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PLEISTOCENE STRATIGRAPHY AND SEDIMENTOLOGY OF WESTERN FLEMISH PASS: A SEISMIC INTERPRETATION

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Abstract

Single channel air gun reflection seismic and Huntec deep towed seismic subbottom profiler data have been used to define the Quaternary geologic framework of western Flemish Pass in the vicinity of the Gabriel and Kyle wells. Long Coring Facility cores up to 11m long provide groundtruth for the high-resolution seismic and a basic chronology.

The upper few hundred metres of sediment are dominated by sedimentation from slope valleys. The valleys originate at water depths of 500 - 600 m, at the limit of till deposition on the upper slope, and were probably cut due to subglacial meltwater discharge. They are incised up to 75m on the slope; the last major erosional event is believed to date from isotopic stage 4. Some valleys show complex cut and fill events, others have been completely filled with stratified sediment. The valleys lead to depositional lobes, analagous to deep sea fans, at the western edge of Flemish Pass. These lobes are loci of sand deposition, and consist of thick sand beds separated by muds. The sediments are charged with shallow gas. The lobes pass distally into alternating mud and sand turbidites on the floor of Flemish Pass.

INTRODUCTION

Flemish Pass has seen extensive hydrocarbon exploration, and four wildcat wells have been drilled in the Pass. The seabed geological conditions are quite different from those typically found on the adjacent areas of the continental shelf. Previous work has identified enigmatic diapir-like structures, the possible presence of shallow gas, shallow debris flows and evidence of in situ sediment failure. Hydrocarbon exploration sites are located at the foot of the steep continental slope leading from the shelf break at the edge of the Grand Banks. The area therefore also provides an opportunity to examine upper continental slope processes applicable elsewhere on the East Coast offshore.

The present study is a continuation of previous surveys of the western margin of Flemish Pass in the vicinity of the Gabriel C-60 and Kyle L-11 well sites (Fig. 1). The purpose of the study is to define the regional Quaternary geological framework of Flemish Pass, to allow more detailed studies of geotechnical properties, facies development and biostratigraphy of the Quaternary sediments. The study was also intended to map the distribution of near-surface sediment instability features and other constraints to hydrocarbon exploration and, potentially, production. The detailed study area is outlined in Figure 1: it extends along the western side of Flemish Pass between the Kyle and Gabriel well sites.

A seismo-stratigraphic framework for eastern Flemish Pass was proposed by Piper and Sparkes (1986). From single channel air gun seismic profiles, they recognised three phases of Late Cenozoic sedimentation:

1. uniform deep water sedimentation in the Early Pliocene. The base of this unit was marked by the "brown" reflector and the top by the "purple".
2. slope progradation associated with shallow slope valleys in the Late Pliocene - Early Pleistocene.
3. till deposition on the upper slope and widespread gullying on the lower slope in the Middle to Upper Pleistocene. The base of this phase is marked by a correlatable horizon, termed "red".

Huntec deep towed seismic (DTS) subbottom profiler data (Piper and Sparkes, 1986) and SeaMARC 1 midrange sidescan sonar imagery (Pereira et al., 1985) suggest that sedimentary processes related to slope valleys have been important in the development of surficial sediments. Valleys up to 75 m deep cut the lower slope. Downslope from these valleys on the floor of Flemish Pass are debris flow deposits and enigmatic diapir-like features. Piper and Sparkes (1986) distinguished two acoustic facies - stratified and transparent - but lack of suitable cores prevented an interpretation of the sedimentary significance of these two facies. The transparent facies was interpreted as representing sediment failure and a horizon - termed "alpha" - was identified 5 to 10 msec subbottom which can be correlated over most of the study area (Piper and Sparkes, 1986).

A large number of short (< 2m) cores have been examined for their geotechnical properties by Morin and Pereira (unpublished manuscript) from well site surveys. Alam (1979) described one 6 m long piston core from the Gabriel well site. Piper and Sparkes report preliminary data on two cores, 3 and 7.5 m long; Pereira (pers. comm. 1987) has examined biostratigraphy of these cores and Christian (pers. comm. 1986) has made geotechnical measurements on the cores. A detailed account of these core samples is in preparation for a later report.

METHODS

Approximately 132 line km of Huntec DTS boomer profiles and 168 line km of 40 cu in air gun single channel seismic reflection profiles were collected on Hudson cruise 87-008 in the area previously investigated by Pereira et al. (1985) and Piper and Sparkes (1986) (Fig. 2). From these previous cruises, 280 line km of Huntec DTS and air gun seismic reflection profiles are available. Five long piston cores, up to 11 m in length, were collected with the Long Coring Facility during Hudson cruise 87-008. These cores were on average 40% longer than those collected nearby in comparable lithologies with a 900 kg piston corer on previous cruises, namely cruise 86-018 (six cores), 85-044 (two cores) and a core described by Alam (1979) (core 3-1) from the Gabriel well site.

In addition, we have re-examined acoustic data from previous cruises 80-010, 84-034 (SeaMARC 1 imagery: Pereira et al., 1985), 85-044 (Huntec DTS and air gun profiles: Piper and Sparkes, 1986) and 86-018 (Huntec DTS and air gun profiles).

All sub-bottom depths in metres are based on an assumed velocity of 1500 m/s.

BATHYMETRY

Previous bathymetric compilations of Flemish Pass (Monahan and MacNab, 1974) have been based principally on widely spaced east-west survey lines. These lines run parallel to the main slope valleys on the continental slope between the Grand Banks and Flemish Pass, and do not adequately represent the degree of dissection of this slope by valleys.

A revised bathymetric map is presented in Figure 1. It shows that the shelf break off the outer Grand Banks occurs at about 240 m water depth, deepening to about 300m north of the study area. The upper slope, with a gradient of about 2 degrees, is rather smooth and featureless (except for the presence of iceberg scours: Pereira et al., 1985). Several valleys up to 75 m deep cut the lower slope, which has a gradient of about 2.5 degrees. Below about 1000 m, the gradient decreases rapidly to the floor of the Pass at about 1180 m. There is a pronounced shallowing of the floor of the Pass seaward of a large valley (Gabriel valley) near the Gabriel well site: this feature bathymetrically resembles a deep sea fan seaward of a submarine canyon.

GEOLOGIC SETTING

A general geologic cross section of western Flemish Pass is shown in Figure 3. Subhorizontal sediments on the floor of the Pass unconformably onlap older sediments on the flanks of Flemish Cap to the east of the area shown in Figure 3, and thin (with local onlap) onto the slope from the Grand Banks. This sequence at the edge of the Grand Banks can be correlated with the succession in the Gabriel C-60 well, where Plio-Pleistocene strata disconformably overlie Early Miocene claystones with sand at about 610 m. subbottom (Gradstein, 1981). At the eastern edge of the Pass, older sediments rise to the surface on the flanks of Flemish Cap, separated by a major fault from the sediments on the floor of Flemish Pass (seen in industry seismic and detectable in our airgun profiles, such as illustrated in Fig. 4). There is widespread acoustic masking in surficial sediments, apparently by shallow gas (Figure 5) along this fault zone.

The flat lying facies on the floor of Flemish Pass thicken westwards, and become acoustically better stratified eastwards, suggesting an eastward increase in the proportion of muds. Available piston cores confirm this trend in the upper 10 m of sediment.

There is onlap of flat lying sediments on the floor of Flemish Pass onto the slope sequence at the eastern edge of the Grand Banks. Large acoustically amorphous mounds of sediment occur at the ends of the large slope valleys, and the general aspect of the sediment is less stratified than in the centre of the Pass. It is unclear whether this is the result of less primary stratification and more sand, or whether there is partial masking by shallow gas.

The western slope of Flemish Pass, off the eastern edge of the Grand Banks, has a complex history of cut and fill throughout the later Quaternary. These sediments grade upslope at about 550 m into a zone of incoherent high amplitude reflectors previously interpreted as till and other coarse ice-contact deposits (Piper and Sparkes, 1986). Within the study area, two large valleys are recognised: the complex Gabriel valley system in the north and the Kyle valley in the south (Fig. 6).

DETAILED DESCRIPTION OF SEISMO-STRATIGRAPHY

Definition of key reflectors

The stratigraphic marker horizons defined by Piper and Sparkes (1986) have been correlated over much of the study area. These markers are summarised in Table 1. The large numbers of cross-overs available provide an internal check on the consistency of correlation. This correlation is illustrated in a series of seismic reflection profiles, the location of which is shown in Figure 2.

In Huntec DTS profiles, reflector alpha, about 10 msec subbottom, is the only horizon that can be correlated with any certainty over the study area (Table 1). Deeper reflectors are discontinous and locally cut out at a widespread unconformity a short distance below alpha. In the extreme north of the area, a second deeper horizon, beta, has been correlated.

On air gun profiles (e.g. Fig. 7), it is difficult to correlate shallow reflectors because of the large amount of valley cut and fill in the upper part of the section. No reflector above red (100-300 ms subbottom) can be correlated over a large area. The purple and brown reflectors defined by Piper and Sparkes (1986) have been correlated over much of the study area. An additional reflector, blue, just above purple, has also been widely correlated.

Section below the red reflector

The deeper section below red has been stratigraphically divided according to the scheme of Piper and Sparkes (1986). The brown reflector, correlated with the Pliocene - Miocene disconformity in the Gabriel C-60 well, is too deep to be seen on many of the air gun profiles. The overlying strata, up to the purple reflector, show uniform parallel stratification, and no clear valleys are seen on the continental slope.

Just above purple, rare small valleys or gullies, up to 20 m deep and 2 km wide, are seen in air gun profiles (e.g. 'a' at extreme southern end of profile in Figure 7). A more pronounced phase of slope valley cutting is seen 70 - 100 m above purple, above the correlatable reflector termed blue (e.g. 'b' in Fig. 7). This erosional phase includes a broad paleo-valley, 13 km wide, with levee crests 35 m above the paleo-valley floor which is developed beneath the northernmost part of the modern Gabriel valley system (Fig. 7). Much smaller depositional irregularities, which may reflect gully cutting, are seen just above blue, north of the modern Kyle valley (a on Fig. 8). Both the broad paleo-valley and the smaller gullies are filled with a drape of stratified sediment; the next prominent valley cutting event in the region occurs approximately at the level of the red reflector, and these valleys are maintained to the present surface (coarse valley fill in these valleys is indicated by stipple in Fig. 7).

Gabriel valley system

The modern Gabriel valley system is a complex valley system about 10 km wide which extends downslope west of the Gabriel well-site and leads to a prominent depositional lobe on the floor of Flemish Pass (Fig. 6), previously termed the "Gabriel high" (Piper and Sparkes, 1986). Bathymetric profiles show that there are two gullies developed at the present seabed, one on the north side and one on the south side of the valley system, which are visible in air gun seismic profiles (Fig. 7). The northern gully is about 20 m deep, with a 5 m thick drape of stratified sediments over erosional valley walls and floor seen on DTS profiles (Fig. 9). The unconformable contact of the stratified drape with the eroded older sediments occurs a short distance below reflector alpha. The sediments immediately above the unconformity are less well stratified.

Airgun seismic profiles show that the southern gully is more deeply incised and appears to have a longer history than the northern gully. Valley fill facies occur subbottom to the depth of the red reflector (indicated by stipple in Fig. 7). The most recent erosional event is overlain by about 20 m of stratified sediment (Fig. 10), which interfingers with the proximal margin of the depositional mound at the mouth of Gabriel Valley (Fig. 11).

Gabriel depositional lobe

The surficial depositional mound at the mouth of the Gabriel Valley system is clearly fed by the northern gully. In a downslope profile through the valley and depositional mound, there is a noticeable convexity at water depths around 800 m. (Fig. 12). There is a second convex area between 900 and 970 m, at the proximal end of the depositional mound, where it is still constrained within valley walls. The edge of the depositional mound at the floor of the Pass is marked by transition from stratified lower slope to acoustically amorphous mound sediments (Fig. 13) and an abrupt change in elevation of the sea floor of about 10 m (Piper and Sparkes, 1986, Fig. 3). There is in places a clear interfingering of amorphous and stratified facies at the edge of the mound, with the amorphous facies thickening in a tongue-like manner towards the mound (Piper and Sparkes, 1986, Fig. 3). Elsewhere, there appears to be an abrupt contact between amorphous and stratified sediments (Fig. 13), except that the strongest reflectors in the stratified sequence can be traced into the amorphous section without change in thickness. The change in acoustic character might result from shallow gas, or an abrupt change in sediment facies. There are no clear seismic pull downs or phase inversions which might be expected from a thick gassy section. However, cores contain significant amounts of gas, and coring does not indicate any abrupt changes in sediment type, although sand is more abundant in the amorphous areas (see below).

The surface of the mound is characterised by stratified sediments extending down to below the alpha horizon. These overlie acoustically amorphous sediments. At the edges of the mound, diapir-like features (Piper and Sparkes, 1986, Figs. 3 & 5) are common. These are typically about 100 m wide and result in local elevations of 1 to 2 m at the sea floor. The core of the diapir-like feature is acoustically amorphous and passes laterally into stratified sediments.

The thickness of sediment above the reflector alpha on the depositional mound is only about 2 to 4 msecs (Fig. 15), substantially less than the 6 to 8 msec on the flanks of the Gabriel Valley and 8 to 12 msec found between the Gabriel and Kyle valleys.

Immediately north of the Gabriel Valley system is a thick sequence of stratified sediments. This is the only place in the study area where sediments a short distance below reflector alpha lack acoustically amorphous facies (Fig. 16). Isopachs of thickness above the deepest correlatable reflector (beta, Fig. 17) shows that the thickest sediments occur in a north-south band at about 1030 m water depth (Fig. 18). A short distance below reflector beta there is an unconformity over gently undulating sediments (Fig. 17).

Airgun seismic profiles show that below the surface depositional lobe there are other thick sequences of similar acoustically transparent sediment, which thin out westwards and northwards (Fig. 19). The red horizon occurs about 300 msecs subbottom in the centre of the Pass, compared with only 180 msecs further south in the Pass at 47 00'N (Fig. 20).

The seismic data is most clear at the northern edge of the depositional lobe (Fig. 17) where the amorphous sediments pass northwards into a stratified levee or base of slope sequence. This section shows three or possibly four cyclic sequences developed above the red reflector. The top of each cycle consists of a continuous packet of reflectors extending from the levee-like feature at the base of slope across the depositional lobe. In the youngest cycle (cycle 1), this corresponds to the stratified sediments at the seabed (1a in Fig. 19). This youngest sequence is underlain, disconformably locally on the levee crest, by stratified sediments on the levee flank and crest that pass laterally into amorphous sediments on the lobe (1b in Fig. 19). Locally, reflectors on the lower levee flank onlap against the upper levee flank. Sequence 1b rests disconformably on irregularly stratified reflectors with local development of acoustically amorphous facies on the lower levee flank, and more continuous amorphous facies beneath the lobe (1c in Fig. 19). This basal unit, 1c, is most clearly seen in the uppermost cycle, 1, but is difficult to distinguish from facies b in the deeper cycles. It in turn rests on the continuous stratified sequence at the top of the next cycle (2a in Fig. 19).

Continental slope south of the Gabriel Valley system

The slope off the Grand Banks south of the Gabriel Valley system is relatively smooth, but is cut by another major valley, Kyle Valley, at about 47 02' N. A few smaller valleys occur up to 10 km both north and south of Kyle Valley (Fig. 6). Kyle valley is deeply incised: in water depths of 840 m, it is incised to a depth of 75 m down to almost the "red" reflector (Fig. 8). Airgun profiles show no buried older valleys immediately beneath the modern valley, and unlike the Gabriel Valley, there is no surficial drape of sediments within the valley. The steep northern wall of Kyle Valley can be readily traced on SeaMARC imagery to the floor of Flemish Pass. Off the end of the valley, there is a local thickening of sediment above reflector alpha. This is the only place in the southern part of the study area where acoustically amorphous sediments are found above reflector alpha (Fig. 15). Acoustically amorphous sediments are also well developed below reflector alpha, with the local development of diapir like features similar to those described from the Gabriel depositional mound.

The valley 3 km north of Kyle Valley is the second largest valley in this southern area (Fig. 6). In water depths of 900 m, it is incised to a depth of 45 m, but dies out downslope. It contains a 5 m thick drape of stratified sediments that rest unconformably on older strata at a horizon a short distance below reflector alpha (Fig. 10). Unlike Kyle Valley, there are no significant sediment deposits at the mouth of this valley.

Still further to the north of the Kyle valley, there are several sub-surface valleys which have been masked by stratified fill and are visible at the seabed only as shallow depressions (Fig. 8).

LITHOLOGIC CONTROL

Principal Facies Recognized

The location of cores collected are shown in Figure 1 and their relationship to reflector alpha and age control is summarised in Figure 21.

Four principal sedimentary facies are distinguished:

a) grey mud with ice rafted detritus, reflecting glacial supply principally from the Grand Banks margin.

b) grey muds, silts and graded sand beds up to several decimetres thick, reflecting turbidite supply from the Grand Banks margin.

c) rapidly varying carbonate rich brownish sediments including gravelly mud beds, probably reflecting predominant supply by ice rafting from the north and reworking by bottom currents respectively.

d) greenish shelly sand beds, probably derived from Flemish Cap.

A full account of the cores and their physical properties and biostratigraphy will be presented in a subsequent report.

Significance of the acoustically amorphous facies

Preliminary interpretation of downcore grain size and geotechnical measurements in core 85-044-003 shows that the acoustically amorphous facies in the seismic reflection profiles (Piper and Sparkes, 1986) do not correspond to thick sands or debris flow deposits, but do correlate well with zones of more silty or sandy mud. Evidence of gas release was seen in cores 87-13 and 87-16 when the cores were split on board ship.

Chronology

Two finite AMS radiocarbon dates have been obtained. A shell at 737 cm in core 87-13 yielded an age of 19.2 ka (Table 2). A second shell at 645 cm in core 87-15 yielded an age of 23.6 ka. This sample is about 1 m below the alpha horizon. An infinite radiocarbon date of >33 ka was obtained from a scaphopod at 7.6 m in core 85044-003. This corresponds to a horizon about 4 m below the alpha reflector. Alam (1979) suggested on sedimentological and biostratigraphic grounds that isotopic stage 2 corresponds to a depth of about 2 m in core 3-1 (Figure 21) and that the bottom of the core at 6.2 m fell within the Wisconsinan, probably stage 3. Reflector alpha occurs at a depth of 1.5 to 2 m in core 3-1. In none of the cores collected is there any sedimentological evidence that isotopic stage 5e (interglacial) sediments have been reached.

SYNTHESIS

Origin of the amorphous zones

Several lines of evidence suggest that the acoustically amorphous zones results from shallow gas dispersed within more permeable sediments.

- gas was directly observed in several of the cores
- sandier zones within the cores correspond to more amorphous zones within the seismic reflection profiles.
- major reflectors can be seen to continue within some of the

amorphous zones, even where there is a very abrupt margin to the zone (Fig. 13)

The new data shows that the breaks are downslope from slope valleys, and are thus probably the result of valley erosion followed by deposition of sandier sediment within the valley. We have re-examined the abrupt breaks in seismic continuity shown in Figure 4 of Piper and Sparkes (1986), which were interpreted as resulting from in situ sediment failure. We do not consider this as the only, or most likely hypothesis. Since the evidence presented suggests that possibly small variations in gas content may produce the amorphous acoustic character then the abrupt breaks may result from localized gas seepage.

Origin of the diapir-like features

The new work has provided few new insights into the origin of the diapir-like features, initially described as mounds (Pereira et al, 1985). Piper and Sparkes (1986) presented seismic evidence that the features were diapiric. Many of the sediments in western Flemish Pass are very silty and are readily mobilised by coring operations. In an alternating sequence of muds and silts, the resistance to diapiric flow may be low. The abundance of shallow gas would also promote diapirism. It is possible that gas release might be augmented by the formation of gas hydrates and subsequent release due to pressure changes accompanying changes in sea level.

The new seismic data does show that shallow diapirism is particularly abundant at the margin of the Gabriel lobe. In this setting, loading by rapidly deposited sand may in part be responsible for the diapiric activity.

Paleoseismicity

A previous study of the area (Pereira et al., 1985), based on SeaMARC I sidescan data, led to the suggestion that a mid-Wisconsinan seismic event was responsible for slumping and the deposition of a debris flow. The new data demonstrates that features previously identified as slump scars are erosional valley walls; that the possible debris flow may well be a turbidite deposit related to the valleys; and that features interpreted as in situ failure probably have a different origin.

No clear evidence for paleo-seismic events has been found anywhere on the continental slope from the new seismic data. Except in the Huntec DTS profiles, it would be very difficult to distinguish the effects of slumping from those of rapid slope erosion by gully and valley cutting activities.

Chronology of the surficial valley cutting events

The major valleys are the most prominent features on the slope off the Grand Banks and the isopach maps suggest that they are the main transport route for sediment to the floor of the Pass. The valleys do not appear to breach the shelf break - they have not been recognised in water depths shoaler than about 600 m (although N-S bathymetric profiles are lacking) and appear to disappear upslope into till or other acoustically amorphous sediments. Thus they resemble slope valleys elsewhere on the Eastern Canadian continental margin which head in water depths of several hundred metres near the downslope limit of glacial till. Piper (in press) has suggested that such valleys are related to subglacial meltwater discharge.

A major erosional event, marked in many areas by an unconformity, occurs at about twice the depth of horizon alpha, and somewhat below the horizon corresponding to the >33ka date. It is tentatively suggested that this erosional event corresponds to the maximum Wisconsinan glacial advance in the region in isotopic stage 4. The main amorphous sediment lobe in the Gabriel Valley system also appears at around twice the depth of horizon alpha, and may be of a similar age.

Acoustically amorphous sediments are of very limited extent above the alpha reflector, occurring only within the lower part of Kyle Valley, where the sequence was sampled by core 27. The radiocarbon dating indicates that horizon alpha occurs within isotopic stage 2, and is a little younger than 23 ka. This implies that there was little delivery of coarse sediment in the late Wisconsinan.

Cyclic deposition on the northern margin of the Gabriel Lobe

The prominent cyclic deposition observed at the northern edge of the Gabriel lobe can be interpreted in the light of the glacial and sealevel controls inferred for the near surface sediments that have been cored. The origin of the levee-like feature north of the lobe is unclear. Deep in the section, between the "blue" and "red" reflectors, the feature appears to have grown in a levee-like manner. Above the red reflector, its relief relative to the lobe has gradually diminished as a result of onlap. It is unclear whether this feature is a true levee, or if drift sedimentation has played a role in its development.

The upper unit of each cycle - the stratified drape - correponds to the muds recovered in most of the cores. It consists principally of glacially derived hemipelagic sedimentation, perhaps augmented by southward current flow. It is, in essence, a continuation of the type of glacially augmented drift sedimentation seen in Sackville Spur. Some of the sediment may be of turbidite origin, but not sufficient to lead to visible ponding in lows.

The middle unit of each cycle - amorphous sediments in the lobe, stratified sediments locally onlapping the levee flanks - is interpreted as having a higher turbidite component which generally drapes but locally onlaps the levee. The transition from presumed coarser sediments on the lobe to finer stratified sediments on the levee flanks is masked by gas.

The lower unit of each cycle reflects a greater degree of channelisation of turbidity currents. The presence of erosion on both the levee and the flat area adjacent to the lobe suggests that these channels may be related to sediment supply on the upper slope, rather than to distributary channels from the lobe.

The extensive coarse sediments in the lowest unit of each cycle result from increased sediment supply due to either a low stand of sea level, or discharge from many points along an ice margin on the upper slope. The middle unit represents concentration of coarse sediment within Gabriel Valley. The upper unit represents a lack of coarse sediment supply, probably due to a submerged shelf break, but abundant supply of fine suspended sediment, presumably related to glacial supply either from the Grand Banks or from the north (via the Labrador Current).

A general model for sedimentation above the red reflector

Piper and Sparkes (1986) identified red as the deepest reflector to pass upslope into acoustically incoherent deposits interpreted as till or coarse ice-contact sediments. Underlying strata continue upslope beneath the incoherent till succession. Downslope from the inferred till, the sequence above red is well stratified and thickens towards the floor of Flemish Pass. The slope is cut by valleys, which appear at several different stratigraphic intervals above red. Some have been filled, whereas others persist to the present seabed. These valleys are interpreted to have been supplied by subglacial meltwater streams, and to have transported coarse sediment in turbidity currents to the floor of the Pass. Furthermore, both in the valleys and on the depositional lobes, thick muds of glacial origin were deposited after ice recession removed the immediate source of coarser sediment.

Depositional patterns below the red reflector

Below the red reflector, our limited seismic reflection profiles show that subparallel reflectors can be traced up to the outer shelf, suggesting either hemipelagic or fluvial deposition. Our data provide no new information on the disconformity and onset of sandy deposition in the Gabriel C-60 well at the brown reflector: this event might correspond to the Late Miocene lowering of sea level.

This event is followed by deposition of a thick sequence of parallel stratified reflectors interpreted as hemipelagic deposits. This sequence is cut by a broad shallow paleo-valley near the the site of the present narrower Gabriel Valley. This broad valley cutting event might correlate either with the mid-Pliocene event that cut similar broad valleys on the central Scotian Slope (Piper et al., 1987), or with Early Pleistocene low stands of sea level and gully cutting also seen on the Scotian Slope. There was a minor gully-cutting event on the Grand Banks slope shortly before this broad paleo-valley was cut.

IMPLICATIONS FOR HYDROCARBON DEVELOPMENT

1. This report presents a comprehensive depositional model for Flemish Pass and its western flank, with a generalised chronology. This provides a framework within which site-specific geologic and geotechnical interpretations can be made.

2. By analogy with slope channels on the Scotian Margin, unstable hole conditions might be encountered on valley floors on the

western flank of Flemish Pass.

3. Silty sediments, which appear rather susceptible to liquefaction, are widespread on the floor of Flemish Pass.

4. Shallow gas is widespread in cores on the floor of Flemish Pass.

5. Diapir-like structures are located in particular at the edge of lobe-like deposits of turbidite sands at the end of slope valleys. They may be related to the shallow gas.

CONCLUSIONS

1. Use of the Long Coring Facility increased penetration of the section by about 40%. This increased penetration allowed sampling of important deep seismic facies, such as clear developments of transparent acoustic facies; and allowed sampling of deep datable horizons.

2. The floor of Flemish Pass consists of turbidites that were derived from the continental margin off the Grand Banks. These turbidites onlap slope strata on either side of the Pass. The sediments along the edges of the Pass contain shallow gas, perhaps related to escape of gas along faults bounding the Flemish Pass graben.

3. A few deep valleys cut the lower continental slope off the Grand Banks. These valleys terminate upslope around 600 m: the continental slope above this depth is underlain by glacial till. The valleys have been important conduits of sediment to the floor of Flemish Pass. They terminate in prominent sandy lobe-like deposits.

4. Transparent acoustic facies may be related to sands, silts, sandy muds and silty muds. Cores from these sediments contain gas, which is probably either dissolved in pore water, or occurs as gas hydrates in situ. The diapir-like features, previously described, are most common around the margins of sandy depositional lobes at the end of slope valleys. They are probably related to excess pore pressures associated with rapid deposition of sand on the lobes or with changes in gas hydrate abundance

with changes in sea level.

5. The deeper section on the slope off the Grand Banks shows a sequence of geologic events similar to those recognised on the central Scotian Slope. The first supply of coarse clastic sediments to the floor of Flemish Pass may be related to the late Miocene sea level lowstand, and a major valley cutting event on the slope may correspond to a mid-Pliocene or Early Pleistocene sea level lowstand. Between these two events, predominantly hemipelagic sediments accumulated on the continental slope. The possible Plio-Pleistocene valley is filled by a stratified drape of sediment, but widespread gullying and upper slope till deposition occurs above the overlying red reflector.

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Table 1. Definition of key seismic reflectors

reflector	typical depth (ms)	Type of record
alpha*	10	Huntec DTS profiles, e.g. Fig 11
unconformity 1**	15	Huntec DTS profiles, e.g. Fig. 10
unconformity 2**	25	Huntec DTS profiles, e.g. Fig. 10
[beta**	30	Huntec DTS profiles, e.g. Fig 17]
red*	120	Air gun profiles, e.g. Fig. 7
blue	300	Air gun profiles, e.g. Fig. 7
purple*	400	Air gun profiles, e.g. Fig. 7
brown*	600	Air gun profiles

* defined by Piper and Sparkes (1986)

** local extent only

Table 2. Radiocarbon dates on mollusc shells

Core and sample depth	Age	Lab number
85-044-003, 760 cm	>33,000	Beta 16483
87-008-013, 737 cm	19,200 +- 450	Beta 22232
87-008-015, 645 cm	23,600 +- 380	Beta 22233

FIGURE CAPTIONS

Figure 1. Map showing general bathymetry of Flemish Pass, location of wells, cores and seismic reflection profiles, and location of detailed study area. Bathymetry based on Monahan and Macnab (1974), modified by our new bathymetric data and SeaMARC imagery.

Figure 2. Map showing location of seismic reflection profiles figured in this report.

Figure 3. Schematic stratigraphic cross-section from the Grand Banks to Flemish Pass through the Gabriel C-60 well (from GSI profile NF-79-114).

Figure 4. Air gun seismic profile of the eastern margin of Flemish Pass showing onlap of Quaternary turbidites on the floor of the pass onto (?)Miocene-Pliocene strata on the flanks of Flemish Cap; shallow faulting (f) along this edge of the Pass; and the widespread occurence of acoustic masking (m) suggesting shallow gas.

Figure 5. Huntec DTS profile across the base of slope. This shows a lack of clear reflections below a few msec sub-bottom, in contrast to most areas on the floor of Flemish Pass. This may be due to the presence of shallow gas.

Figure 6. Map showing principal surface and selected sub-surface morphological features in the detailed study area. See Figure 1 for data control for this compilation.

Figure 7. Air gun seismic reflection profile across the Gabriel Valley system, showing the two surface valleys of the Gabriel Valley system and the deep broad valley just above the blue reflector. 'a' and 'b' are erosional events discussed in text. Stipple indicates coarse valley fill deposits within the northern and southern gullies of the Gabriel Valley system.

Figure 8. Air gun profile showing Kyle Valley, with valley wall erosion almost down to the red reflector. 'a' is area of reflector irregularity just above the blue reflector.

Figure 9. Huntec DTS system profile showing unconformity (u) (probably unconformity 1) on valley walls of Gabriel Valley system a short distance below the alpha reflector.

Figure 10. Huntec DTS profile across small valley just north of Kyle Valley showing unconformities 1 and 2 a short distance below the alpha reflector.

Figure 11. Huntec DTS system profile showing draping of thick stratified sequence at southern margin of the Gabriel Valley system. Arrows indicate unconformity (probably unconformity 2).

Figure 12. Line drawing of longitudinal and cross profile of the sediment mound at the mouth of Gabriel Valley, showing the convex profile of the upper part of the mound and the abrupt change in relief at the margins of the distal part of the mound.

Figure 13. Huntec DTS system profile showing depositional mound in centre of Gabriel Valley system

Figure 14. Air gun profile from the northern edge of the Gabriel depositional lobe. Note how some prominent reflectors in the stratified sequence to the north can be traced into the acoustically amorphous facies, suggesting that this acoustic character is in part due to shallow gas.

Figure 15. Map showing sub-bottom depth to the alpha reflector (in msecs) and the character of the sediments above alpha.

Figure 16. Map showing acoustic character of sediments about 10 msec below alpha reflector.

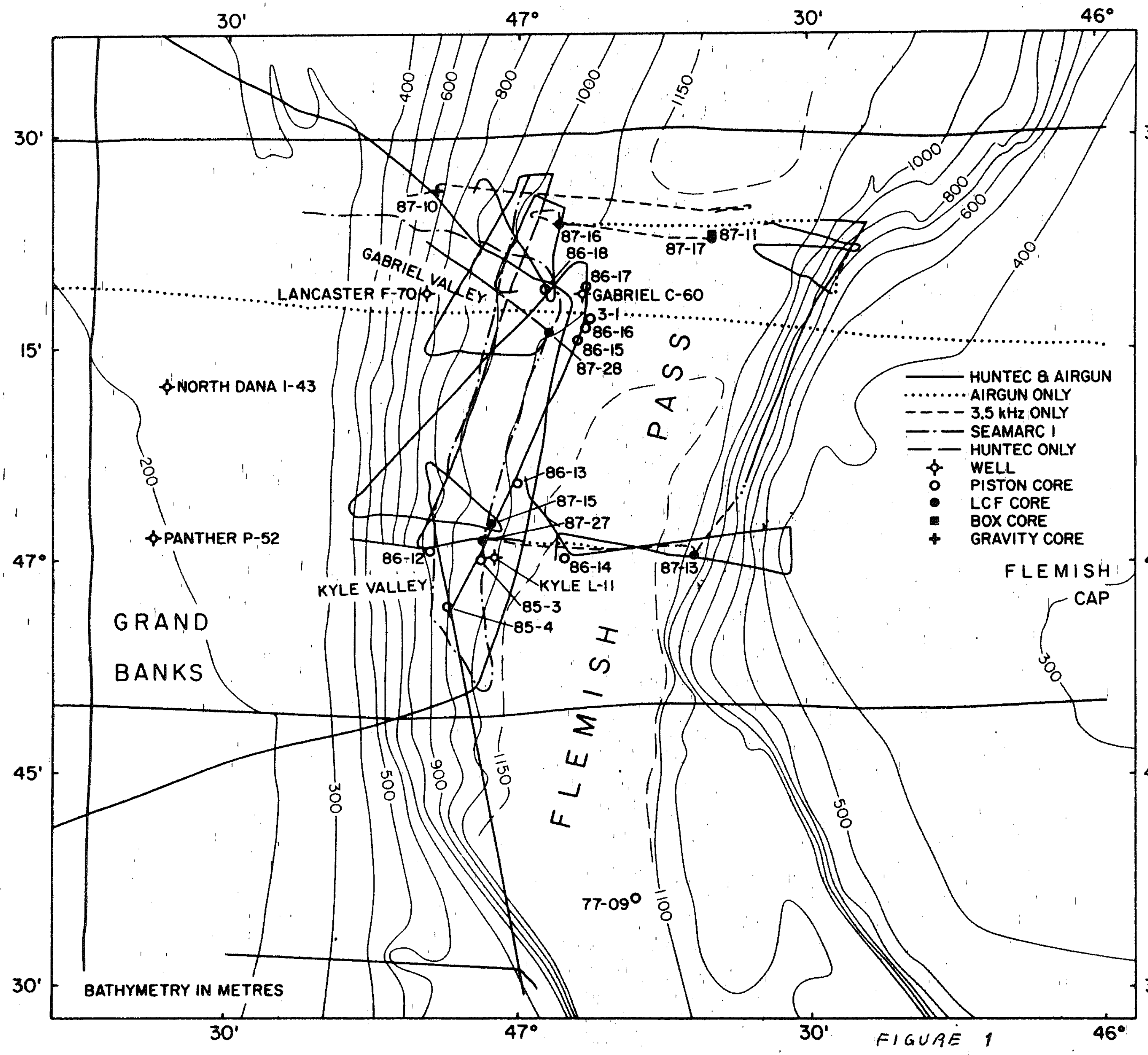
Figure 17. Huntec DTS profile north of the Gabriel Valley system showing correlatable reflectors alpha and blue, and the underlying unconformity.

Figure 18. Map shows sub-bottom depth to the beta reflector.

Figure 19. Air gun seismic profile across the northern edge of the Gabriel depositional lobe, showing stacked lobe deposits interbedded with stratified lower slope deposits. For full explanation, see text.

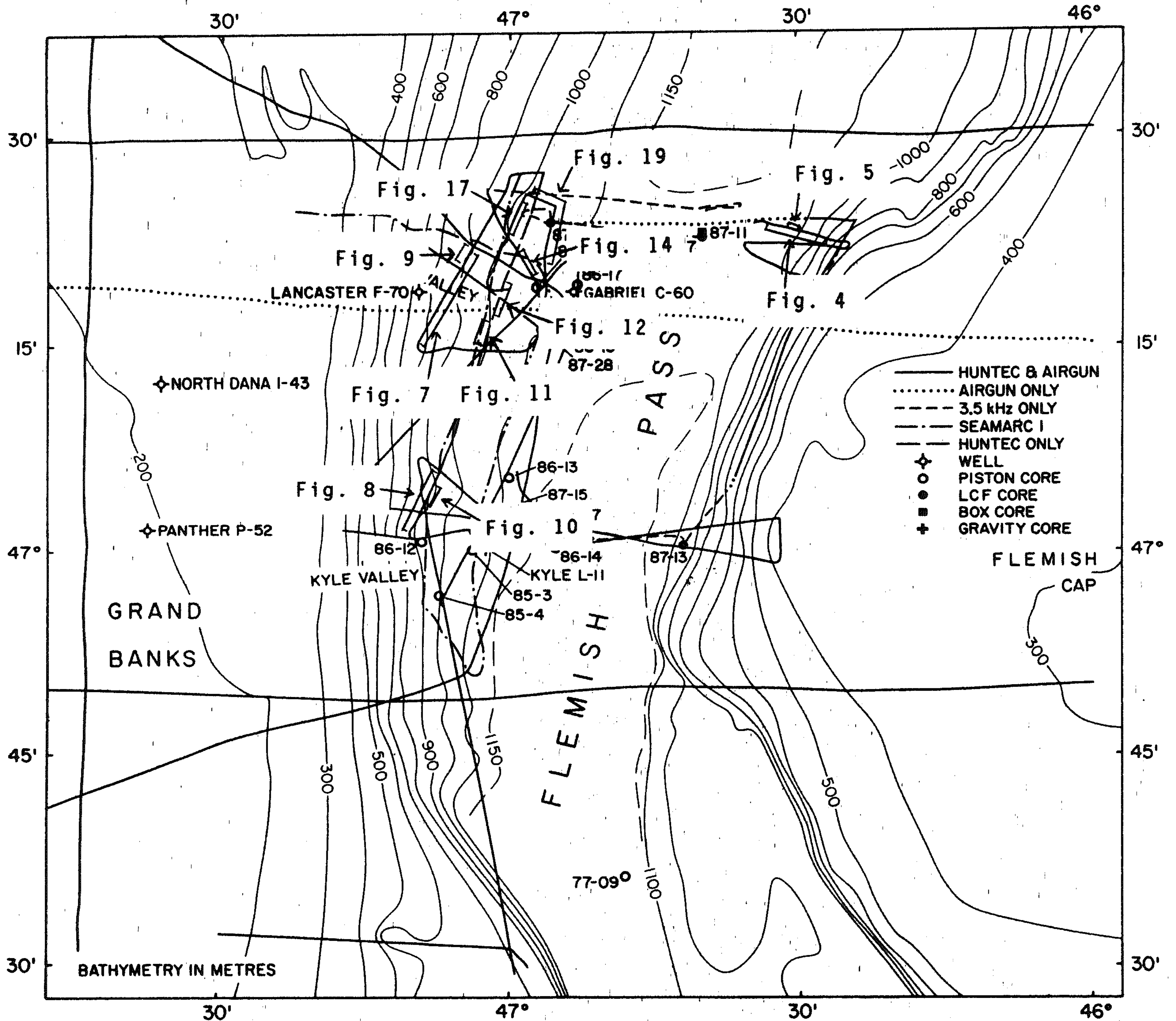
Figure 20. Map showing the sub-bottom depth to the red reflector.

Figure 21. Generalised down-core logs of all cores from the detailed study area, showing correlation of horizon alpha and location of radiocarbon dates.



30'
47°
30'
46°
30'
15'
47°
45'
30'
HUNTEC & AIRGUN
AIRGUN ONLY
3.5 kHz ONLY
SEAMARC I
HUNTEC ONLY
WELL
PISTON CORE
LCF CORE
BOX CORE
GRAVITY CORE
400
600
800
1000
1150
1100
900
500
300
200
87-10
87-16
86-18
86-17
GABRIEL C-60
3-1
86-16
86-15
87-28
87-11
87-17
GABRIEL VALLEY
LANCASTER F-70
NORTH DANA I-43
PANTHER P-52
86-13
87-15
87-27
86-12
86-14
87-13
KYLE VALLEY
KYLE L-11
85-3
85-4
77-09
GRAND BANKS
FLEMISH PASS
FLEMISH CAP
BATHYMETRY IN METRES

FIGURE 1



30'
47°
30'
46°
30'
15'
47°
45'
30'
400
600
800
1000
1150
1000
800
600
400
Fig. 19
Fig. 5
Fig. 17
Fig. 14
87-11
Fig. 9
Fig. 4
LANCASTER F-70
'ALLEY
86-17
GABRIEL C-60
Fig. 12
87-28
NORTH DANA I-43
Fig. 7
Fig. 11
PASS
HUNTEC & AIRGUN
AIRGUN ONLY
3.5 kHz ONLY
SEAMARC I
HUNTEC ONLY
WELL
PISTON CORE
LCF CORE
BOX CORE
GRAVITY CORE
200
86-13
87-15
Fig. 8
PANTHER P-52
Fig. 10
86-12
86-14
87-13
KYLE VALLEY
KYLE L-11
85-3
85-4
FLEMISH CAP
GRAND BANKS
FLEMISH
300
300
500
900
1150
1100
500
77-09
BATHYMETRY IN METRES

FIGURE 2

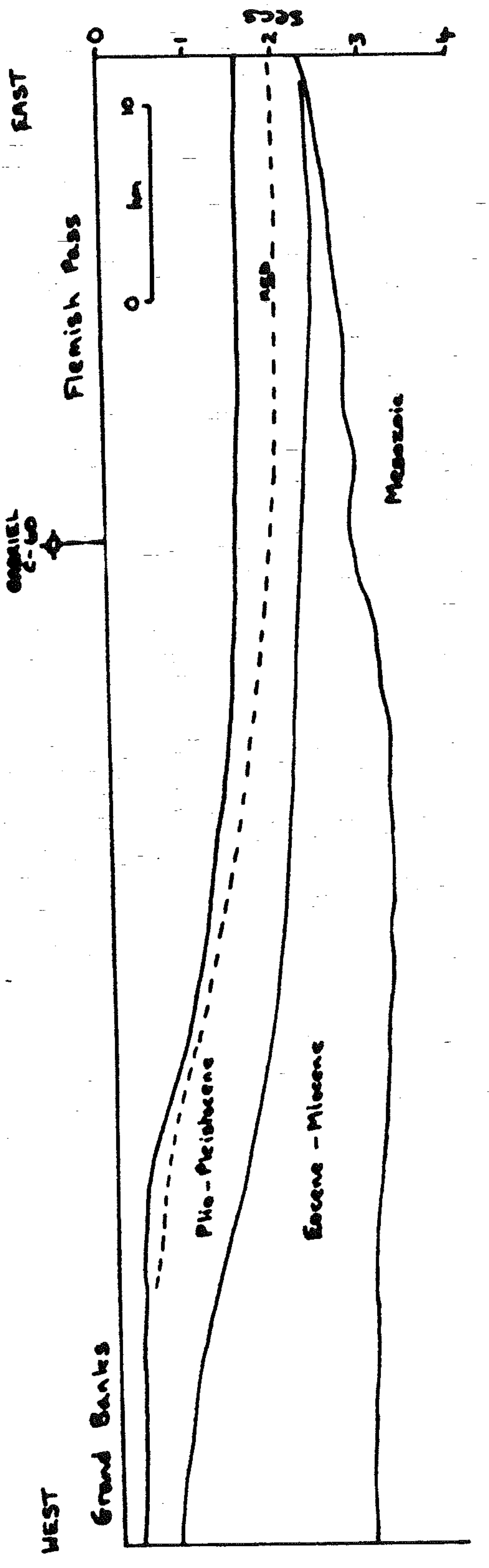

EAST
Flemish Pass
0 km 10
GABRIEL C-60
0
1
2
3
4
SECS
ASD
Mesozoic
Plio-Pleistocene
Eocene - Miocene
Grand Banks
WEST

FIGURE 3

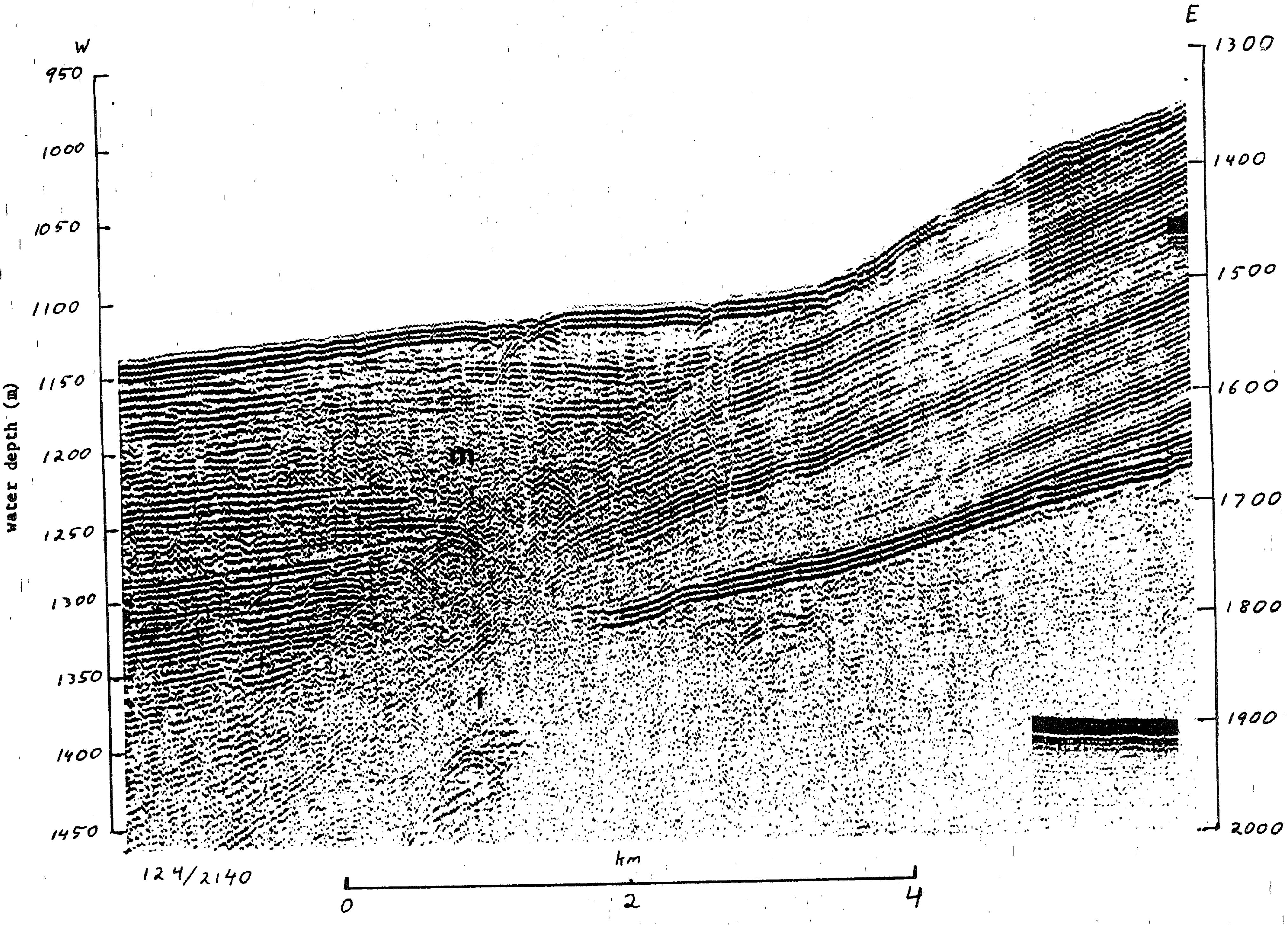
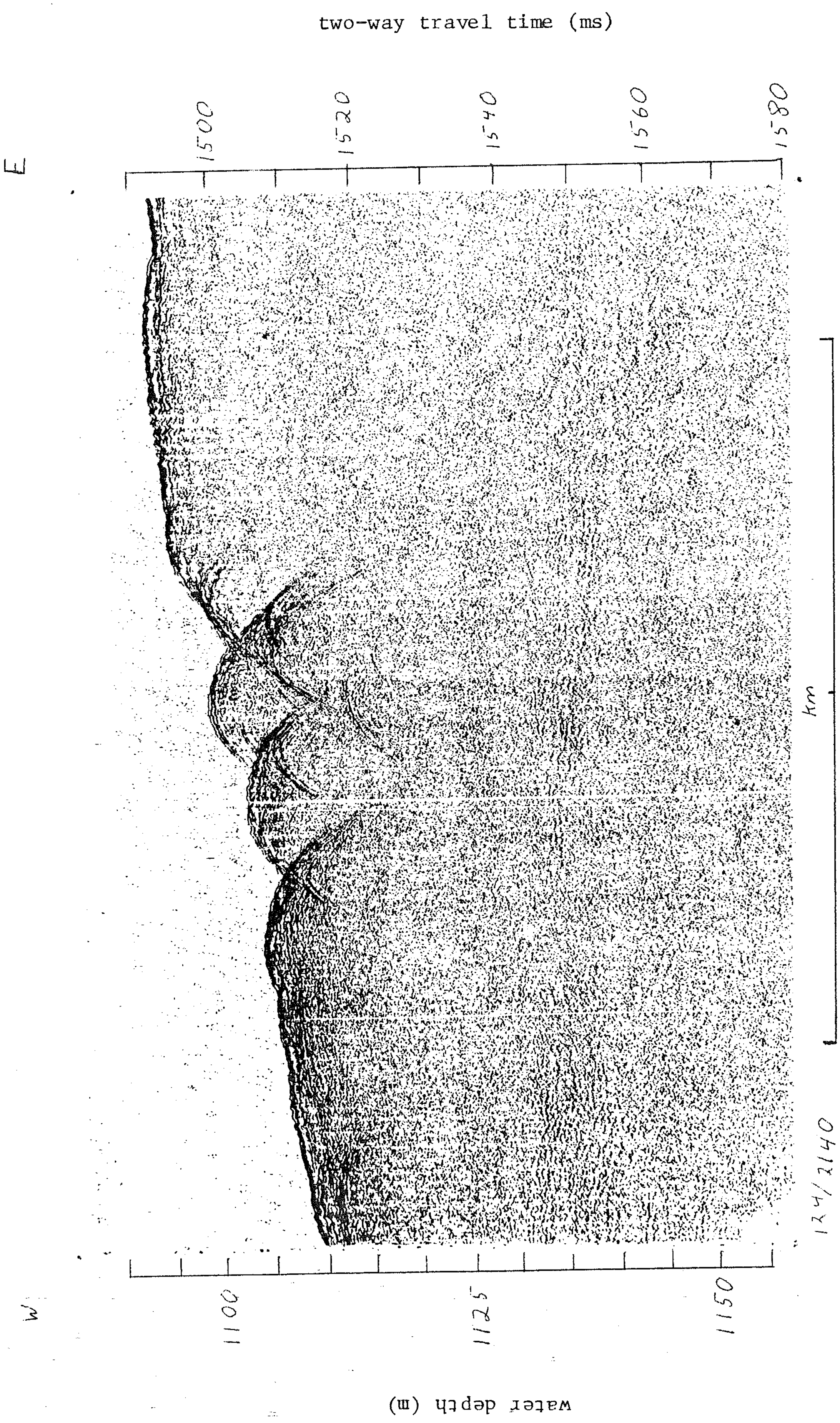
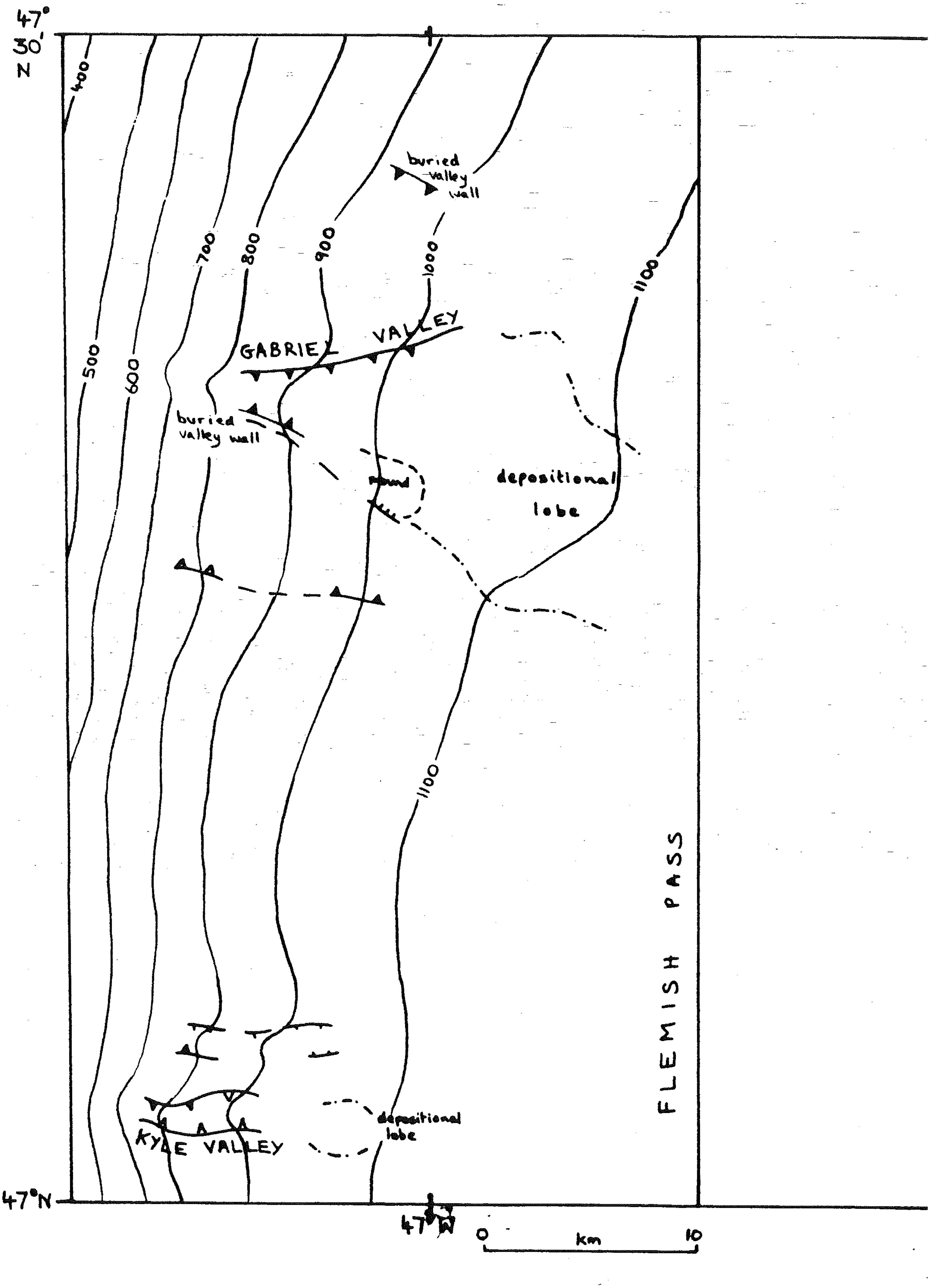

W
E
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
water depth (m)
1300
1400
1500
1600
1700
1800
1900
2000
m
f
124/2140
km
0
2
4

FIGURE 4


two-way travel time (ms)
1500
1520
1540
1560
1580
E
W
1100
1125
1150
water depth (m)
0
0.5
1.0
km
124/2140



47° 30' N
400
500
600
700
800
900
1000
buried valley wall
GABRIEL VALLEY
buried valley wall
mound
depositional lobe
1100
1100
FLEMISH PASS
depositional lobe
KYLE VALLEY
47°N
47°W
0
km
10

FIGURE 6

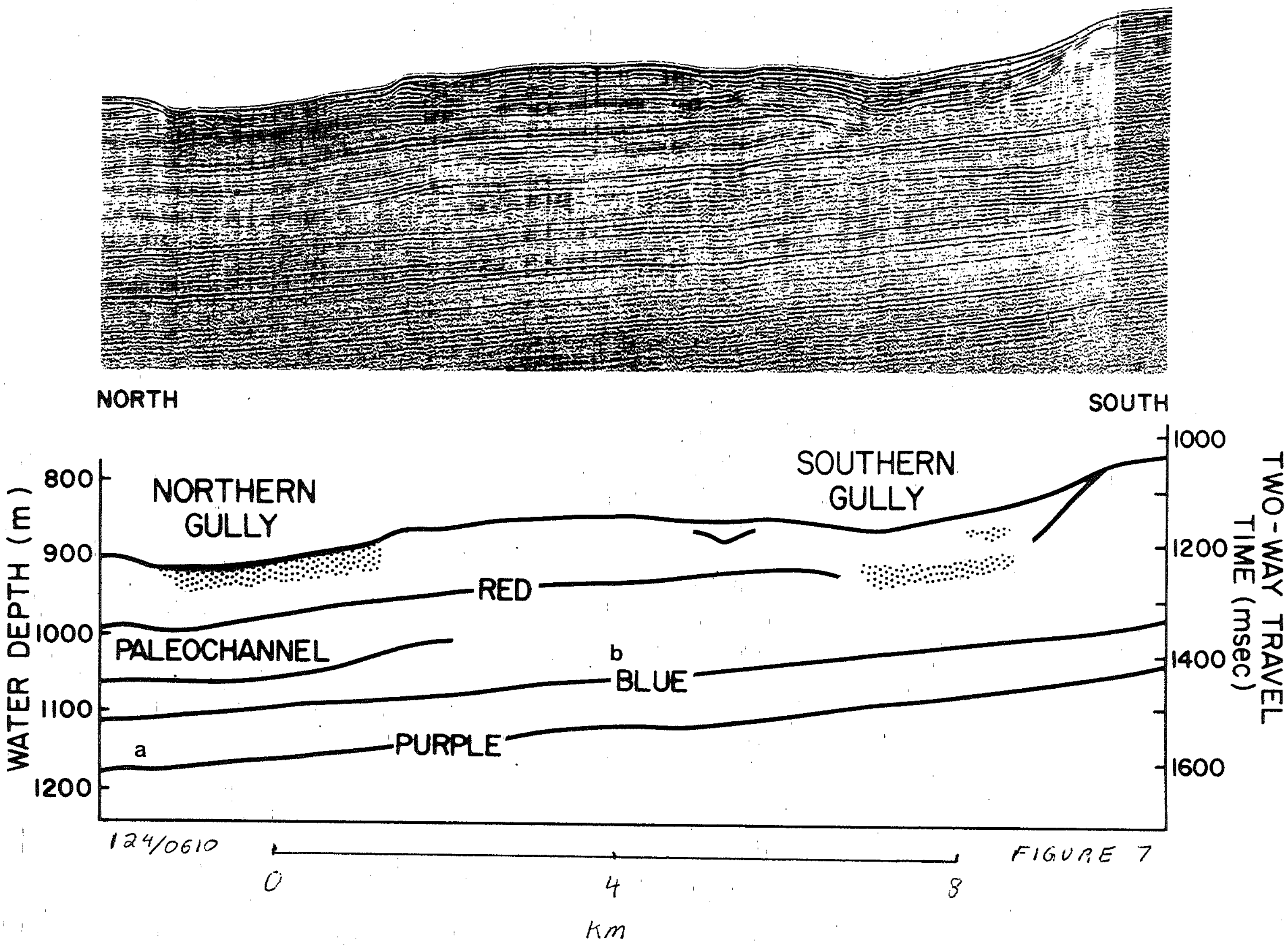

NORTH
SOUTH
NORTHERN GULLY
SOUTHERN GULLY
RED
PALEOCHANNEL
b
BLUE
a
PURPLE
WATER DEPTH (m)
800
900
1000
1100
1200
TWO-WAY TRAVEL TIME (msec)
1000
1200
1400
1600
124/0610
0
4
8
Km

FIGURE 7

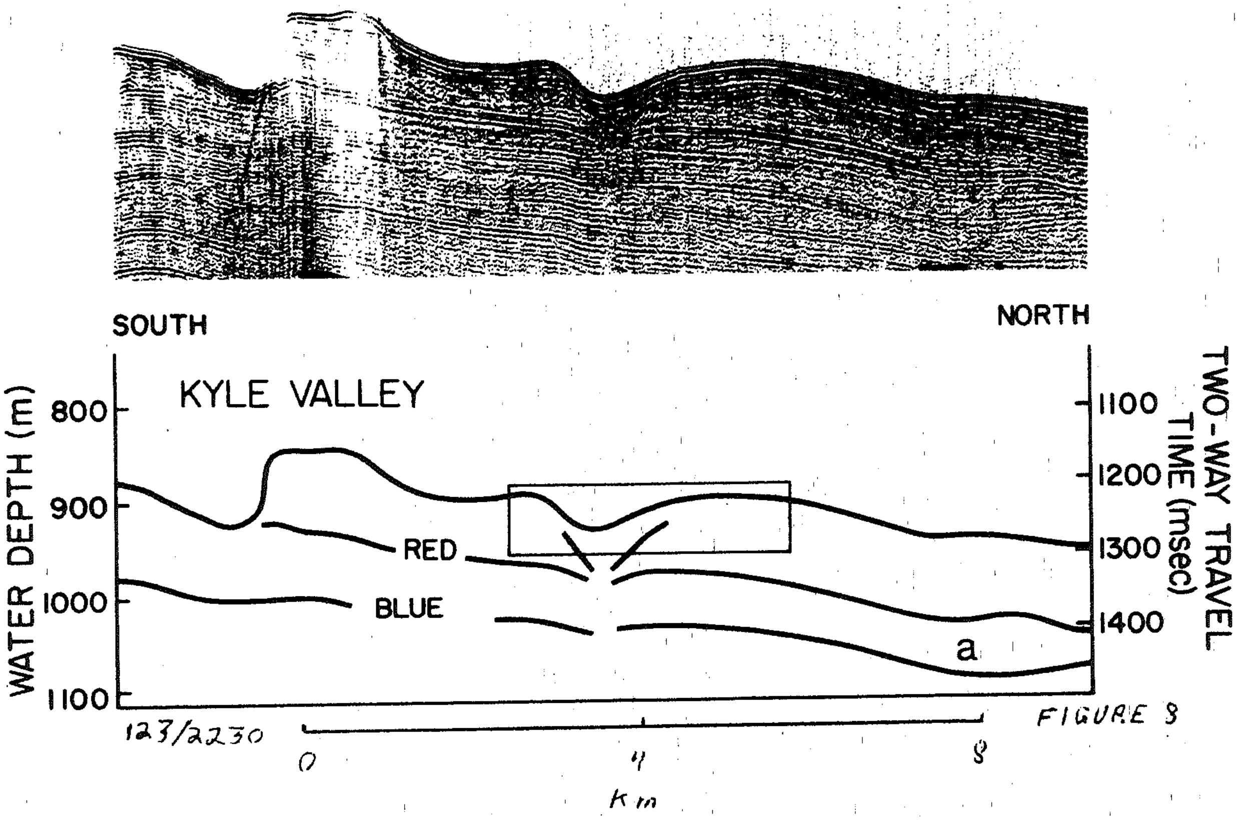

SOUTH
NORTH
KYLE VALLEY
WATER DEPTH (m)
800
900
1000
1100
TWO-WAY TRAVEL TIME (msec)
1100
1200
1300
1400
RED
BLUE
a
123/2230
0
4
8
Km

FIGURE 8

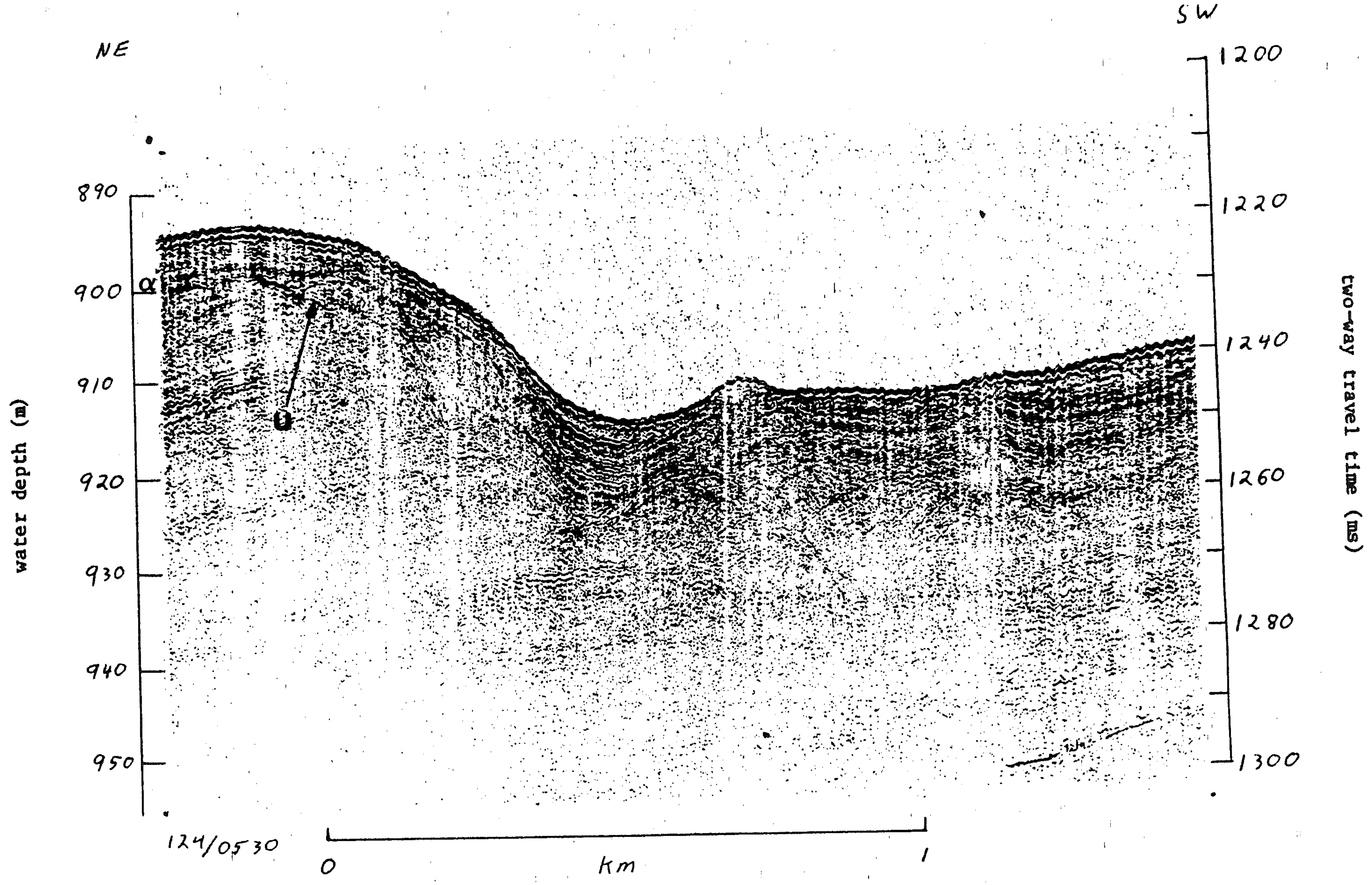

NE
SW
water depth (m)
890
900
910
920
930
940
950
two-way travel time (ms)
1200
1220
1240
1260
1280
1300
α
b
124/0530
0
km
1

Figure 9

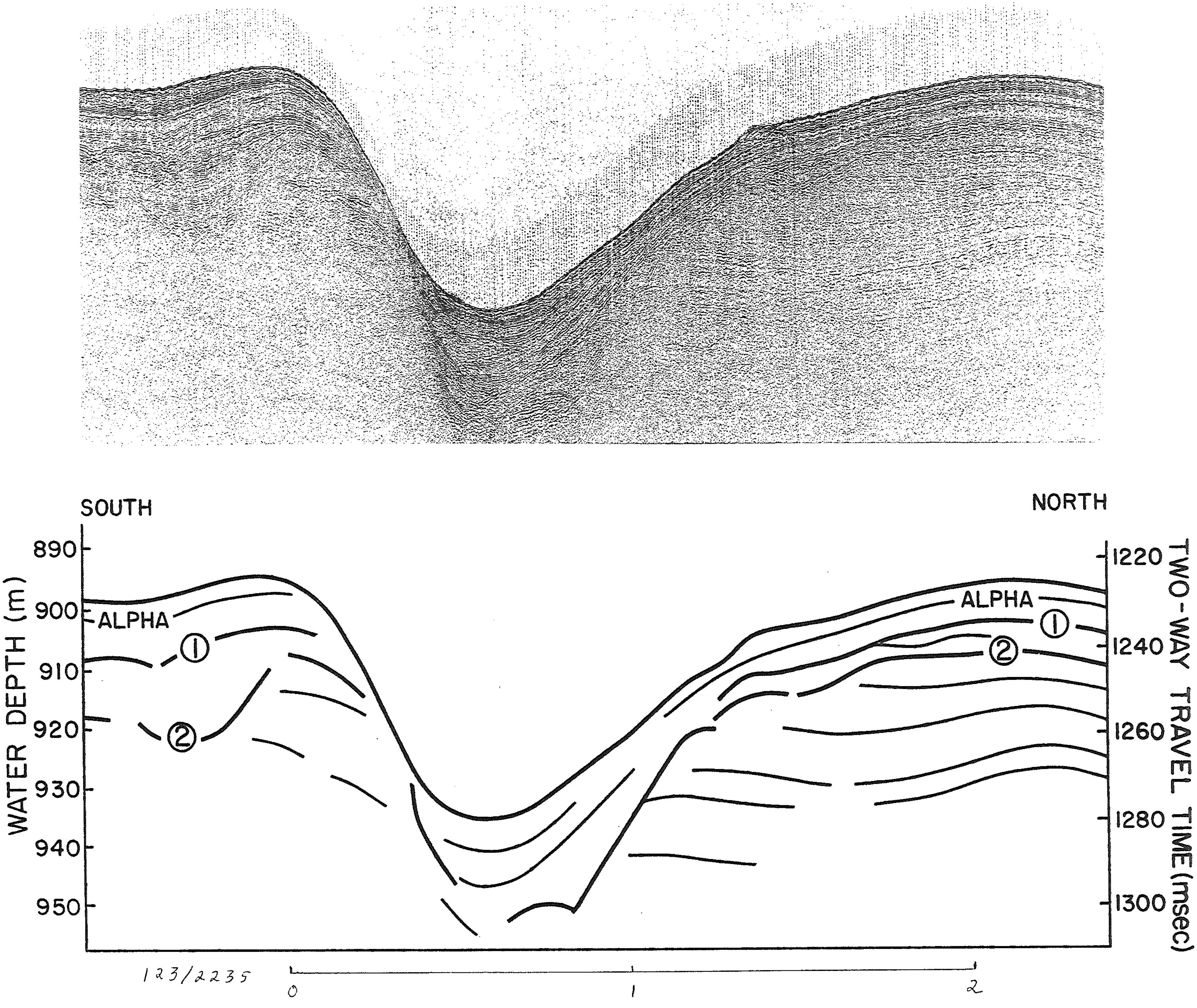

SOUTH
NORTH
WATER DEPTH (m)
890
900
910
920
930
940
950
TWO-WAY TRAVEL TIME (msec)
1220
1240
1260
1280
1300
ALPHA
①
②
ALPHA
①
②
123/2235
0
1
2
km

FIGURE 10

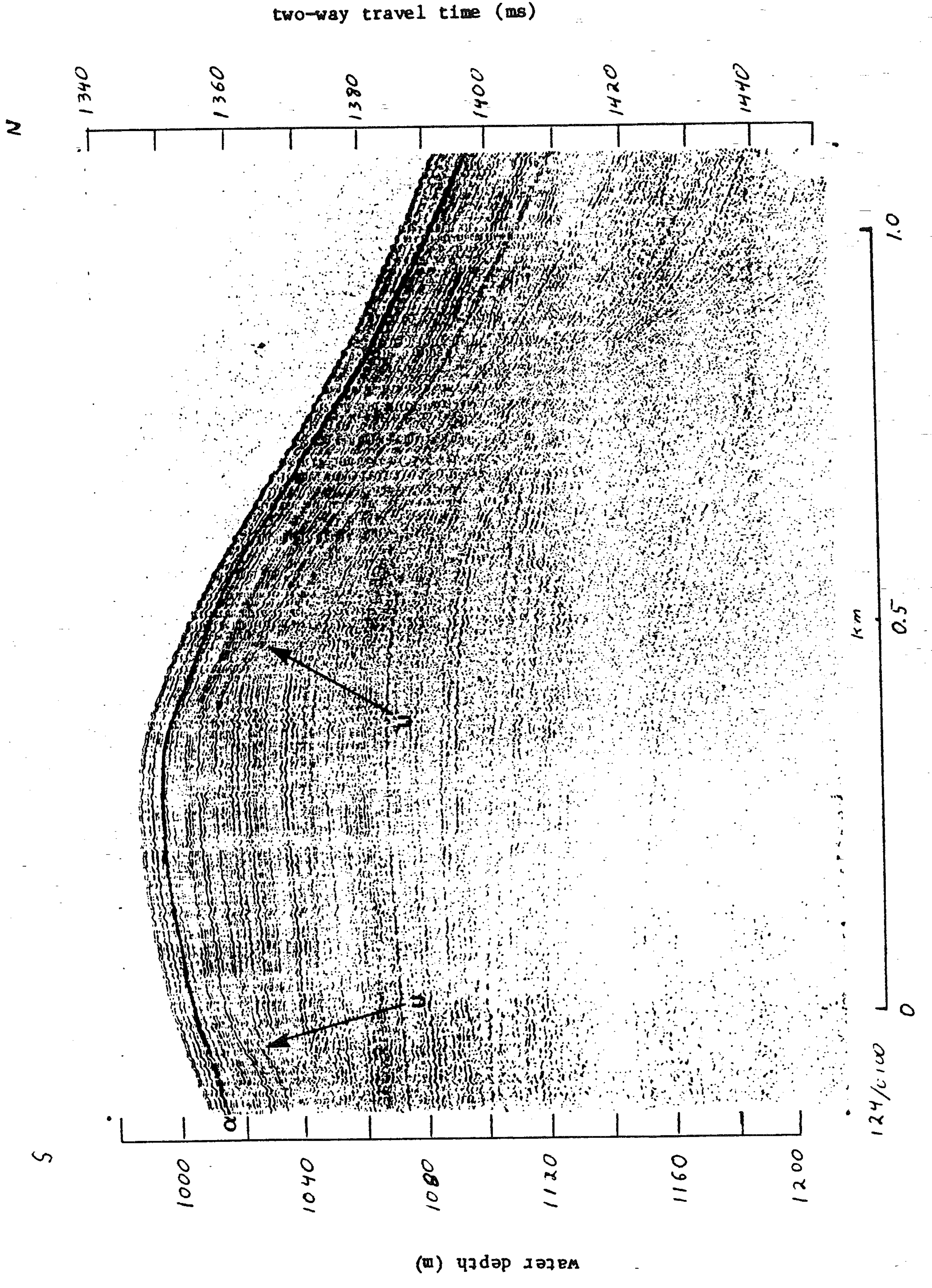

two-way travel time (ms)
1340
1360
1380
1400
1420
1440
N
S
1000
1040
1080
1120
1160
1200
water depth (m)
a
U
U
0
0.5
1.0
km
124/C100

FIGURE 11

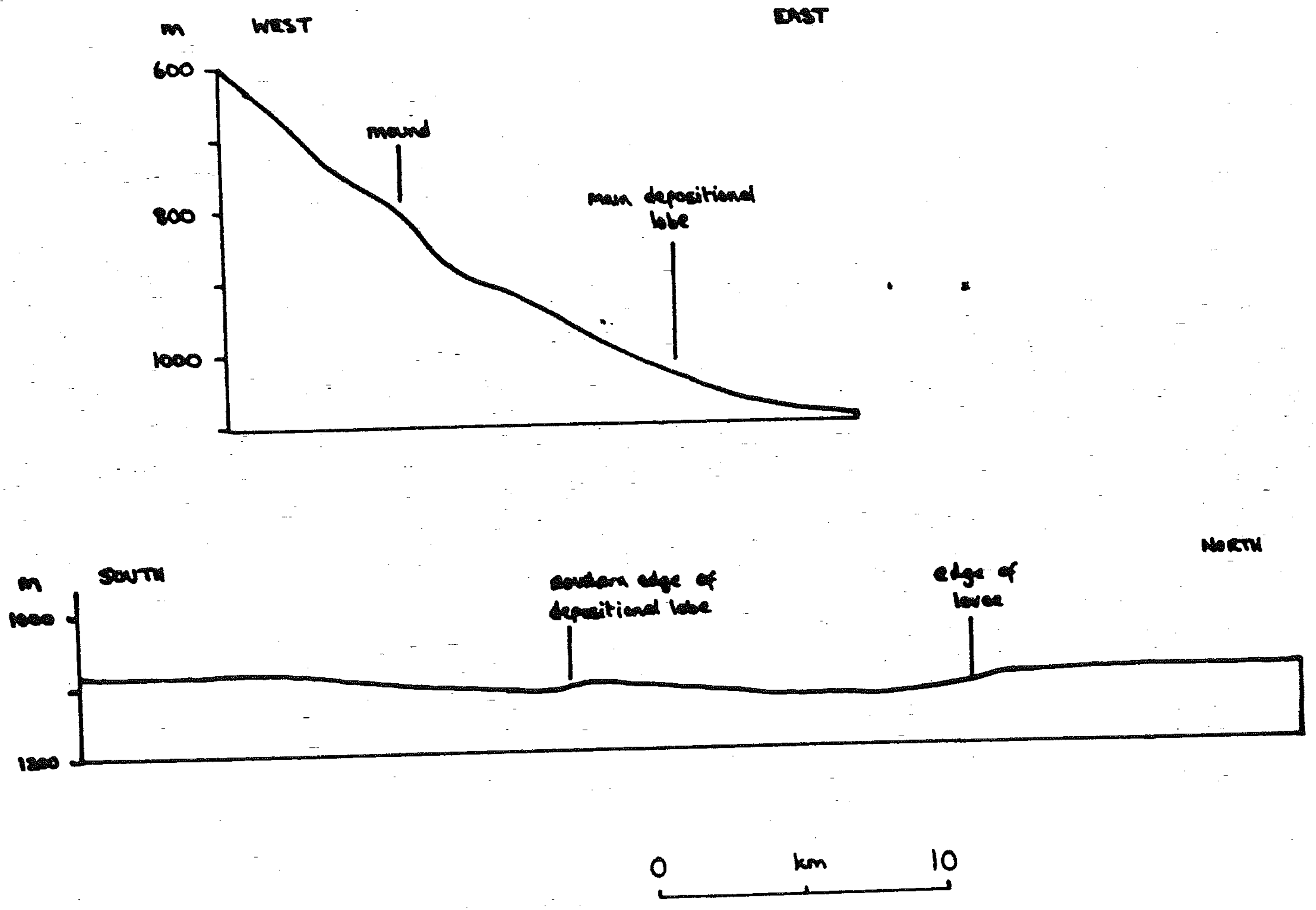

m
WEST
EAST
600
800
1000
mound
main depositional lobe
m
SOUTH
NORTH
1000
1200
southern edge of depositional lobe
edge of levee
0
km
10

FIGURE 12

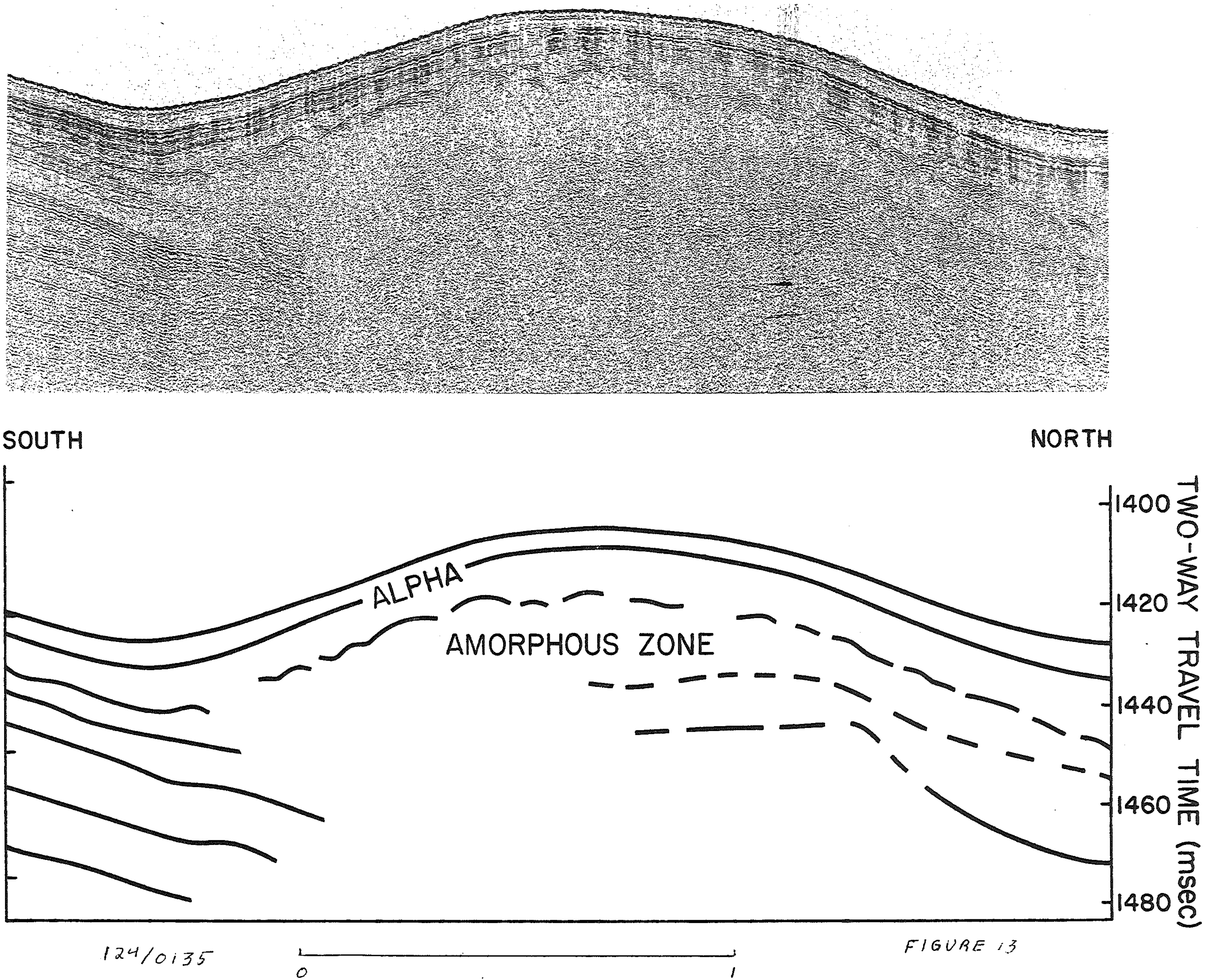

SOUTH
NORTH
WATER DEPTH (m)
1020
1040
1060
1080
TWO-WAY TRAVEL TIME (msec)
1400
1420
1440
1460
1480
ALPHA
AMORPHOUS ZONE
124/0135
0
1

FIGURE 13

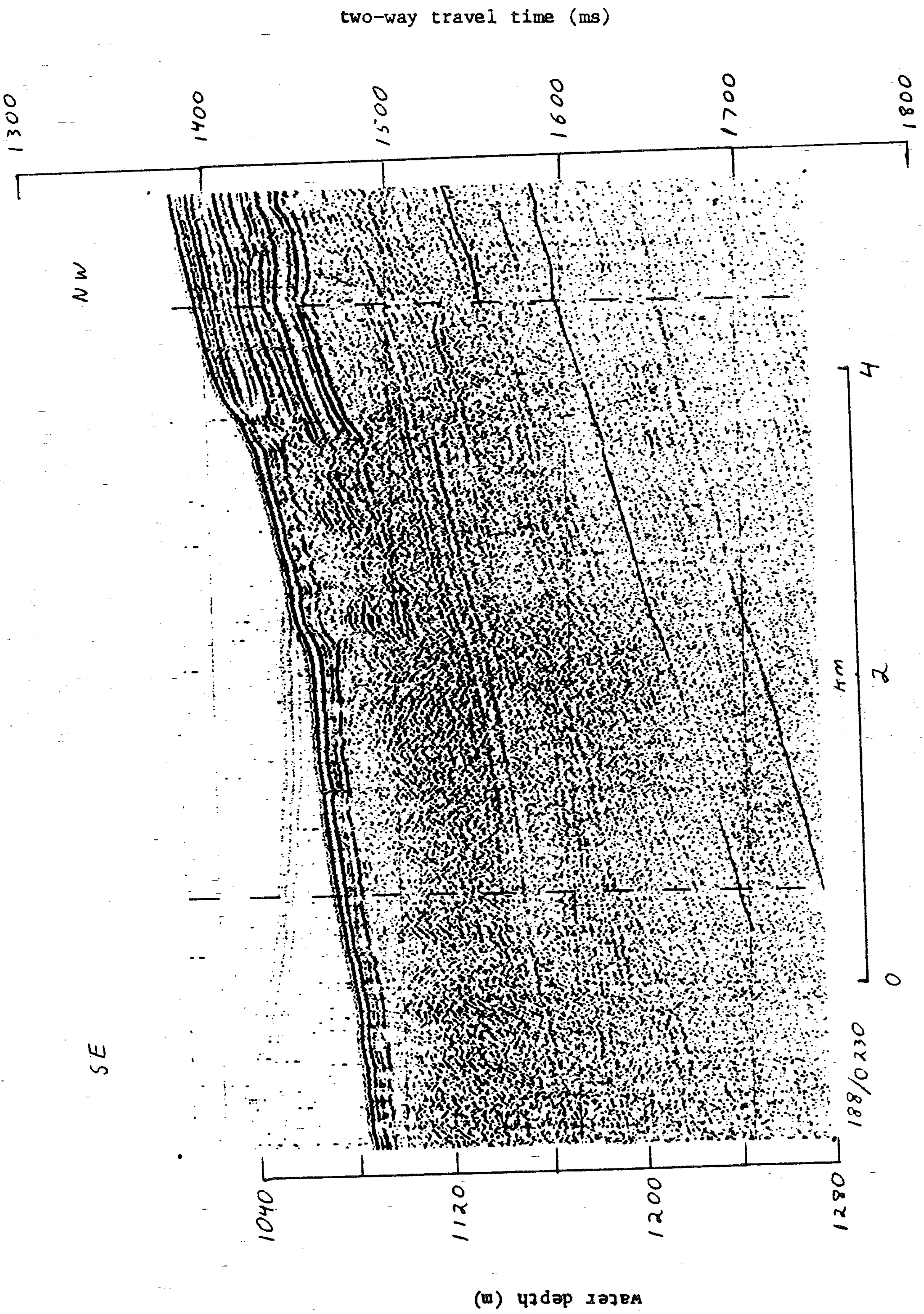

two-way travel time (ms)
1300
1400
1500
1600
1700
1800
NW
SE
4
2
km
0
188/0230
1040
1120
1200
1280
water depth (m)

FIGURE 14

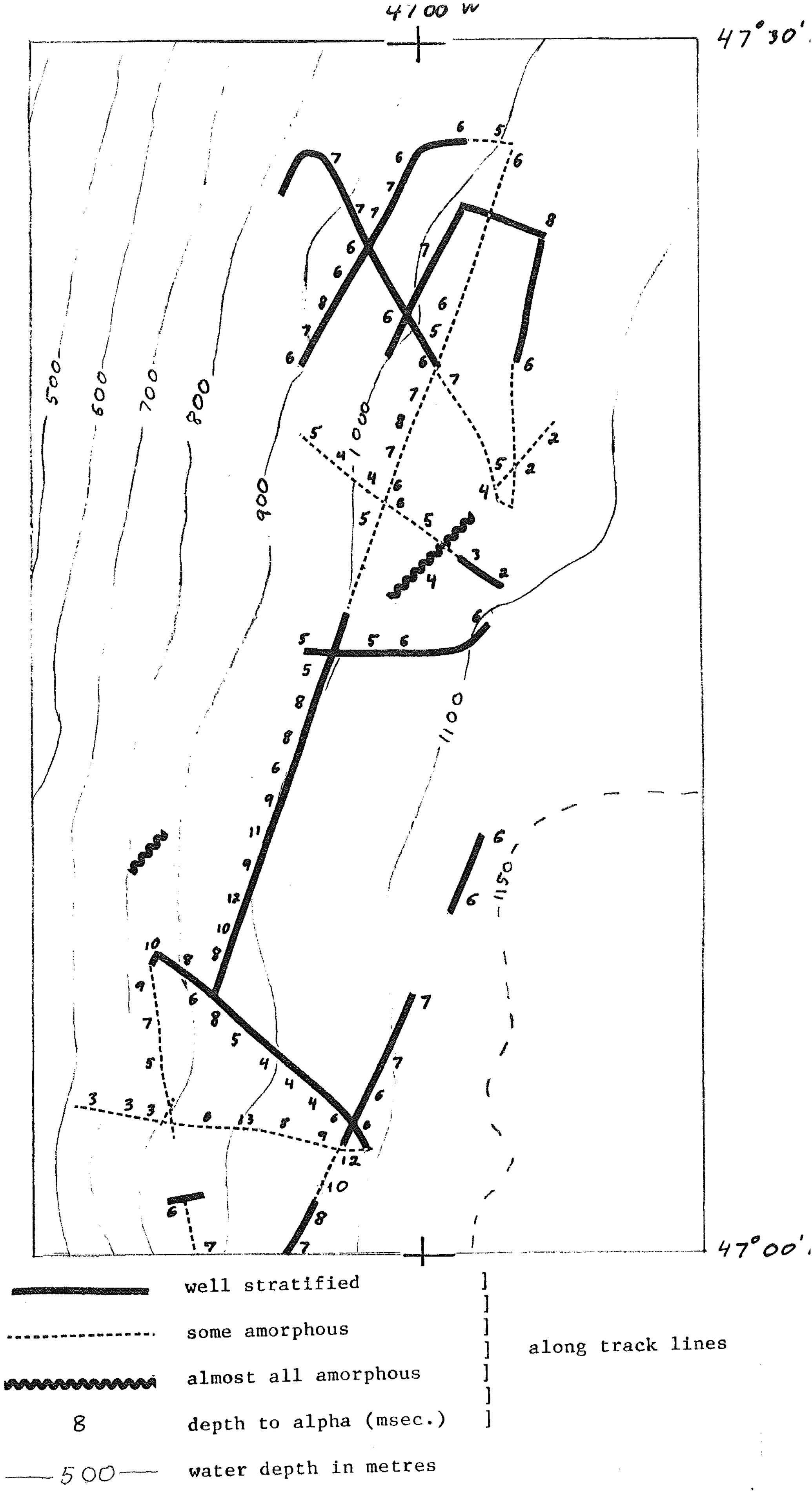

4100 W
47°30'
47°00'
500
600
700
800
900
1000
1100
1150
well stratified
some amorphous
almost all amorphous
8 depth to alpha (msec.)
500 water depth in metres
along track lines

FIGURE 15

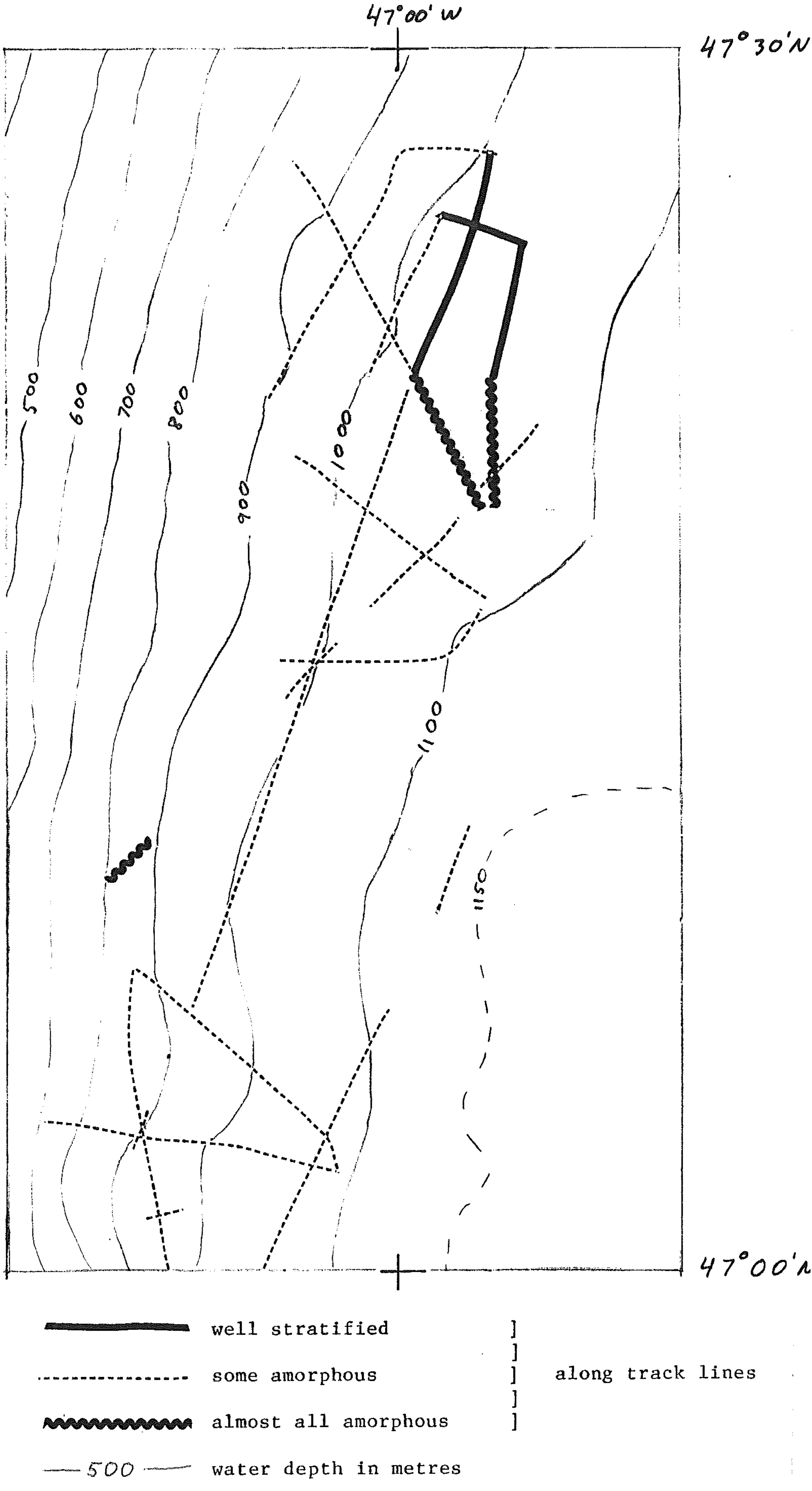

47°00' W
47°30'N
500
600
700
800
900
1000
1100
1150
47°00'N
well stratified
some amorphous
almost all amorphous
along track lines
500
water depth in metres

FIGURE 16

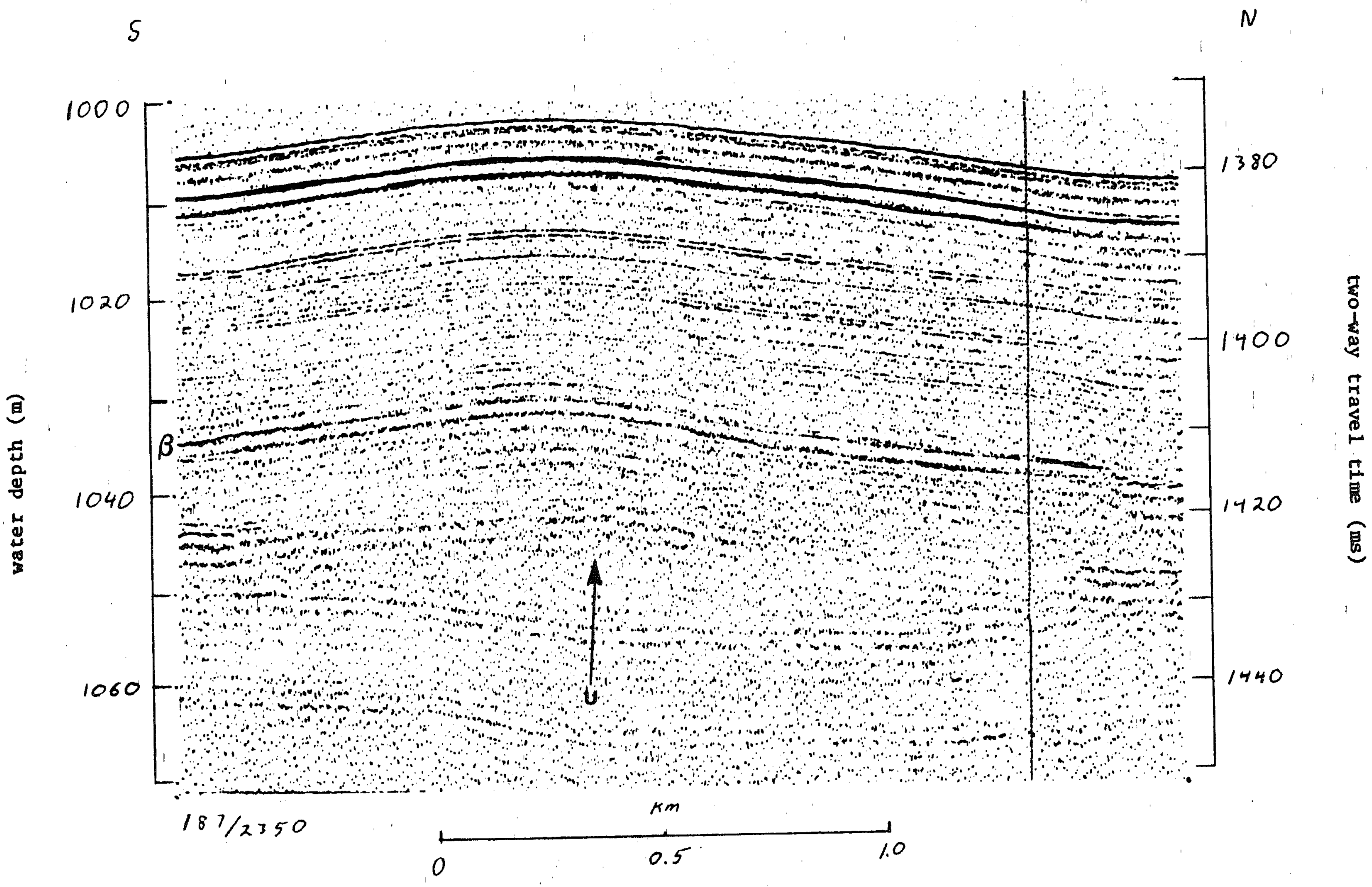
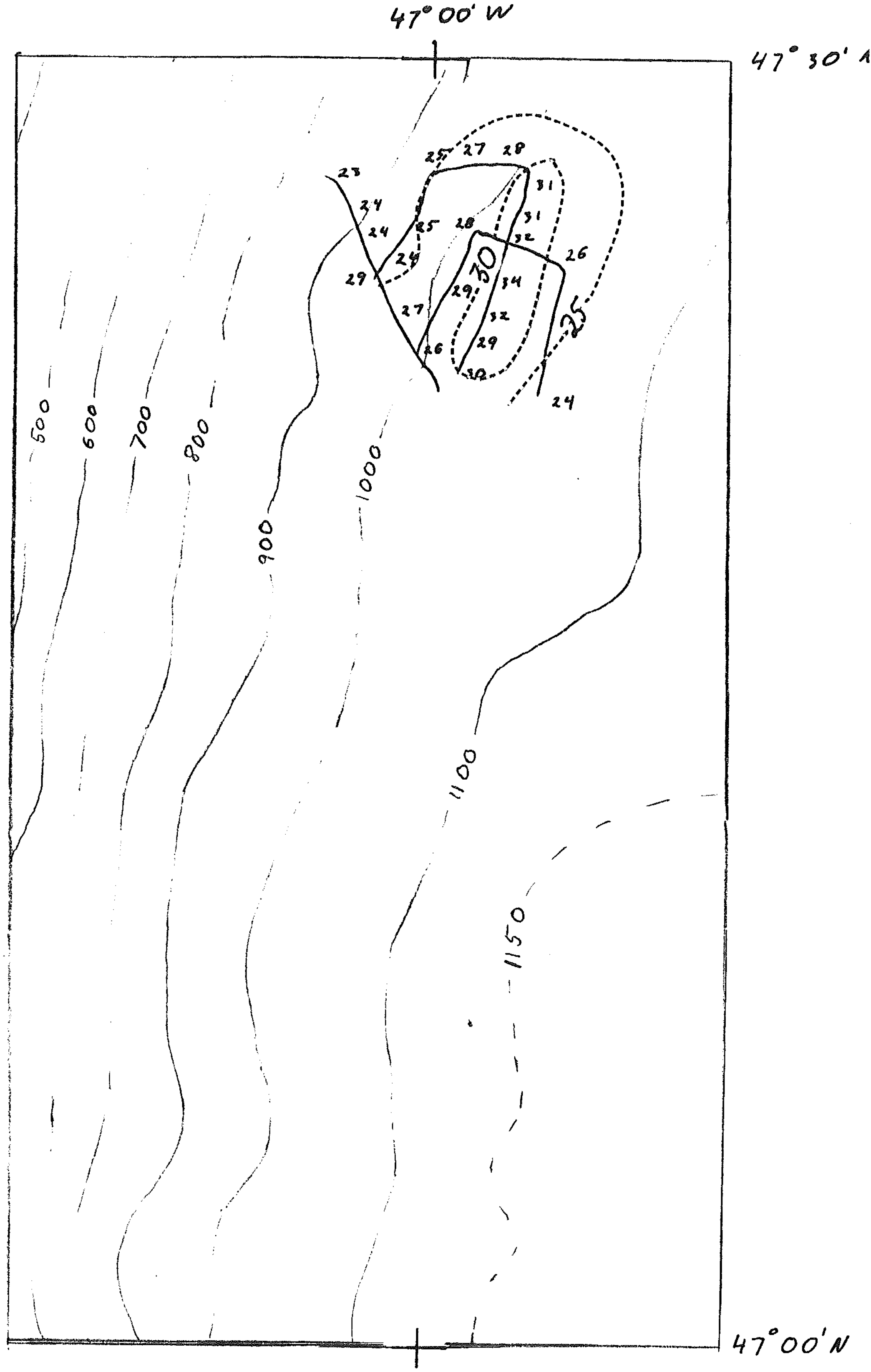

S
N
1000
1020
1040
1060
water depth (m)
β
1380
1400
1420
1440
two-way travel time (ms)
U
187/2350
Km
0
0.5
1.0

FIGURE 17



—— track lines

30 depth of beta below alpha (msec.)

----30---- isopach (msec.)

—500— water depth in metres

FIGURE 18

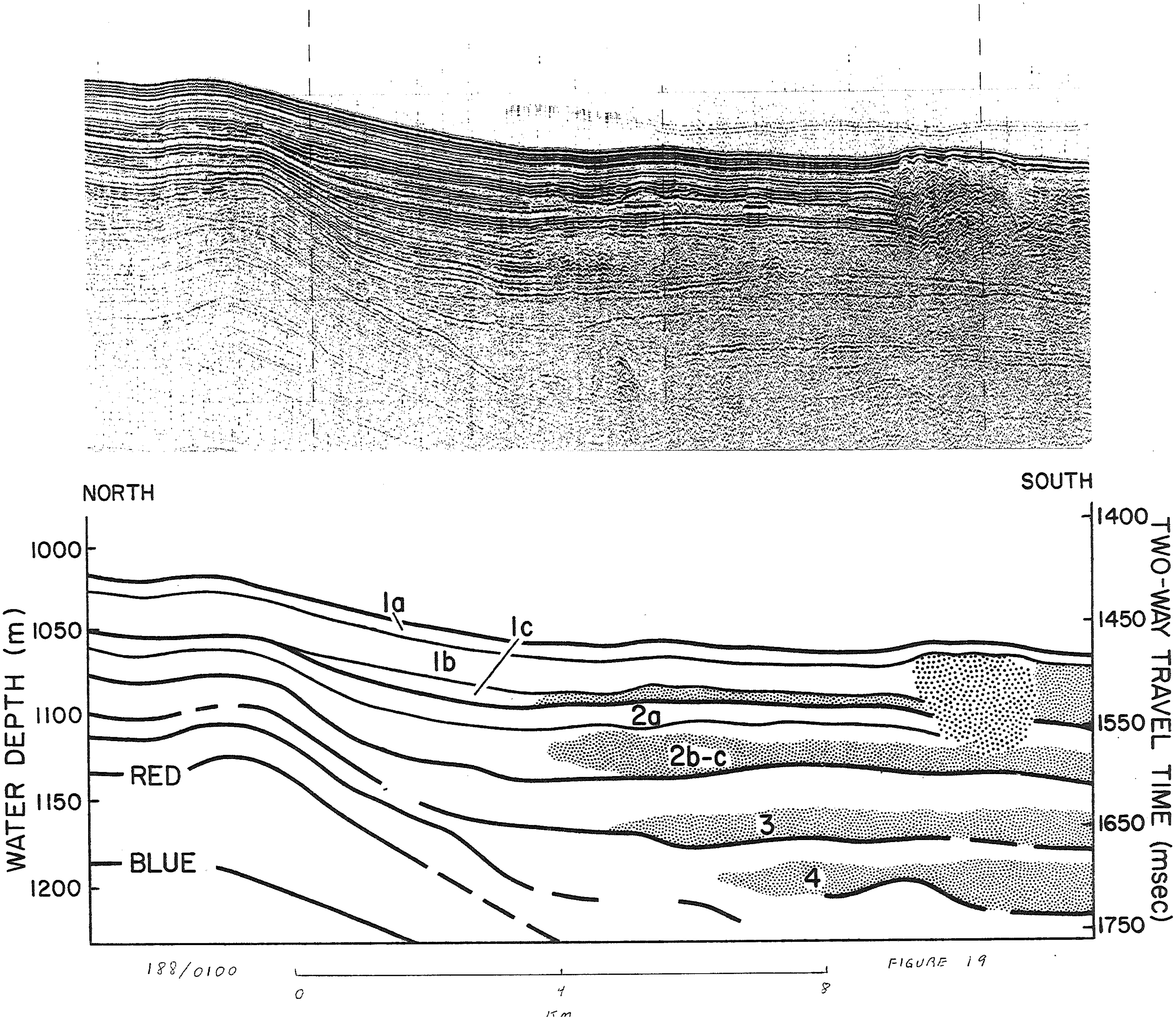

NORTH
SOUTH
WATER DEPTH (m)
1000
1050
1100
1150
1200
TWO-WAY TRAVEL TIME (msec)
1400
1450
1550
1650
1750
1a
1b
1c
2a
2b-c
3
4
RED
BLUE
188/0100
0
4
8
Km

FIGURE 19

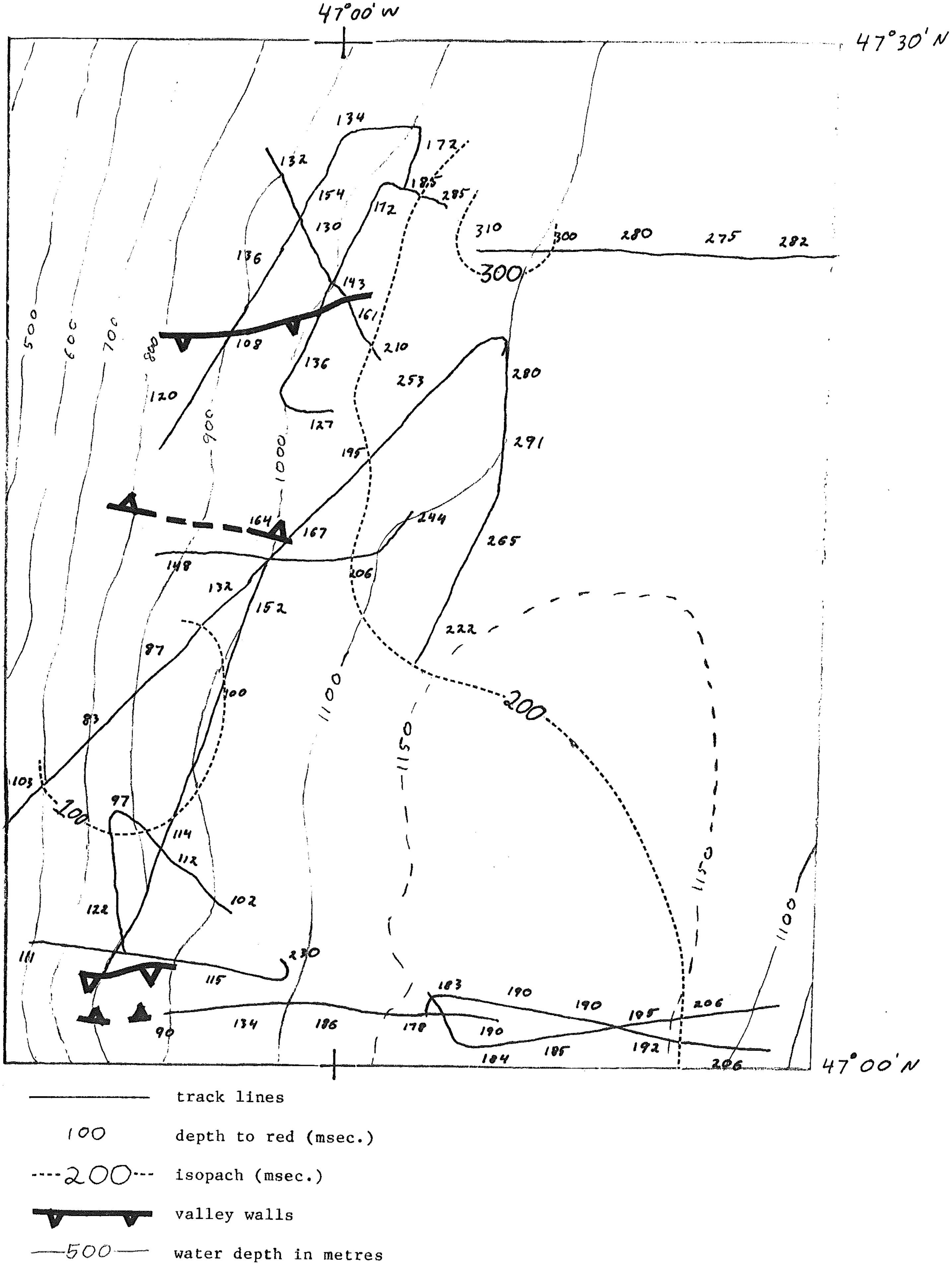

47°00' W
47°30' N
47°00' N
500
600
700
800
900
1000
1100
1150
300
200
100
134
172
132
154
185
285
172
130
310
300
280
275
282
136
143
161
108
210
136
253
280
120
127
195
291
164
167
244
265
148
206
132
152
222
87
100
83
103
97
114
112
102
122
111
230
115
183
190
190
195
206
90
134
186
178
190
184
185
192
206
track lines
100 depth to red (msec.)
200 isopach (msec.)
valley walls
500 water depth in metres

FIGURE 20

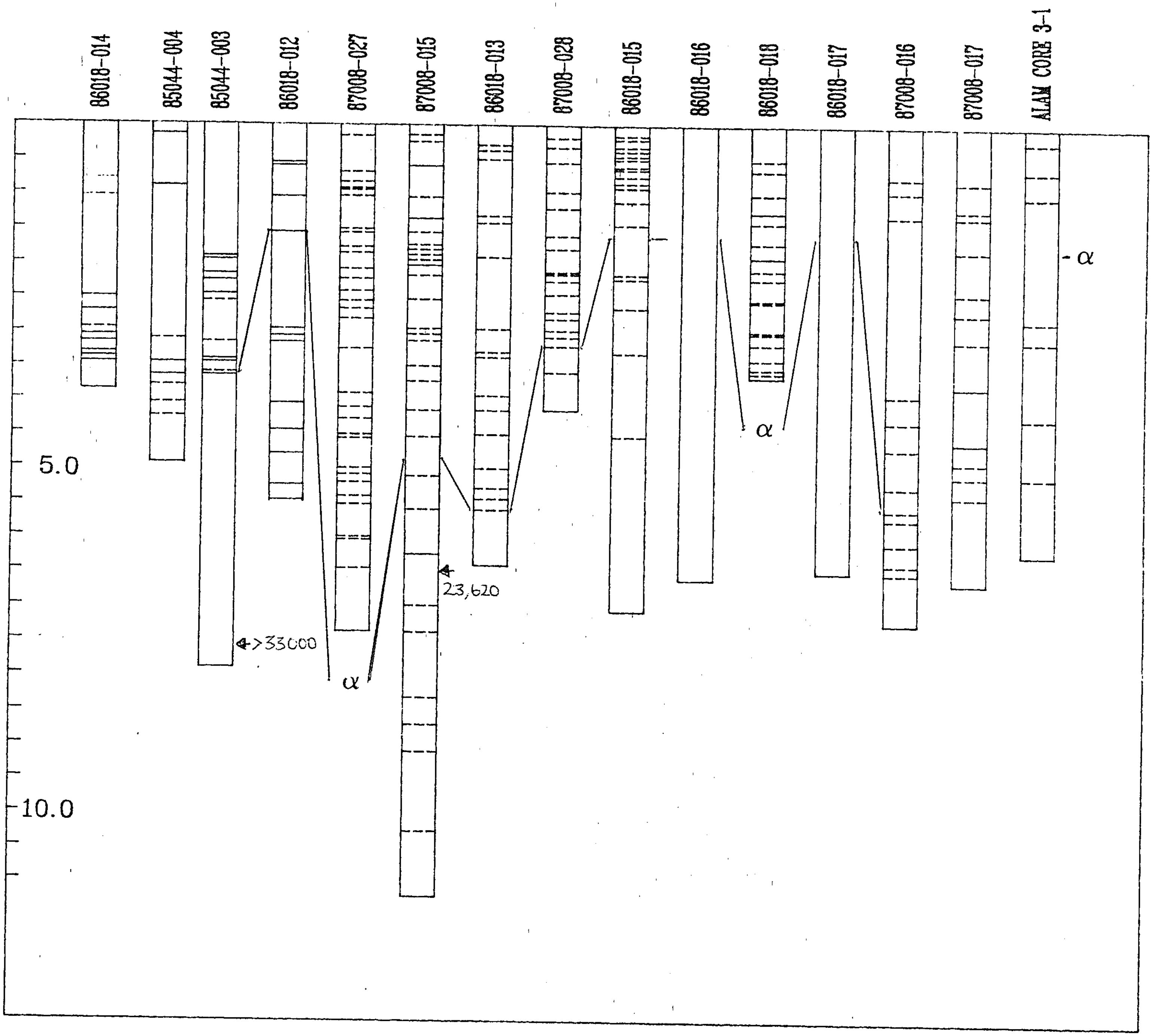

86018-014
85044-004
85044-003
86018-012
87008-027
87008-015
86018-013
87008-028
86018-015
86018-016
86018-018
86018-017
87008-016
87008-017
ALAM CORE 3-1
- α
α
α
23,620
>33000
5.0
10.0

FIGURE 21