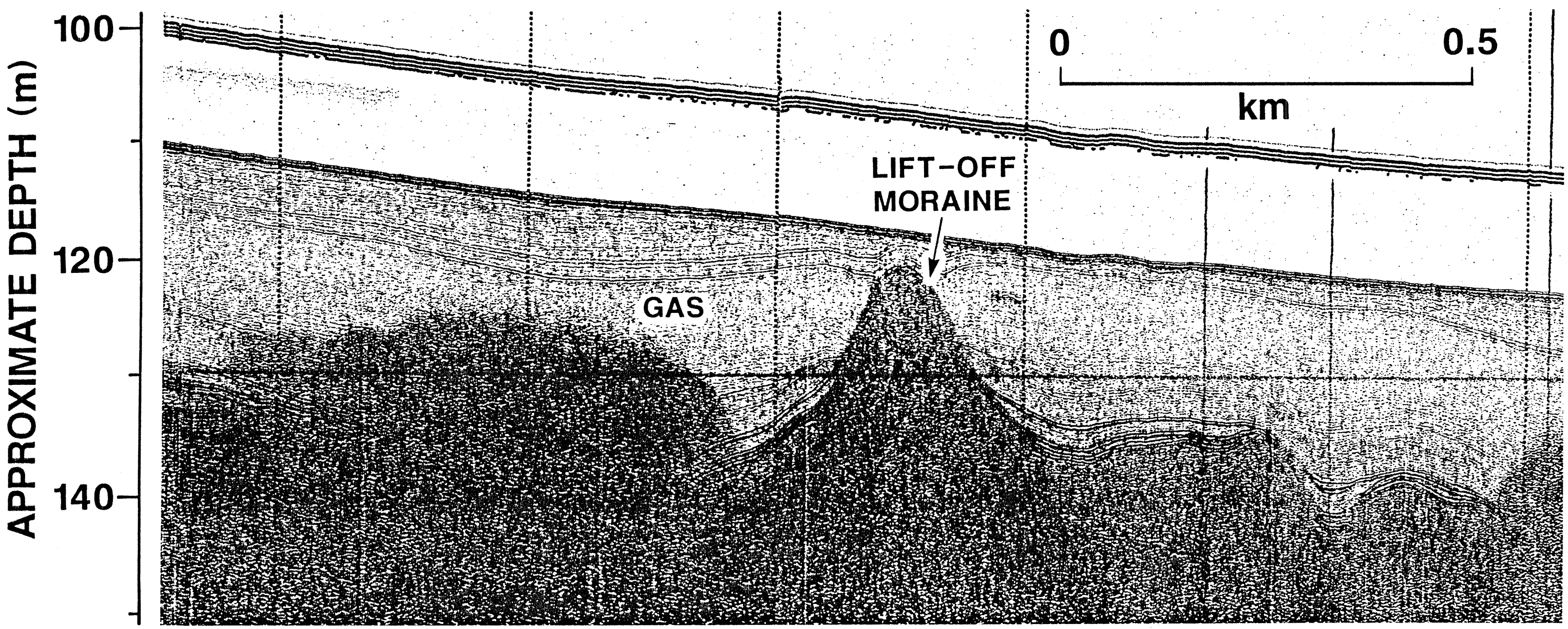
120°
115°

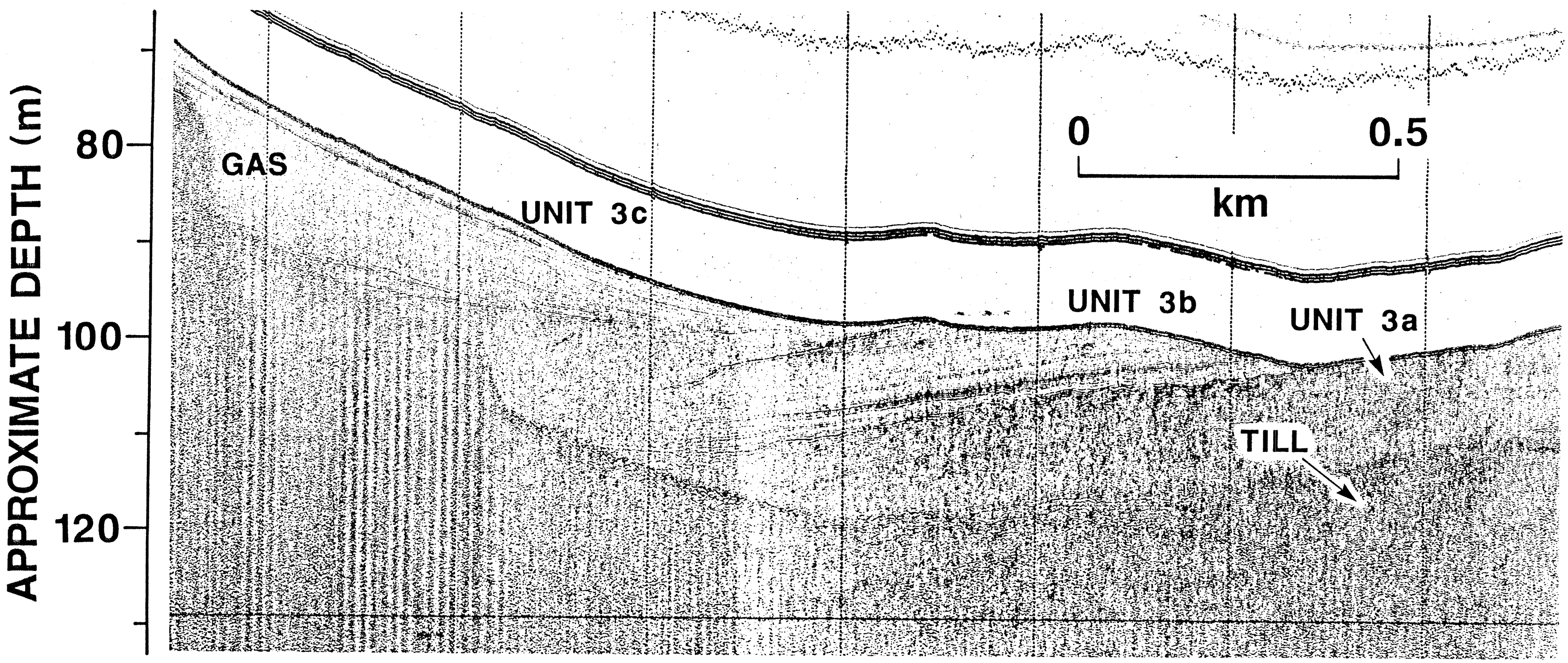

HECATE STRAIT
SURFICIAL GEOLOGY
G - GRAVEL
VCS - VERY COARSE SAND
CS - COARSE SAND
MS - MEDIUM SAND
FS - FINE SAND
VFS - VERY FINE SAND
S - SILT
10 0 km 50
DOGFISH BANK
GRAHAM ISLAND
MORESBY ISLAND
BANKS ISLAND
LASKEEK BANK
LYELL ISLAND
JUAN PEREZ SOUND
2000m
1000m
3000m
54°
53°
52°
132°
131°
130°
129°
DIXON ENTRANCE
QUEEN CHARLOTTE ISLANDS
HECATE STRAIT
QUEEN CHARLOTTE SOUND
BRITISH COLUMBIA
VANCOUVER ISLAND
CANADA
U.S.A.
55°
50°
130°
125°
120°
115°

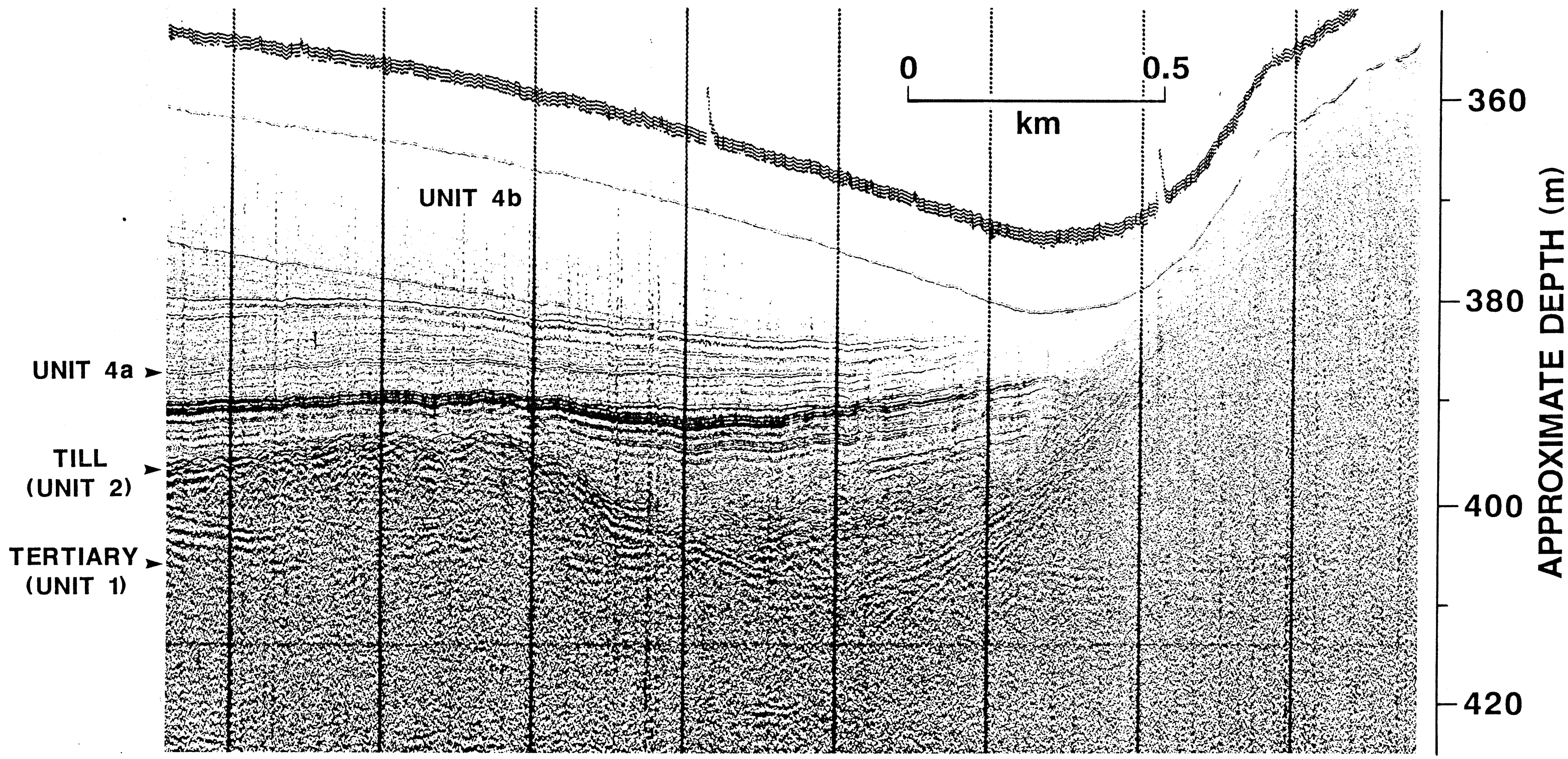

APPROXIMATE DEPTH (m)
120
140
160
TILL SURFACE
(UNIT 2)
UNIT 3
INFILLED
CHANNEL
GAS
0
0.5
km

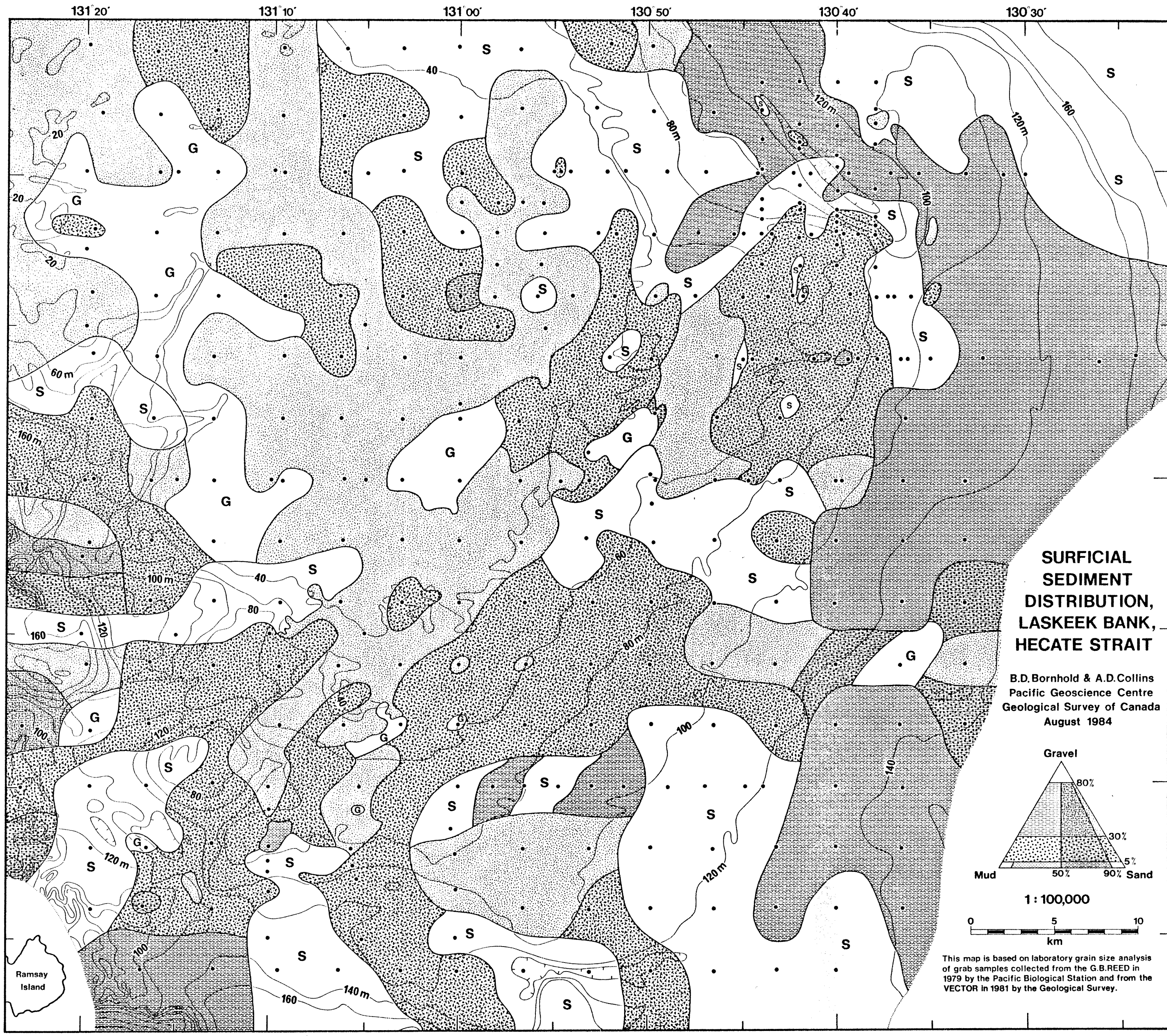
7

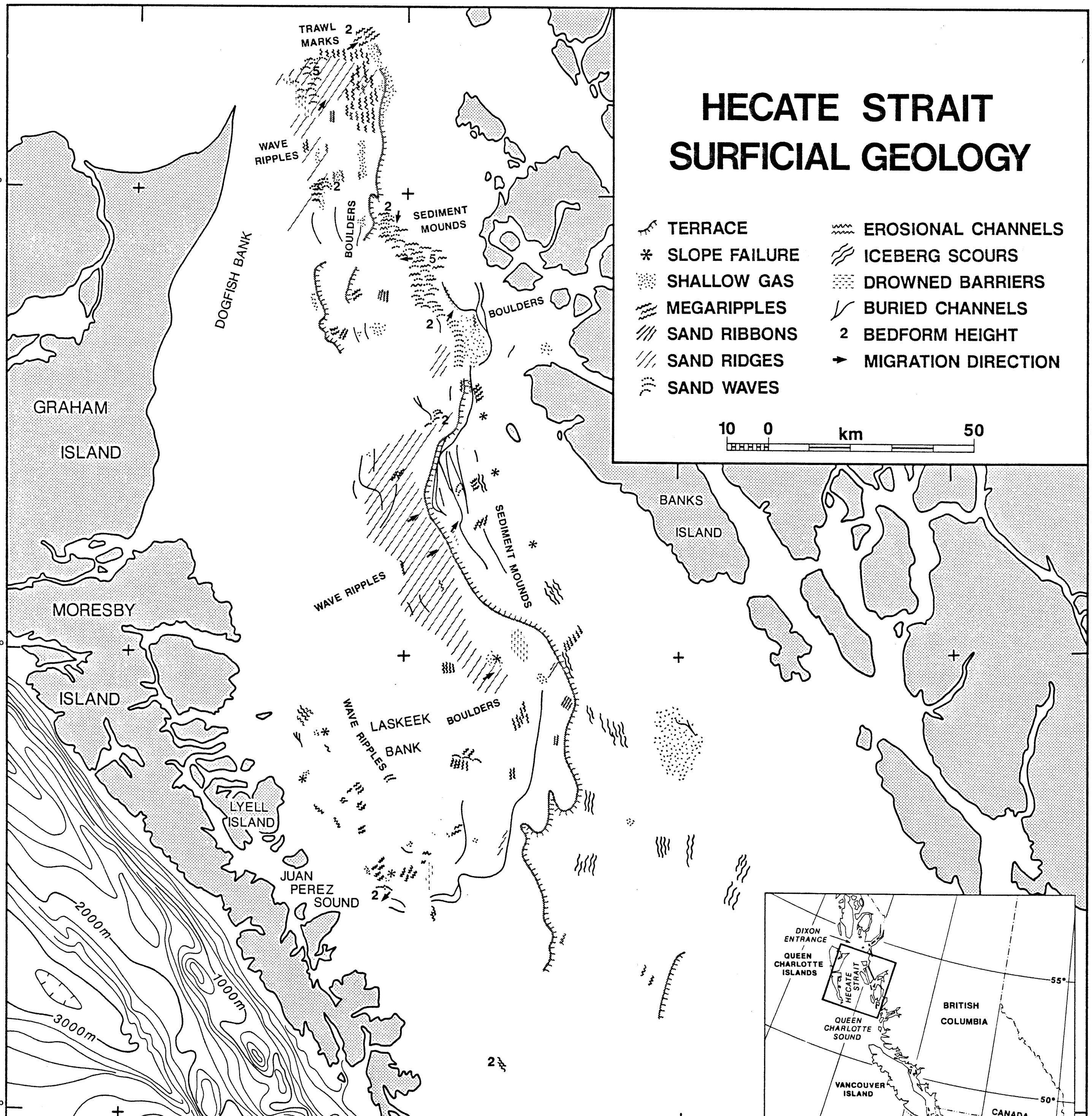


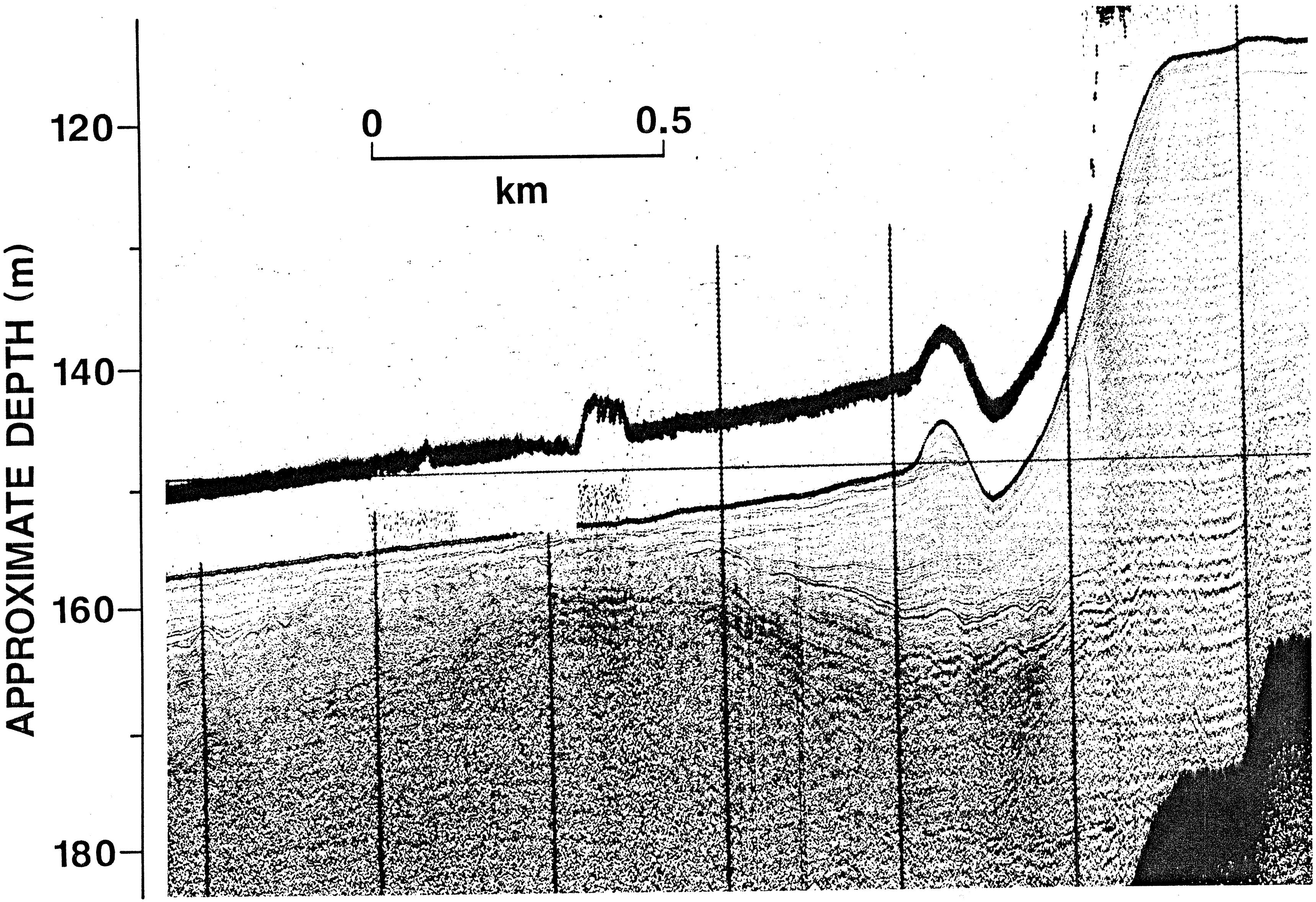
8

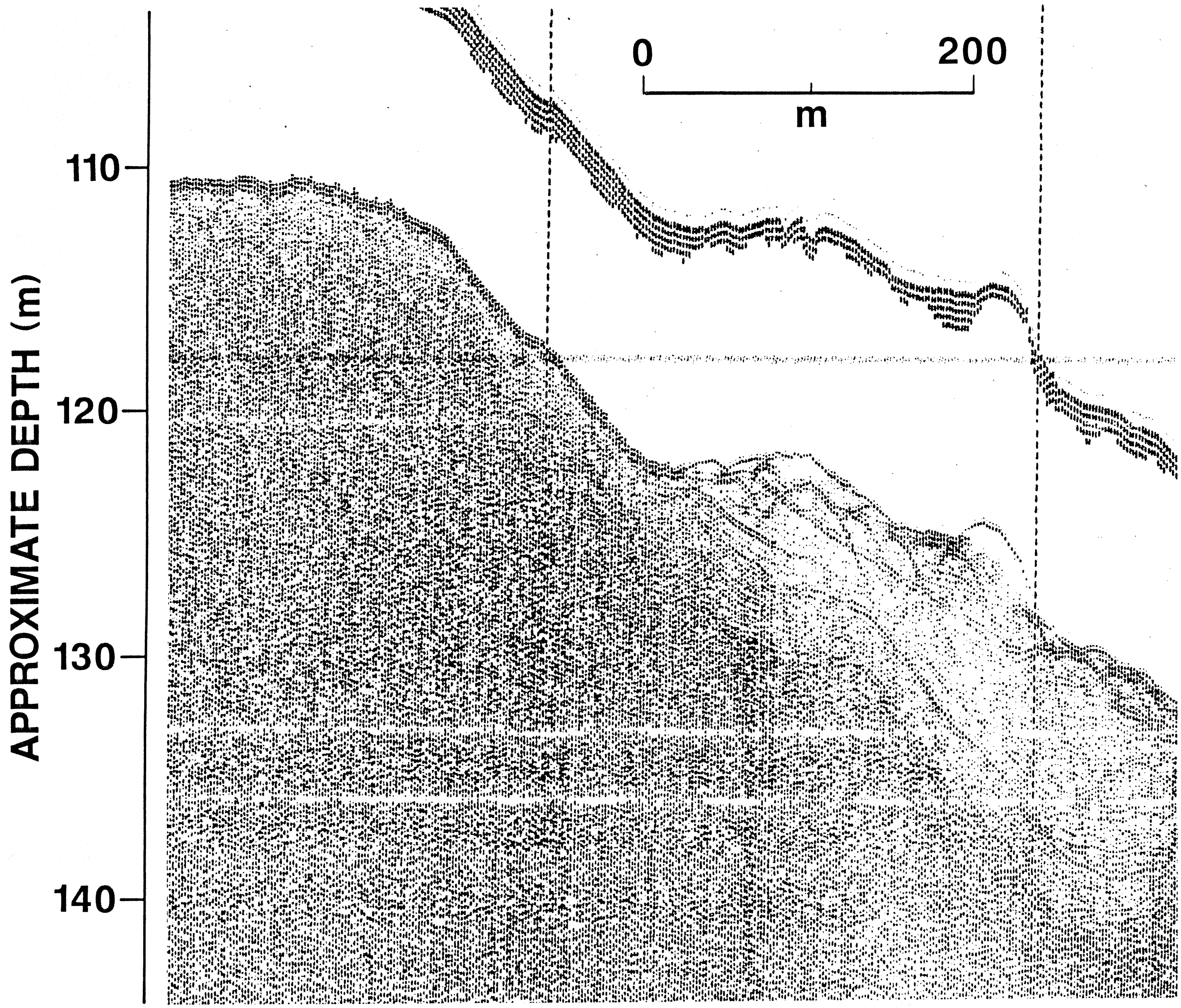

APPROXIMATE DEPTH (m)
80
100
120
GAS
UNIT 3c
UNIT 3b
UNIT 3a
TILL
0
0.5
km

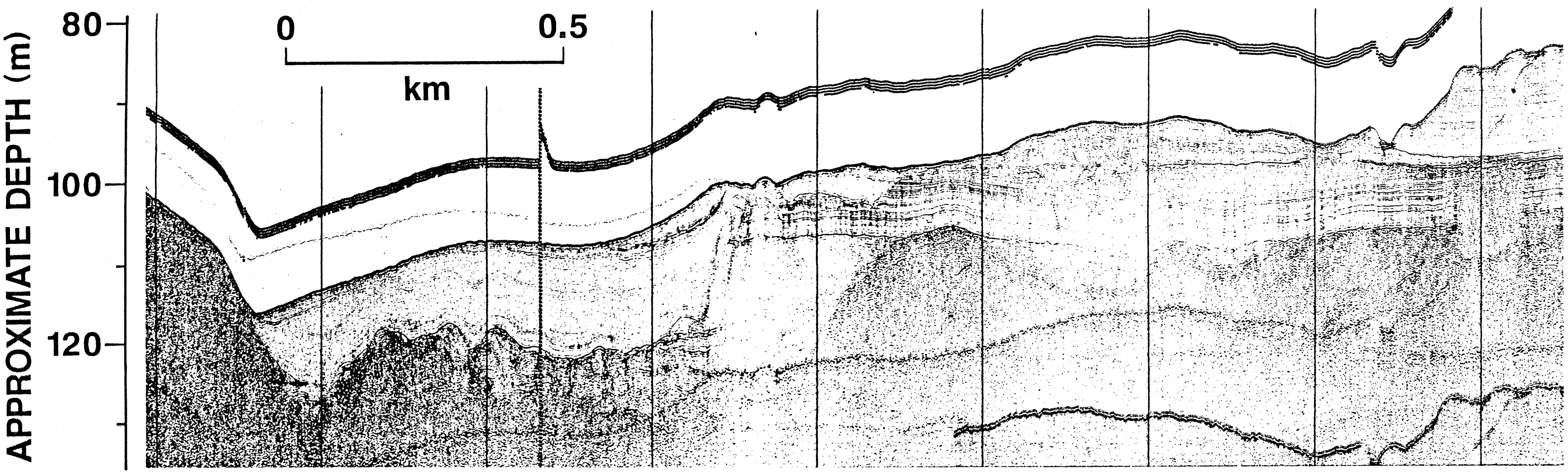

UNIT 4b
0
0.5
km
UNIT 4a
TILL
(UNIT 2)
TERTIARY
(UNIT 1)
360
380
400
420
APPROXIMATE DEPTH (m)

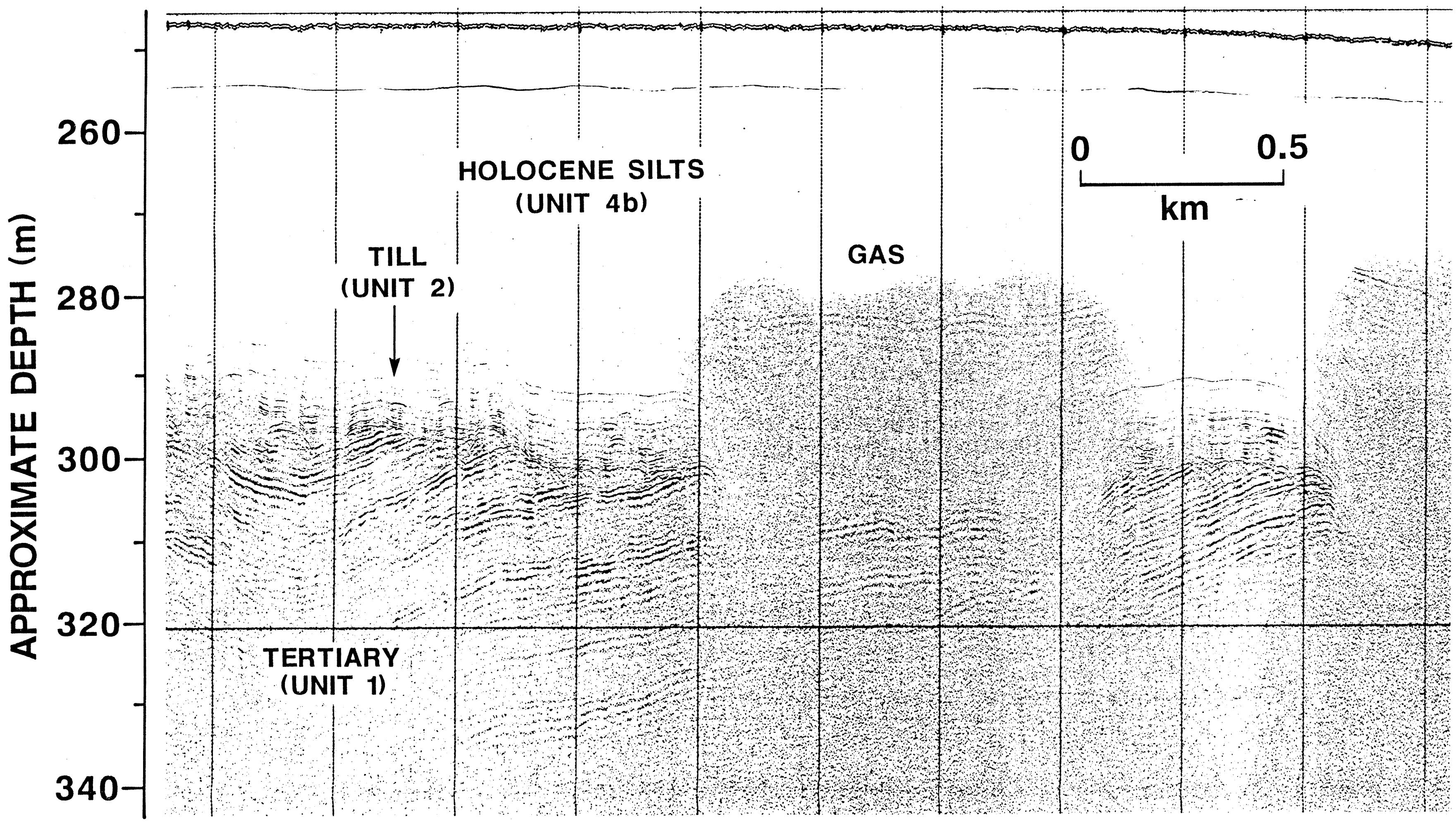

SURFICIAL SEDIMENT DISTRIBUTION, LASKEEK BANK, HECATE STRAIT
B.D. Bornhold & A.D. Collins
Pacific Geoscience Centre
Geological Survey of Canada
August 1984
Gravel
Mud
Sand
80%
30%
5%
50%
90%
1 : 100,000
0
5
10
km
This map is based on laboratory grain size analysis of grab samples collected from the G.B.REED in 1979 by the Pacific Biological Station and from the VECTOR in 1981 by the Geological Survey.
131°20′
131°10′
131°00′
130°50′
130°40′
130°30′
53° 00′
52° 50′
52° 40′
Ramsay Island

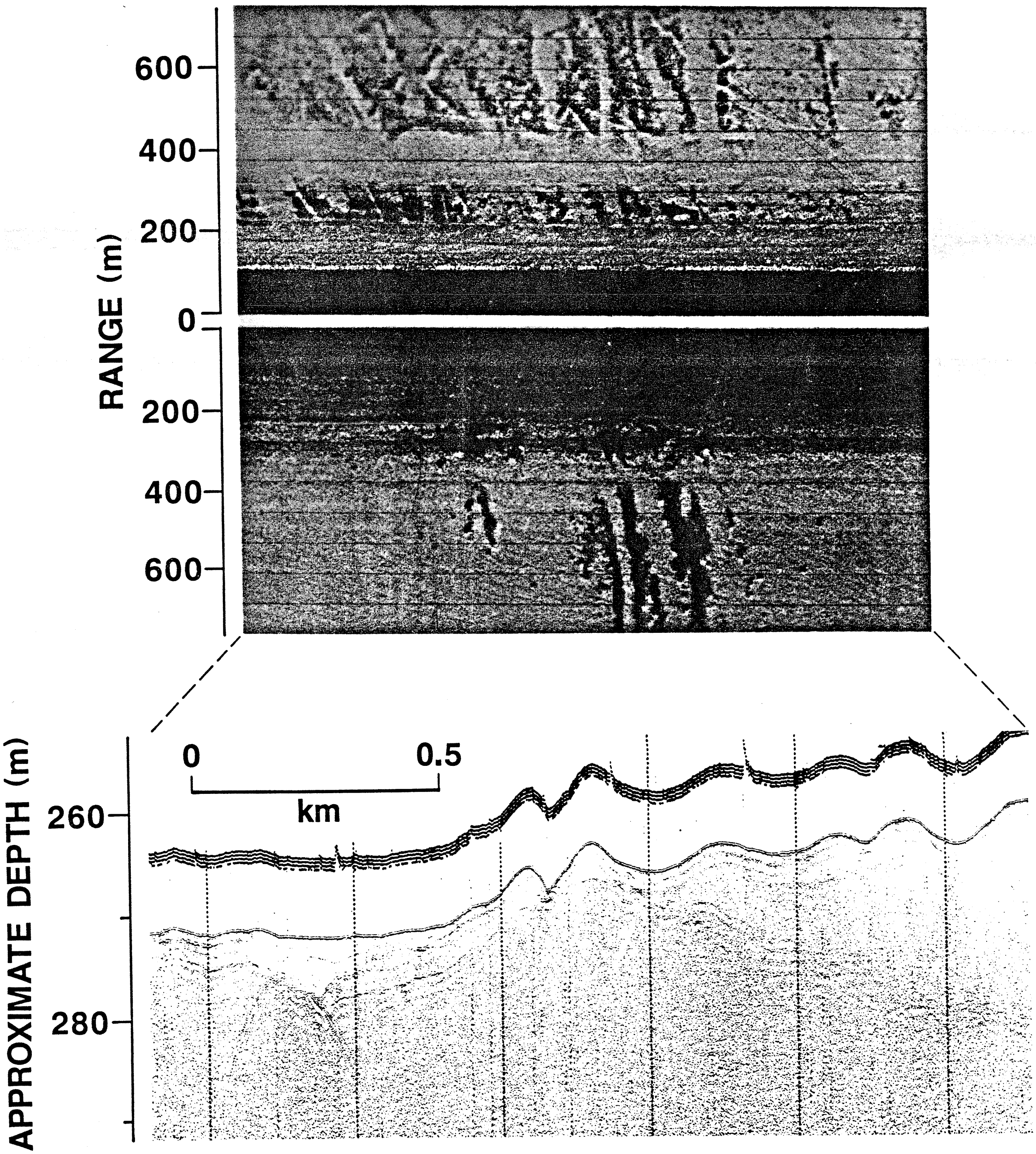

HECATE STRAIT
SURFICIAL GEOLOGY
TERRACE
SLOPE FAILURE
SHALLOW GAS
MEGARIPPLES
SAND RIBBONS
SAND RIDGES
SAND WAVES
EROSIONAL CHANNELS
ICEBERG SCOURS
DROWNED BARRIERS
BURIED CHANNELS
2 BEDFORM HEIGHT
MIGRATION DIRECTION
10 0 km 50
TRAWL MARKS
WAVE RIPPLES
SEDIMENT MOUNDS
BOULDERS
DOGFISH BANK
GRAHAM ISLAND
MORESBY ISLAND
BANKS ISLAND
LASKEEK BANK
LYELL ISLAND
JUAN PEREZ SOUND
2000m
1000m
3000m
54°
53°
52°
132°
131°
130°
129°
DIXON ENTRANCE
QUEEN CHARLOTTE ISLANDS
HECATE STRAIT
QUEEN CHARLOTTE SOUND
BRITISH COLUMBIA
VANCOUVER ISLAND
CANADA
U.S.A.
55°
50°
130°
125°
120°
115°


APPROXIMATE DEPTH (m)
120
140
160
180
0
0.5
km

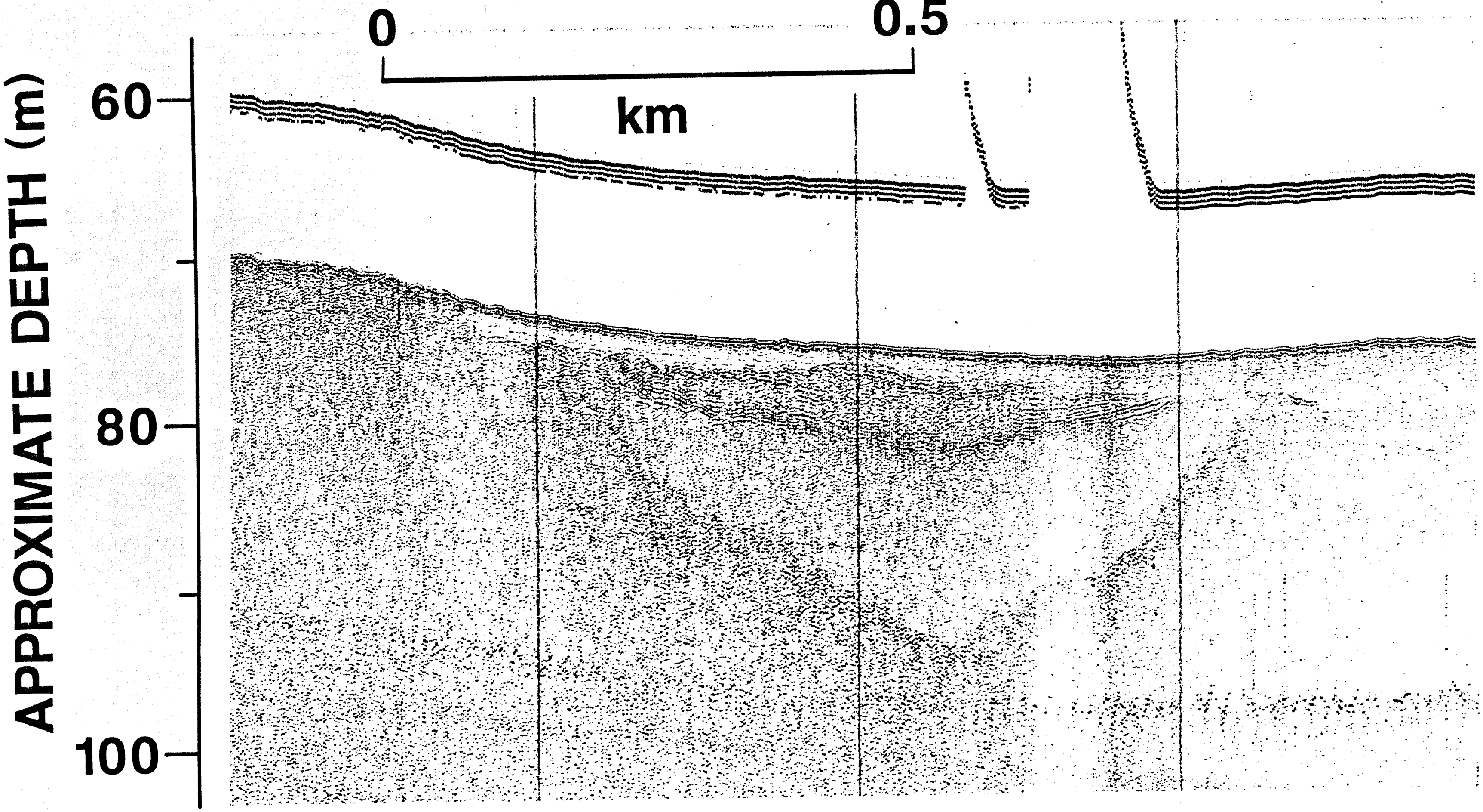

APPROXIMATE DEPTH (m)
110
120
130
140
0
200
m

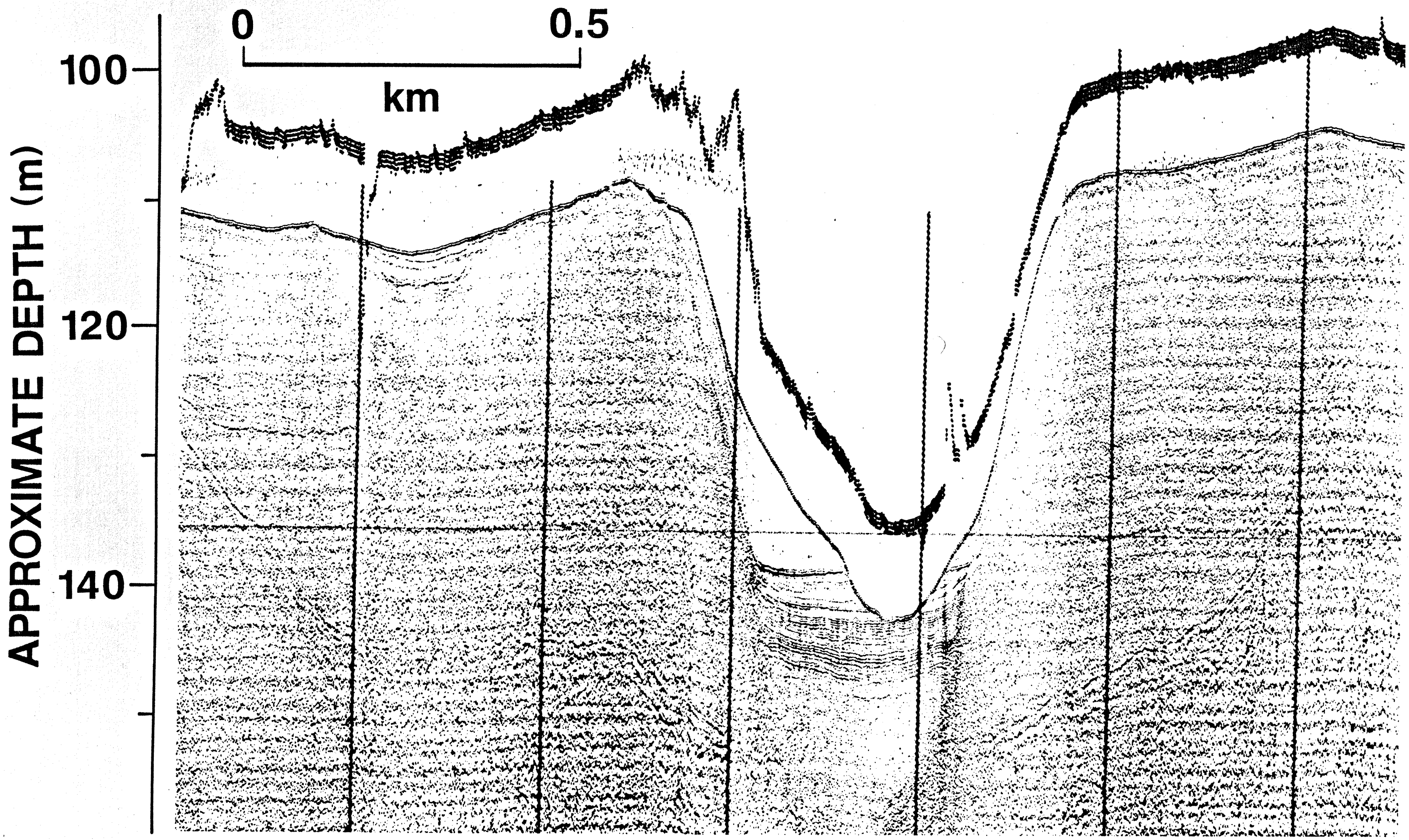

APPROXIMATE DEPTH (m)
80
100
120
0
0.5
km

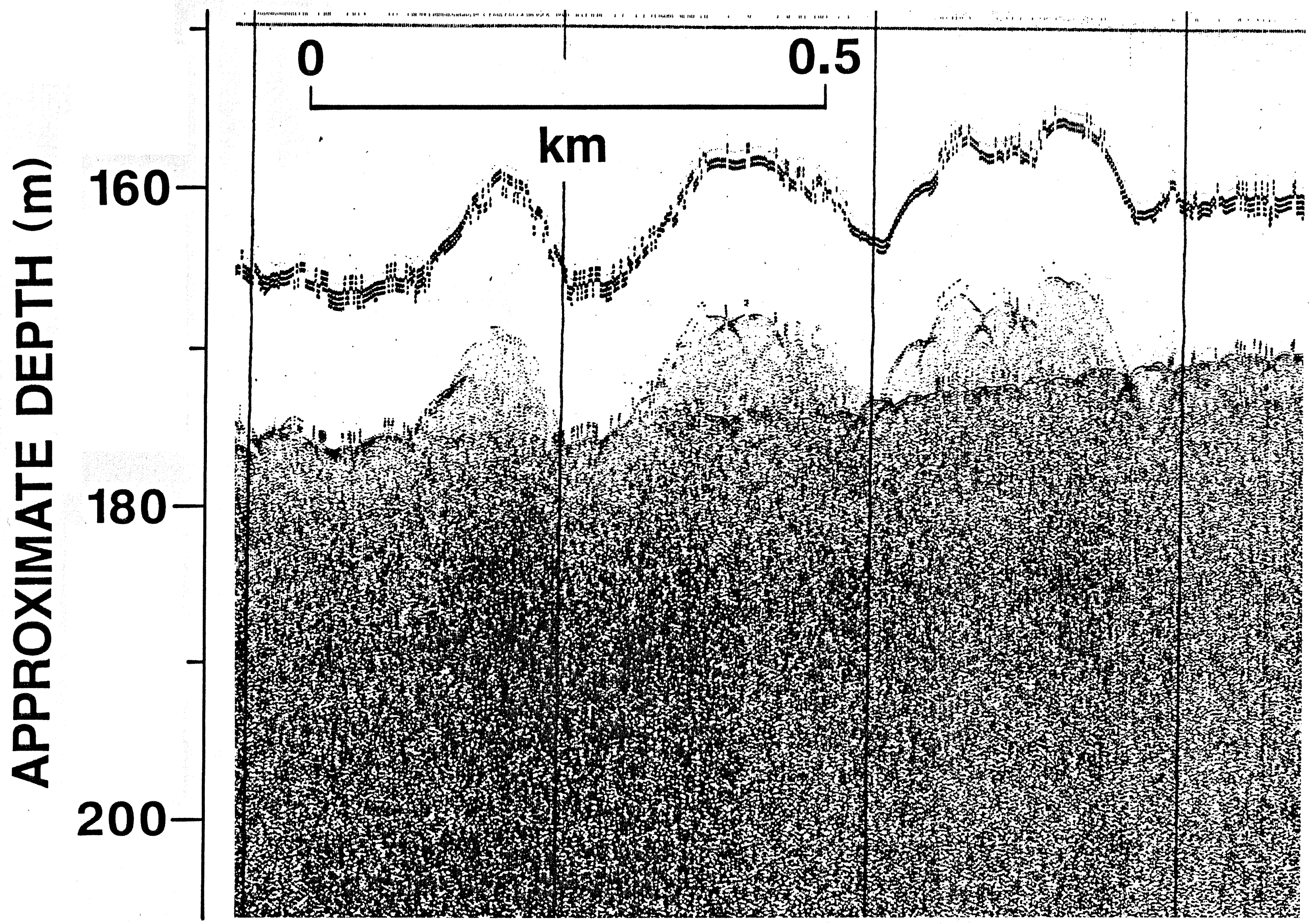

APPROXIMATE DEPTH (m)
260
280
300
320
340
HOLOCENE SILTS
(UNIT 4b)
TILL
(UNIT 2)
GAS
TERTIARY
(UNIT 1)
0
0.5
km



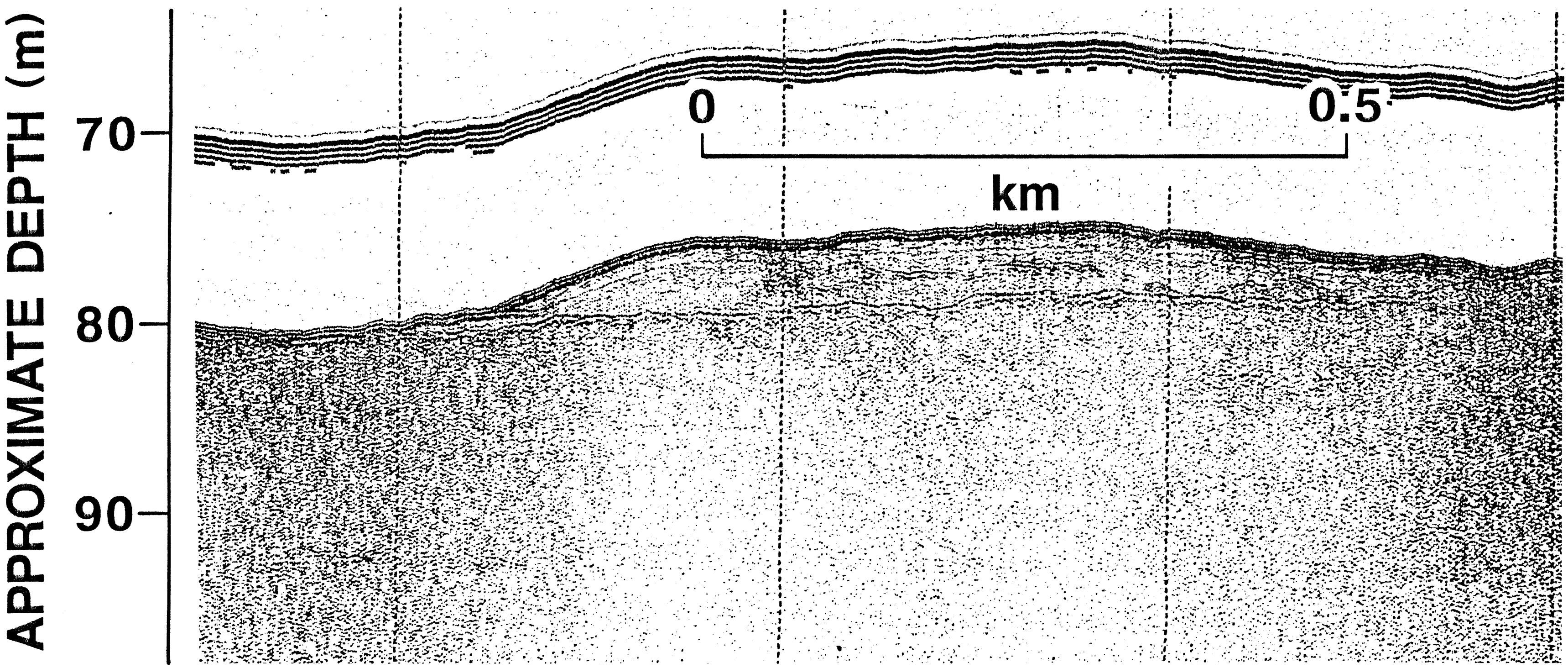
RANGE (m)
600
400
200
0
0
200
400
600
APPROXIMATE DEPTH (m)
260
280
0
0.5
km

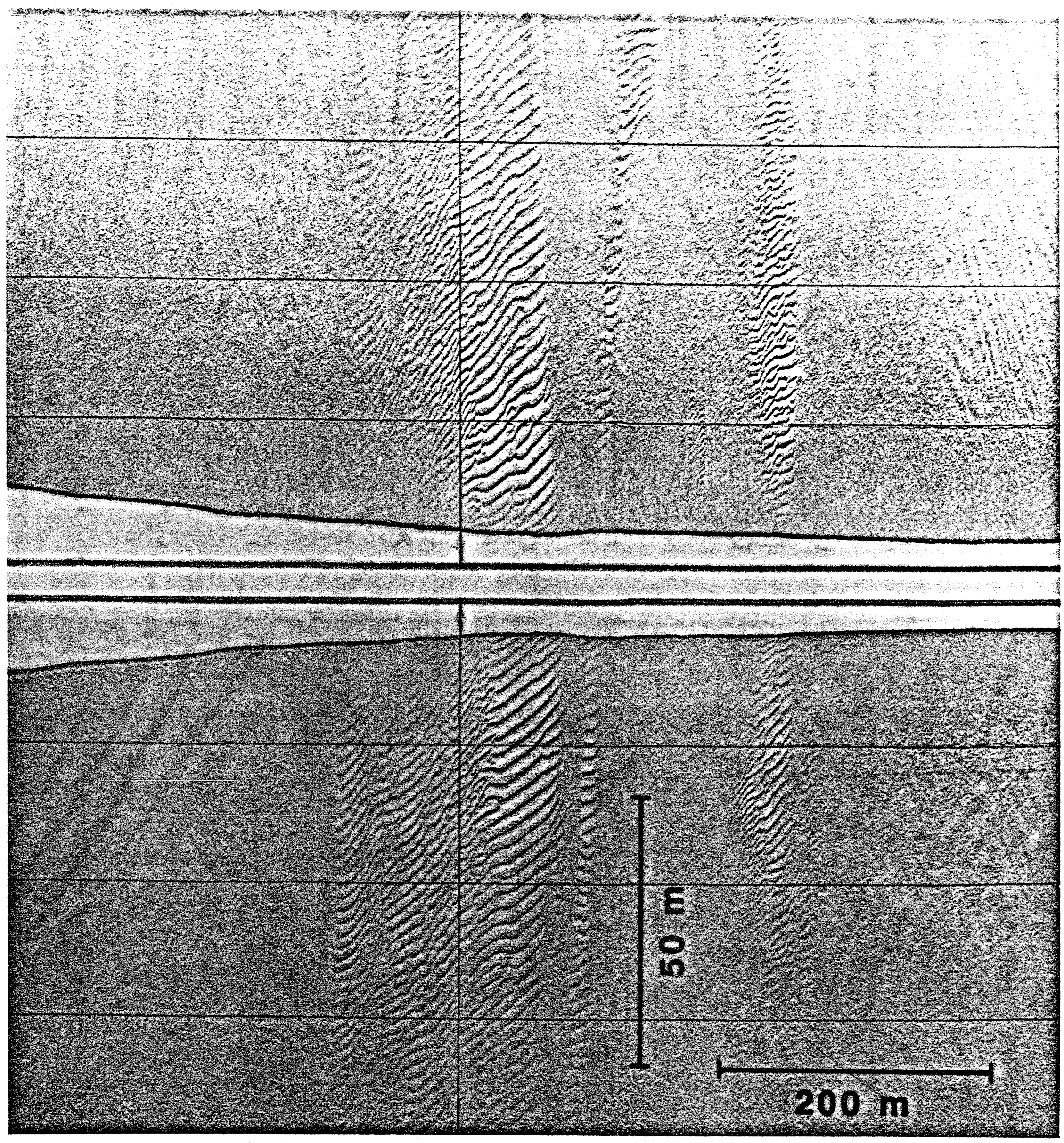

APPROXIMATE DEPTH (m)
60
80
100
0
0.5
km

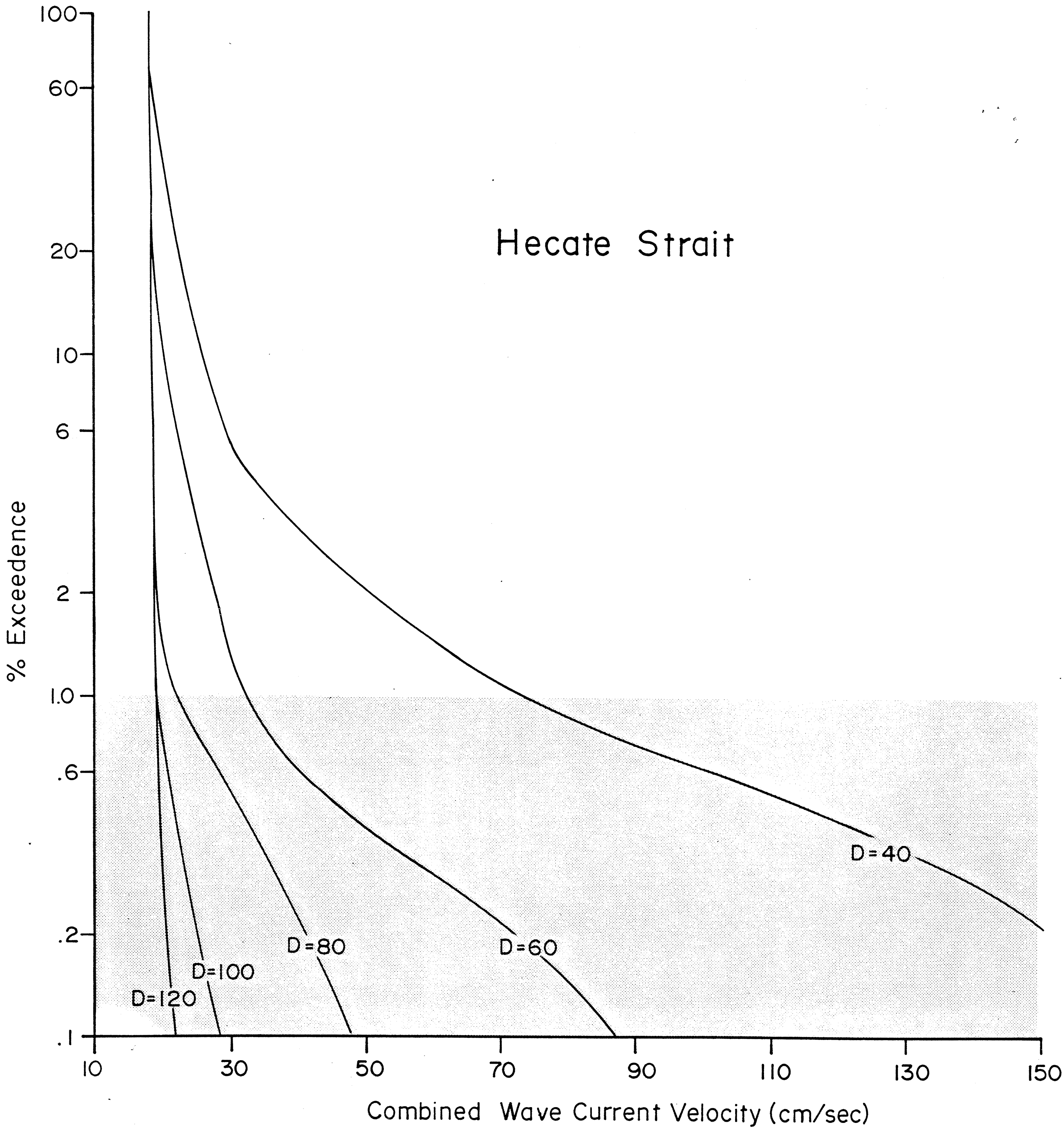

APPROXIMATE DEPTH (m)
100
120
140
0
0.5
km

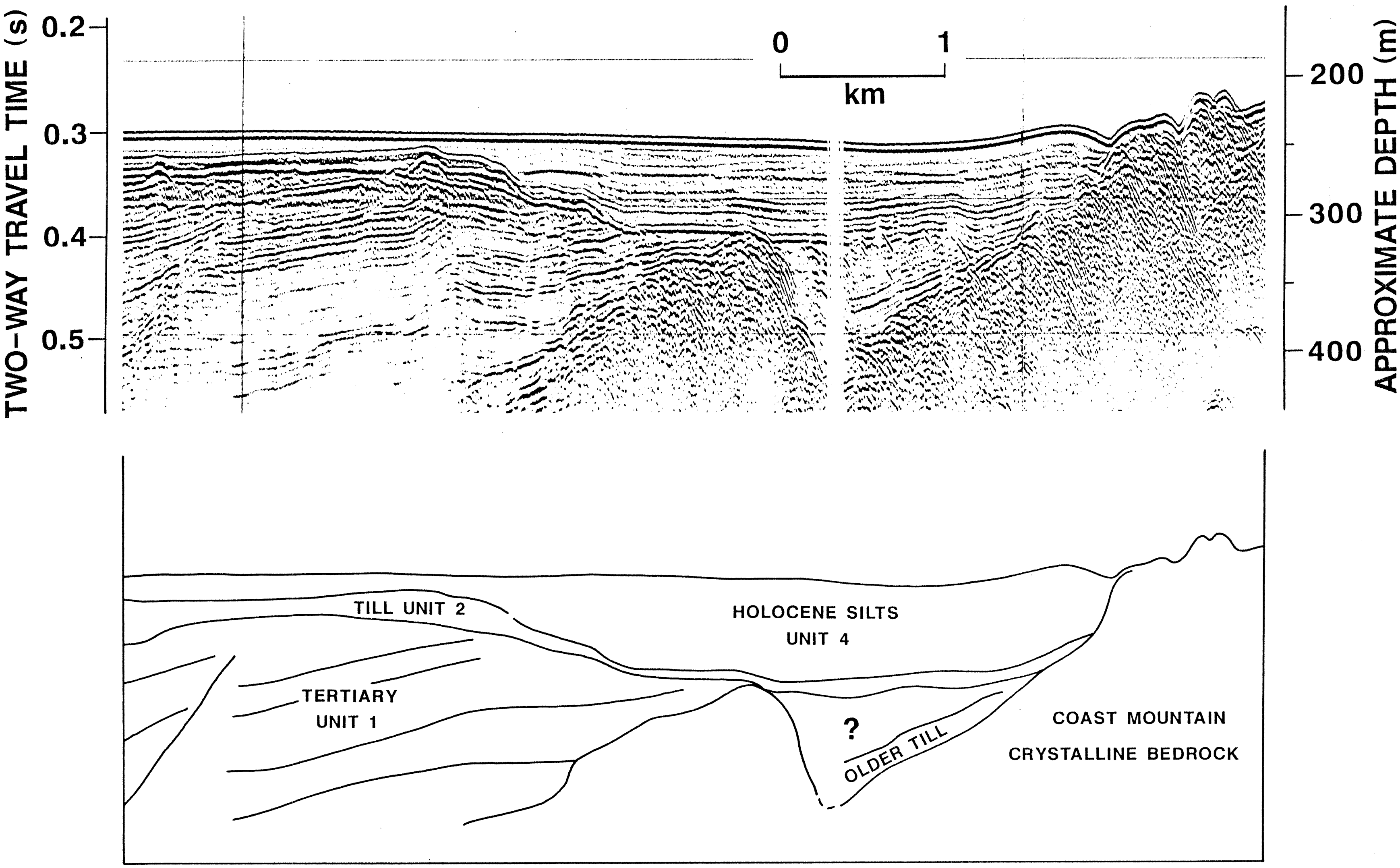


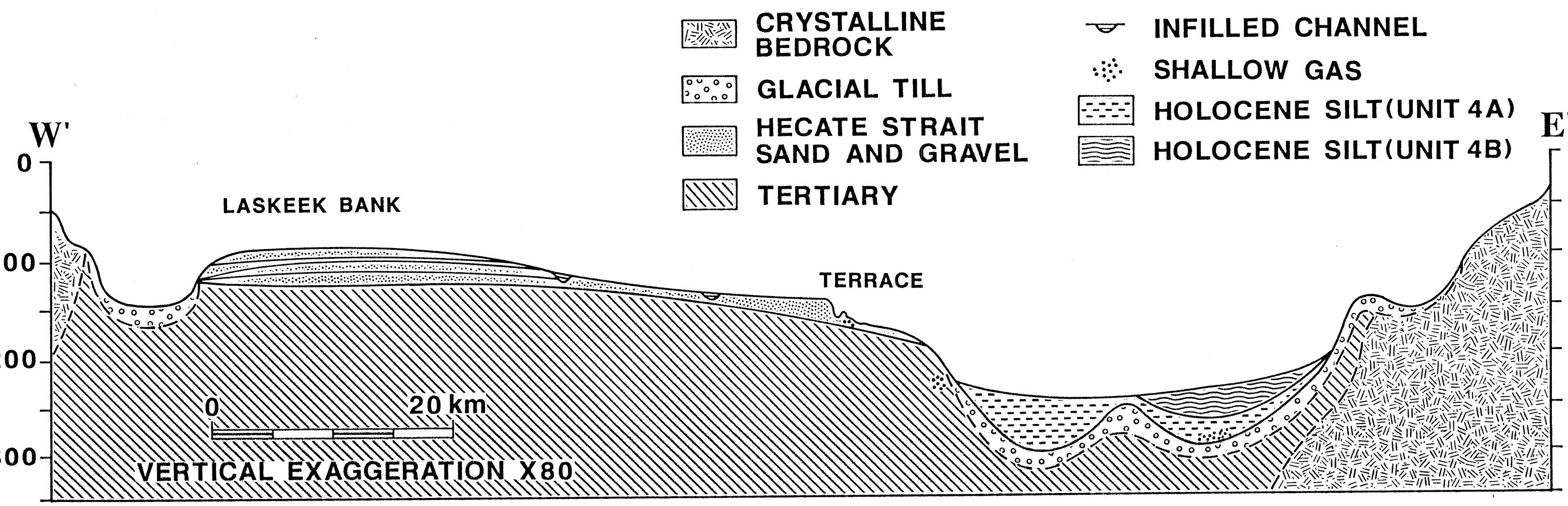
APPROXIMATE DEPTH (m)
160
180
200
0
0.5
km


APPROXIMATE DEPTH (m)
70
80
90
0
0.5
km

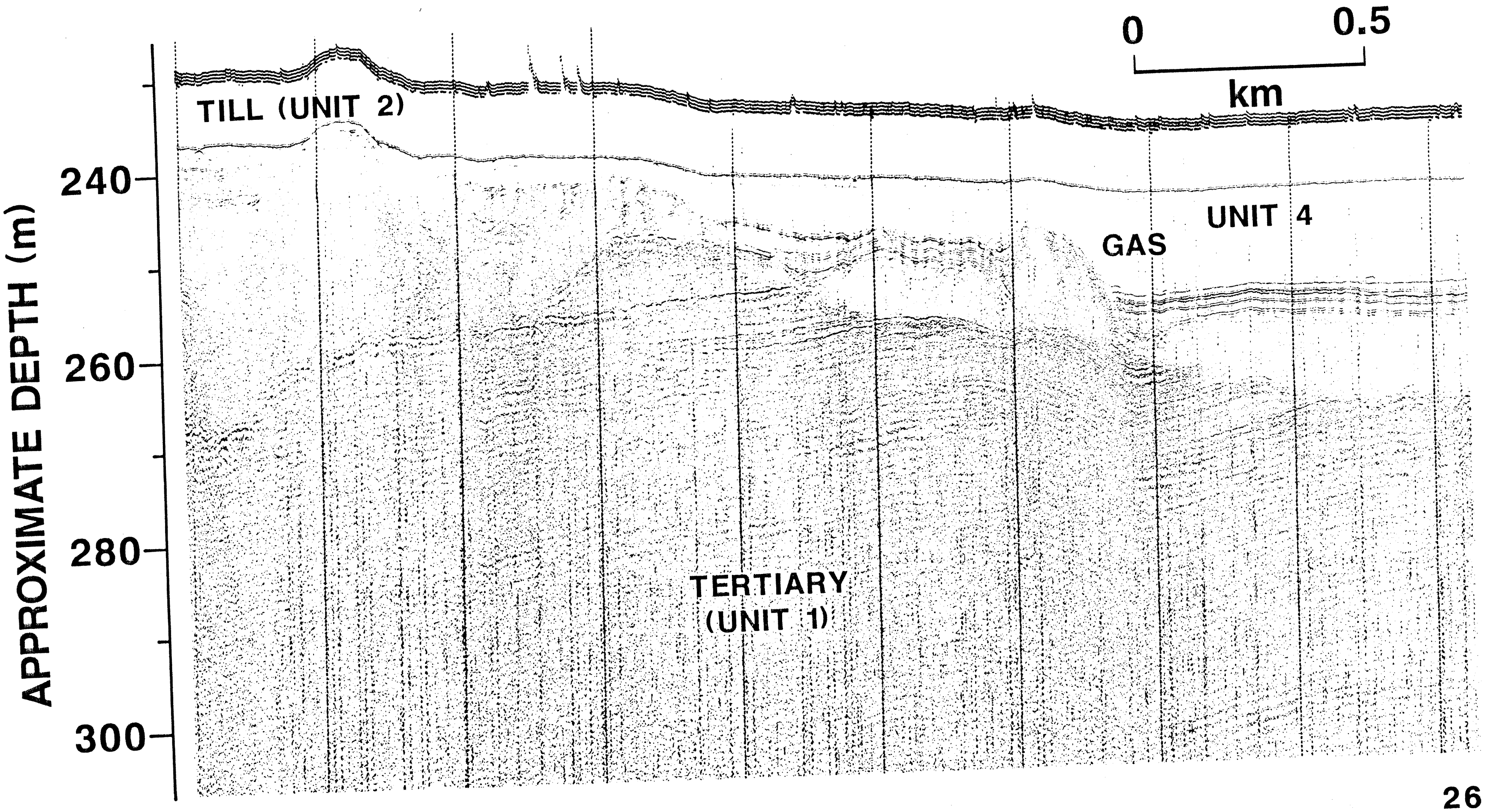

50 m
200 m

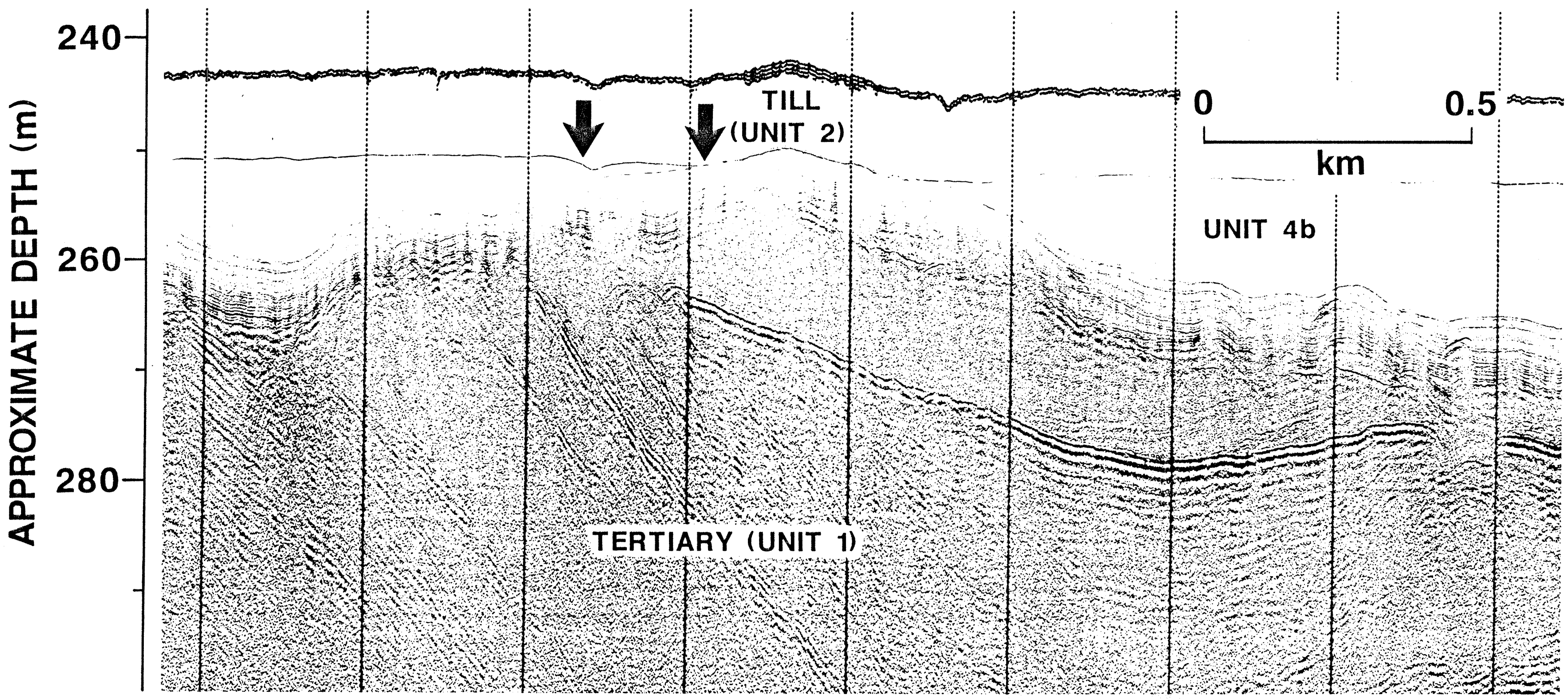

Hecate Strait
% Exceedence
100
60
20
10
6
2
1.0
.6
.2
.1
10
30
50
70
90
110
130
150
Combined Wave Current Velocity (cm/sec)
D=40
D=60
D=80
D=100
D=120


TWO-WAY TRAVEL TIME (s)
0.2
0.3
0.4
0.5
0
1
km
200
300
400
APPROXIMATE DEPTH (m)
TILL UNIT 2
HOLOCENE SILTS
UNIT 4
TERTIARY
UNIT 1
?
OLDER TILL
COAST MOUNTAIN
CRYSTALLINE BEDROCK



W'
E'
0
100
200
300
LASKEEK BANK
TERRACE
CRYSTALLINE BEDROCK
GLACIAL TILL
HECATE STRAIT SAND AND GRAVEL
TERTIARY
INFILLED CHANNEL
SHALLOW GAS
HOLOCENE SILT(UNIT 4A)
HOLOCENE SILT(UNIT 4B)
0
20 km
VERTICAL EXAGGERATION X80


APPROXIMATE DEPTH (m)
240
260
280
300
TILL (UNIT 2)
0
0.5
km
UNIT 4
GAS
TERTIARY
(UNIT 1)


APPROXIMATE DEPTH (m)
240
260
280
TILL
(UNIT 2)
0
0.5
km
UNIT 4b
TERTIARY (UNIT 1)