A DETAILED STUDY OF A SUBMERGED PINGO-LIKE-FEATURE IN THE CANADIAN BEAUFORT SEA, ARCTIC, CANADA

by

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Submitted in partial fulfillment of the requirements for the degree of Bachelor of Science

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August, 1982

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Title: A DETAILED STUDY OF A SUBMERGED PINGO-LIKE-FEATURE IN THE CANADIAN BEAUFORT SEA, ARCTIC, CANADA

Date: Feb 24/83

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ABSTRACT

There is controversy as to the origin of the dome shaped hills (pingo-like-features (PLFs)) found on the Canadian Beaufort Sea continental shelf and slope. A detailed study of a PLF was undertaken to define its characteristics and to determine its origin.

Two cores were obtained, one each from the peak and moat which surrounds the feature and several acoustic survey lines were run over the PLF.

The cores were analyzed and compared for geotechnical properties, pore water cation, gas and organic carbon concentrations as well as foraminifera and palynomorph assemblages.

Core and Acoustic data strongly suggest a mud volcano type mechanism of formation of this PLF.

ACKNOWLEDGEMENTS

I would like to thank Steve Blasco, Martin Gibling, Dale Buckley and Phil Hill for their advice and guidance throughout the duration of this thesis project. I would also especially like to thank those people at AGC who gave their time and expertise, together permitting a broad spectrum of analysis to be completed. These people include Gus Vilks, Peta Mudie, John Bujak, Dale Buckley and Kate Moran. The lab assistance of Bob Fitzgerald, Kim Rideout, Bill LeBlanc and in particular Bob Harmes is gratefully acknowleged. Lengthy discussions with Jim Shearer were instrumental in helping me to clarify my sometimes non-linear trains of thought.

A special thanks goes to the Beaufort Sea Group, (B.S. Group), Fred, Bob, Phil, Kate and Steve for their perserverance and sweat and everbody at the Atlantic Geoscience Centre who made working there an excellent experience. I couldn't have done it without you Phil.

Finally, I would like to thank O.E.R.D. for funding this research and Dome Petroleum for providing some of the data.

CHAPTER 1 INTRODUCTION

1.1 GENERAL STATEMENT AND THESIS OBJECTIVE

The existence of high positive-relief features (Fig. 1), on the Canadian Beaufort Sea continental shelf, was first noted on the echosounder of the CCGS John A. MacDonald, a Canadian icebreaker which was escorting the tanker S.S. Manhattan to Alaska through the Northwest Passage in 1969 (A.D. O'Connor, pers. comm.,1981). Due to the potential navigational hazard that these features present to deep draught vessels, the Canadian Hydrographic Service (CHS), in 1970, launched a long term program to bathymetrically chart the shelf, in an attempt to map their distribution and describe their morphological characteristics. At this time the Geological Survey of Canada (GSC) also initiated a major program to study the surficial geology and marine environment of the shelf and slope. Their aim was mainly to gain a better understanding of the active sedimentary processes and define the late Quaternary history and evolution of the shelf. A study of the nature and origin of the high relief features was an integral part of the research.

To date about 230 of these high relief features have been mapped in the Beaufort Sea. Reports were prepared for the CHS by Campbell, (1979), and Johnson, (1980), which present measurements from echosounding records over 205 and 190 (respectively) of the features detected during CHS surveys in 1970 to 1972. From these data the features can be seen to be generally asymmetric, dome-shaped, mounds or hills from 6 m to 45 m high (average 16 m), with basal diameters from less than 100 m up to 2100 m (average 700 m). Their slopes rarely reach as steep as 1:3 (18°), are commonly 1:10 (6°), but average 1:17 (3.5°). They are found in water depths from 15 to 150 m and few rise to with 15 m of the surface (shallower than the design draught of some tankers).

Due to their morphological similarity to ice-cored hills known as pingos (MacKay, 1979), which are common on the nearby Tuktoyaktuk

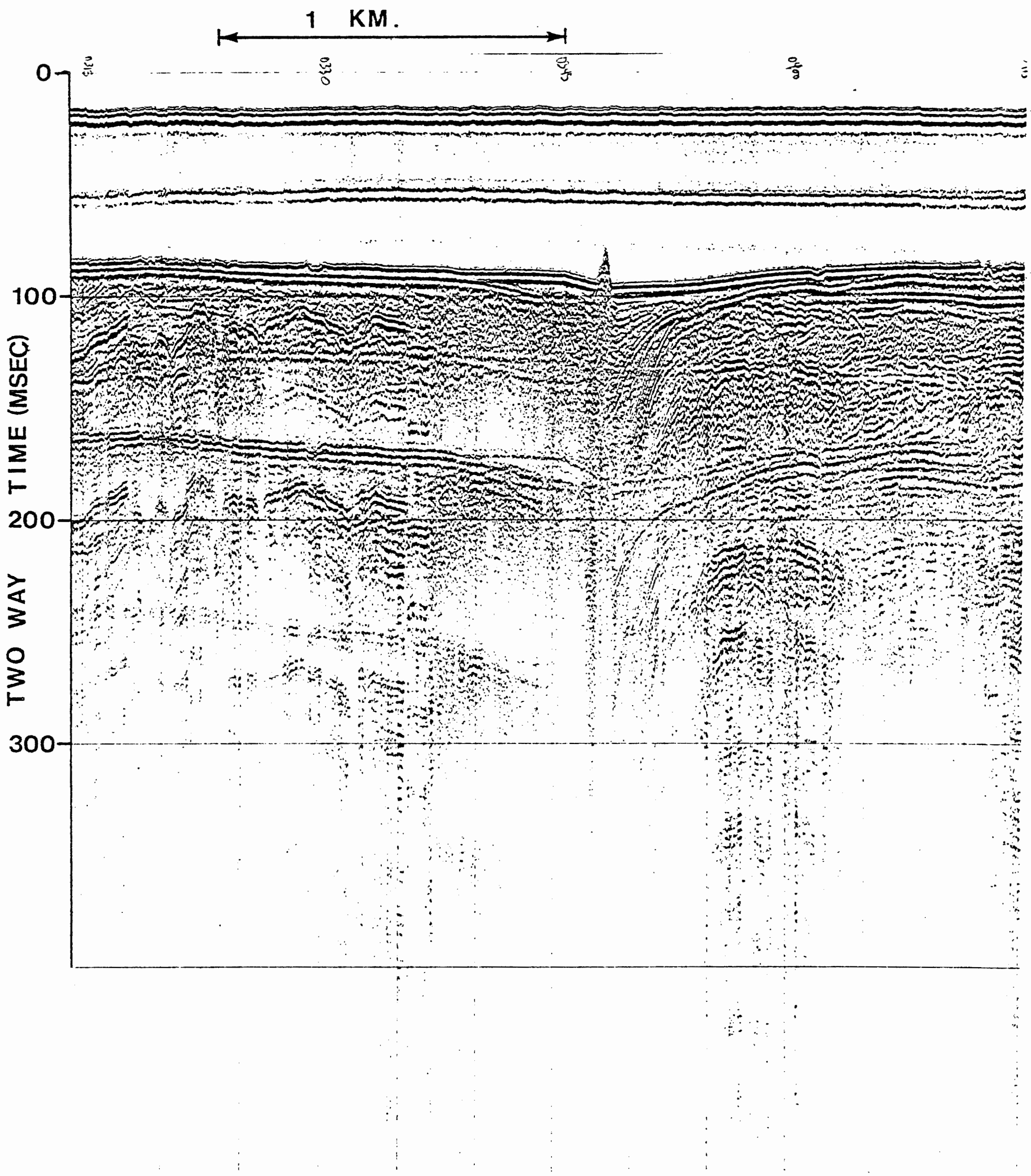


FIG. 1 A TYPICAL PINGO-LIKE-FEATURE

Peninsula, these offshore features have been called pingo-like-features (PLF). Not all PLFs exhibit the same characteristics and they may have been formed by several different mechanisms (Shearer, 1980).

This thesis is a study to assess the geological nature of one PLF in an attempt to gain a better understanding of the mechanisms by which it formed. Figure 2 shows all PLFs mapped as of 1979 as well as the Kopanoar PLF which is the focus of this study. The Kopanoar PLF (Lat. 70^{o} 23' 45"N, Long. 135^{o} 25' 01"W) was discovered by Dome Petroleum Ltd. during a survey in area of the Kopanoar exploratory wells.

1.2 DATA AVAILABLE

Various data have been collected since 1970 and are summarized below:

1. 1970 - 1981: Canadian Hydrographic Service (CHS) obtained sounding records over these features during reconnaissance bathymetry surveys. Several records were from a 12 kHz. sounder with which some sub-bottom penetration was obtained.

2. 1970-1980: Geological Survey of Canada (GSC) produced regional acoustic lines which were related directly or indirectly to PLFs. These include sidescan, sub-bottom profiling, airgun seismic and echosounding lines. GSC 1970 gravity and magnetic data are also available over the entire shelf.

3. 1980-1981: Combined GSC and Dome Petroleum data were collected specifically for this study. These data include:
   a) Two cores obtained from the Kopanoar PLF;
      core 7 - one piston core (4.43 m long) with gravity trigger core

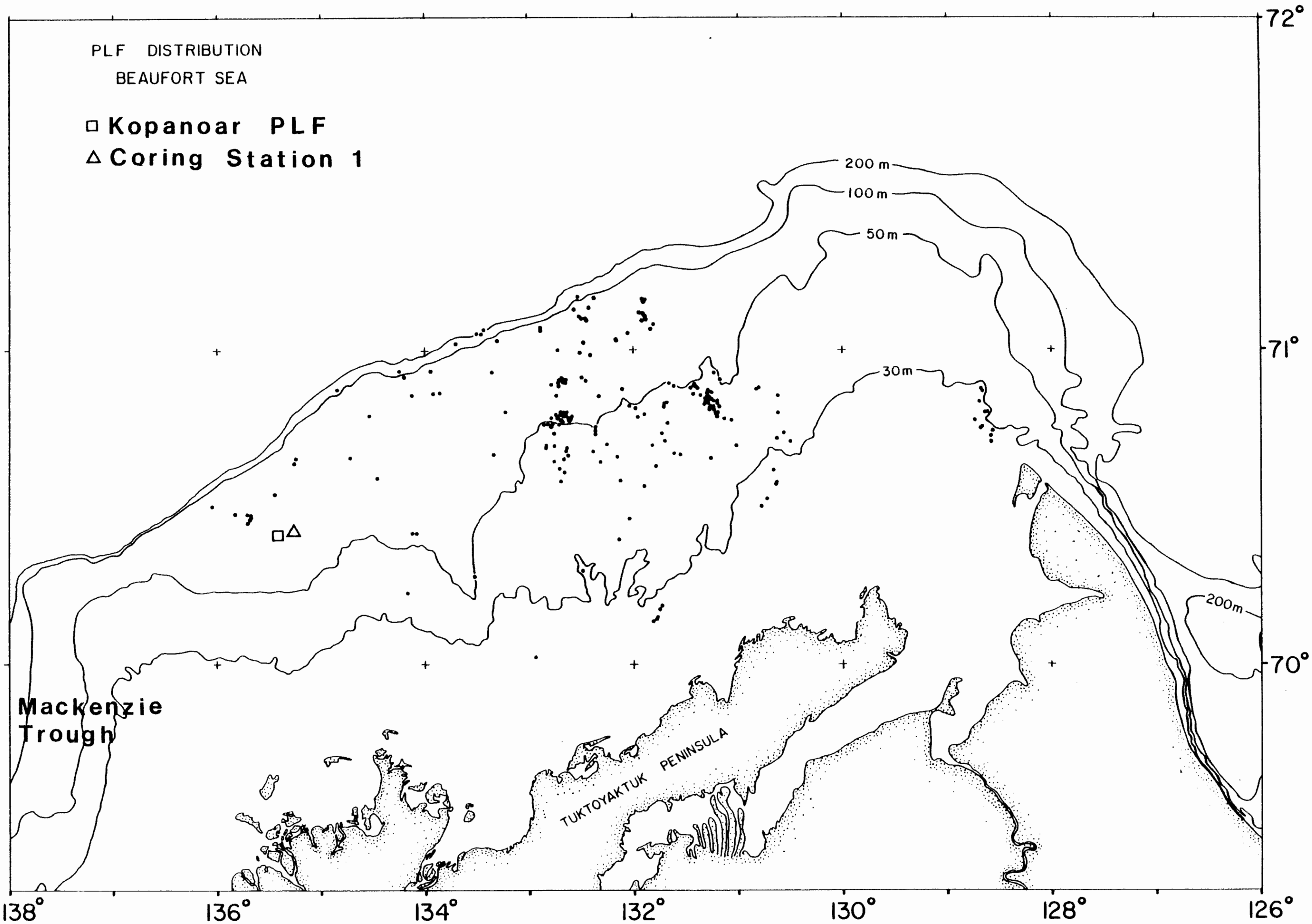


Fig. 2 PLF Distribution in the Beaufort Sea

(1.57 m) from the depression ('moat') surrounding the feature.
core 8 - one gravity core (1.17 m) from the peak of the PLF.

b) Acoustic data from 7 passes over the Kopanoar PLF which include sidescan, sub-bottom profiler and V-fin seismic records.

4. 1981: The GSC obtained a total of 11 cores in PLF (moat and peak) sediments. As the ship did not return south until November only complete cores 7 and 8 were flown off the ship for this study along with some subsamples from the other cores.

1.3 REGIONAL GEOLOGY

A generalized model for the surficial geology of the Beaufort Sea continental shelf, summarized in Figure 3 and Table 1, was proposed by the GSC in 1979 and developed under contract by M.J. O'Connor and Associates in 1980. This model is based primarily on acoustic data with limited ground truth from boreholes.

The model shows three basic stratigraphic units which vary in thickness across the shelf. Unit A, the surficial unit, is a fine-grained marine sequence that was deposited after the last transgression. It grades downwards into Unit B which is a variable, complex, transgressive unit that was deposited during the last transgression. This unit lies unconformably on Unit C which is a much older sequence of sediments deposited in continental and transitional environments and consisting of sands with minor silt, clay and gravel layers. It is believed that the unconformity lies along an old land surface which is extensively underlain by relict permafrost. Following deposition, these units have been modified in varying degrees by processes active on the shelf and slope such as ice scouring, permafrost aggradation and degradation, shallow gas migration and slope instability.

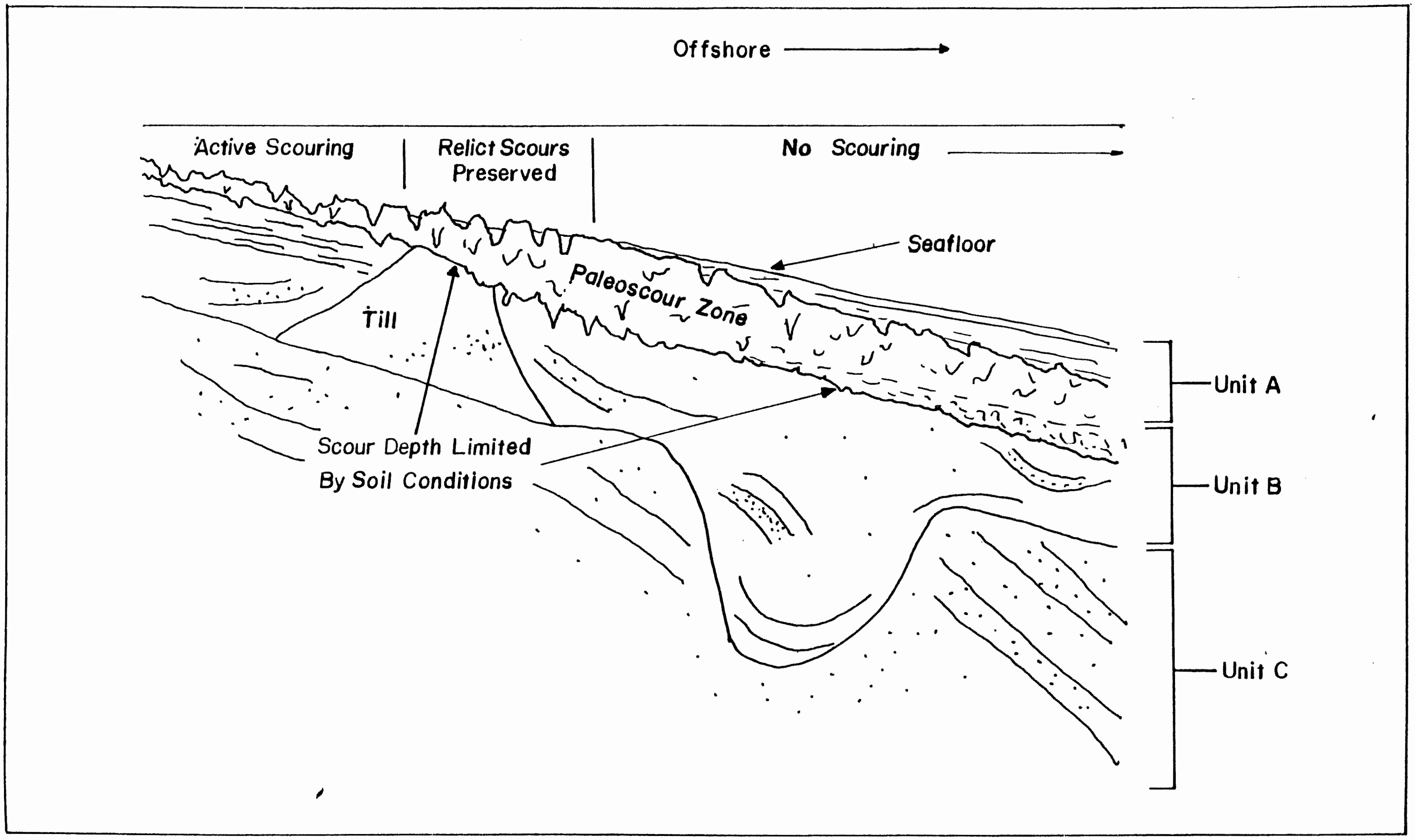


Fig. 3 Model of the Surficial Geology of the Beaufort Sea, from O'Connor (1980)

TABLE 1 Surficial Geology Model Units

UNIT	DESCRIPTION	DEPOSITIONAL ENVIRONMENT
A	-grey to black -soft to firm (rarely shift) -clay to silty clay -traces of fine sand and organics -grade from loose silt near shore to clays further offshore -lower contact gradational or abrupt	-recent marine -acoustically transparent -commonly horizontally stratified and extensively ice-scoured
B	-highly variable sequence of sands, silts and clays -possibly some organic-rich and/or heterogenous stoney clay layers -base lies unconformably on old erosional surface	-transitional (deltaic, lagoonal and littoral) -original characteristics sometimes visible in acoustics (ie. channel deposits) -irregular unconformity often appears as high level of backscatter trancating beds of unit C
C	-mostly variable fine- to medium grained grey-brown or yellow sand -some silt, clay and gravel layers -extensive relict permafrost within this unit particularly on eastern shelf	-old delta(?) sediments from deltaic or littoral environments (pre Wisconsin glaciation) -forset and channel fill reflectors common in acoustics

Presently, coastal erosion by the continuing transgression of the sea provides a significant contribution of sediment to the continental shelf (and probably units A and B), though the main source is believed to be from the Mackenzie River (Pelletier, 1975; Harper and Peland, 1982). River discharged sediment is usually carried eastward along the coast and then westward along the outer shelf except when there are strong westerly winds. Vilks et al. (1979) studied fauna and sediment in 659 surface samples and 49 cores from the shelf and slope. All sediments were found to be early to late Holocene consisting mainly of silt and clay with minor sand and gravel (Fig. 4), and sedimentation rates were estimated at 100 cm/1000 yr in Mackenzie Trough and 3 - 30 cm/1000 yr on most of the outer shelf. Organic production and the distribution of micro and macro-fauna were found to be largely controlled by water salinity which in turn is a function of mixing between Mackenzie River water, melting pack ice and Arctic Ocean water.

1.4 PINGOS

PLFs are morphologically similar to pingos which are found on land. A description of pingos and their mechanisms of formation is in order here for later reference and comparison with offshore PLFs.

'Pingo' is an Inuit word meaning conical hill. These ice-cored hills are found in many arctic environments of the world including Svalbard, Greenland, the Arctic Archipelago and the USSR. There are about 1450 pingos along the Western Arctic Coast (MacKay,1979). A large pingo is shown in Figure 5.

J.R. MacKay has written some 35 papers (1969-79 on permafrost and pingos of the Tuktoyaktuk Peninsula. Much of this work relating to pingos is summarized in one major paper (MacKay,1979) which includes excellent documentation of field studies within the period 1969-1978 on

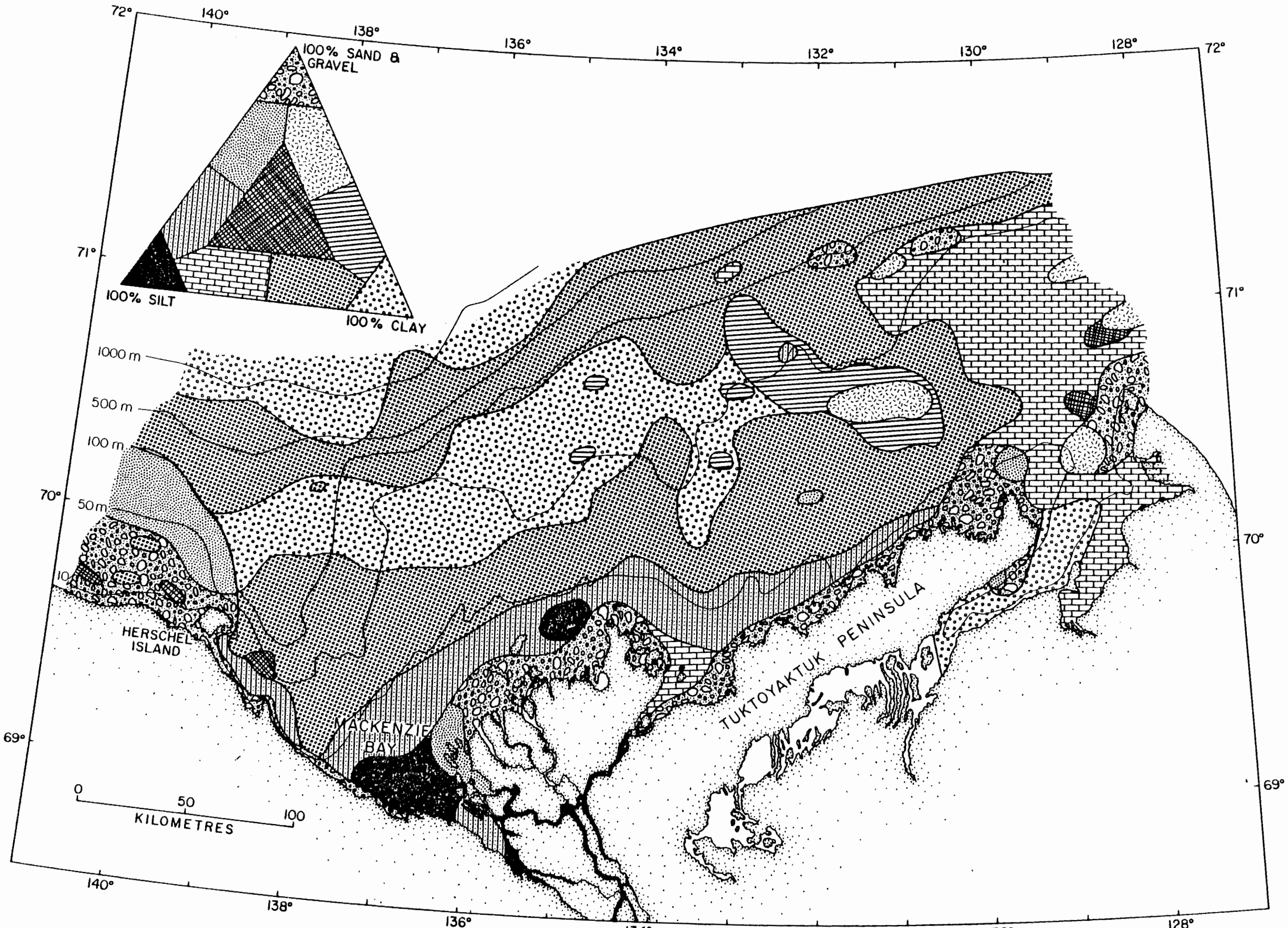


Fig. 4 Surficial Sediment Distribution in the Beaufort Sea from Vilks et al. (1979)

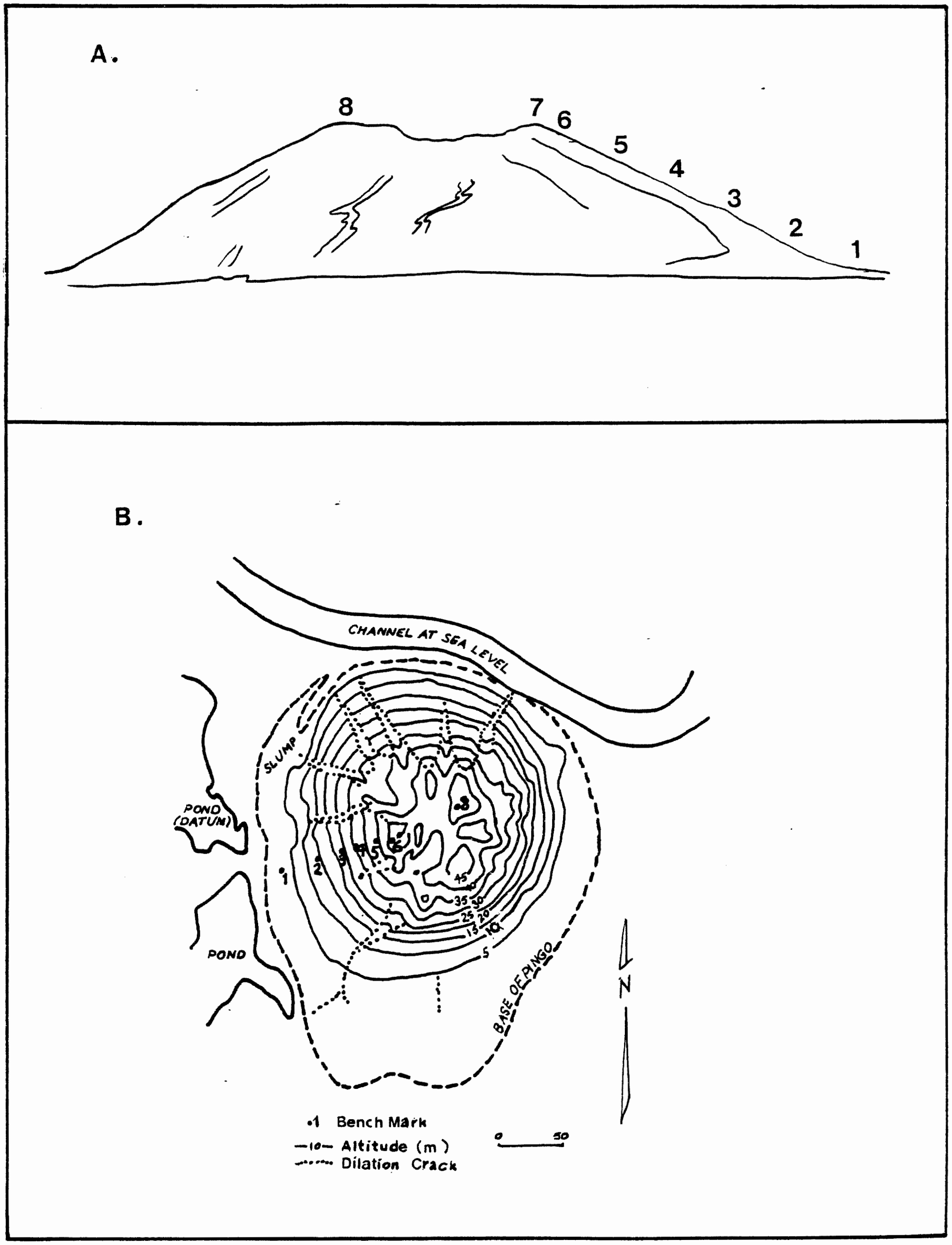


Fig. 5 Ibyuk Pingo (A Large Pingo) from Mackay (1979)

the morphology and growth patterns of 17 pingos. Pingos by definition can only grow and persist in permafrost, and those of the Tuktoyaktuk Peninsula are almost always found in the bottoms of drained lake basins.

Though pingos up to 48 m high are found on the peninsula, MacKay estimates that about 85 percent of them are less than 20 m high. He describes them as up to 600 m in diameter but usually they are less than 250 m. They are most often oval cones ranging from circular to elongate in plan view. A very few are partially encircled by a moat. Slopes rarely exceed 45^{o} (1:1) and most approximate a cosine curve grading gradually down slope into the lake flats. Typically, dilation cracks form on the summit due to stretching of the overburden and a crater results (Fig.5). The craters could be up to 5 m deep and 20 m wide. Ice within the mound can be massive, segrated ice, clear injection ice, pore ice or wedge ice.

MacKay proposes the following mechanism of pingo formation:

1) A lake deeper than two metres does not freeze to its bottom even in winter. This tends to insulate the sediment directly below it, causing a depression in the top of the underlying permafrost table
(talik).

2) The lake drains quickly, (commonly due to ice wedge polygon erosion during coastal recession), leaving a small residual pond.

3) With the insulation effect removed, the 0^{o} C isotherm then migrates downward into and below the lake sediments, causing freezing of pore water from the surface down.

4) As the interstitial water freezes it expands (about 9% by volume). This, combined with the increased loading due to the weight of the newly formed permafrost, causes excess pore water to be

expelled ahead of the freezing plane. However, when impermeable permafrost or an impermeable clay is continuous laterally at depth, water loss is prevented and pore water pressure in a closed system talik rises.

5) The pore pressures may increase until lithostatic load is exceeded and the ground heaves to form a pingo, usually with the intrusion of a sub-pingo water lens.

6) Failure and subsidence of the pingo may follow due to drainage of the sub-pingo water lens and/or exposure of the ice core to melting when the overburden ruptures, erodes, or creeps down the slopes.

Most Tuktoyaktuk Peninsula pingos form in these conditions and are termed 'closed system' pingos. If pore pressure is maintained from water supplied by a distant elevated source ('hydraulic' pingos) then the resulting pingo is termed an 'open system' pingo. Examples of this type are those in Alaska (Holmes et al, 1968). As MacKay points out, it is difficult to determine to which class a particular pingo belongs and gradations between the two classes undoubtedly exist.

1.5 PREVIOUS WORK

Several projects (1970-81) have been undertaken by Fisheries and Oceans, Canadian Hydrographic Service to locate PLF's and document their geometries, probability of occurrence, and acoustic target strengths, in an attempt to establish the best surveying parameters for detection of these features (Johnson 1980, Simpkin 1980, Campbell 1979)

Magnetic field data (precision 1 gamma) and gravity data (precision 1 mgal) were collected in 1970 by the GSC over the entire shelf. No anomalies were observed to 'be associated' with PLF's suggesting the absence of a shallow sub-bottom structure (Shearer et al., 1971).

Shearer et al. (1971) ruled out piercement origin on the grounds that underlying reflectors are continuous on some features they observed (Fig. 6).

They discuss two modes of genesis:

1) PLFs are pingos formed on land and later submerged by the sea.

2) PLFs formed in large lake basins after they were inundated by the sea in a method similar to pingo formation on land.

They further suggested from examination of present-day wave action along the shoreline that ice-cored pingos formed on land would not have survived the post-glacial transgression. The authors then proceeded to explain the second mode of genesis:

1) Large relatively deep lakes with associated underlying 'plugs' of unfrozen material (taliks) are transgressed by the sea, leaving lake basin sediments largely undisturbed.

2) A blanket of marine clays as well as the relative impermeability of the lacustrine sediments inhibits sea water from mixing with the fresh water trapped in the lake sediment interstices.

3) As the sea continues to transgress the bottom seawater temperatures decrease (and are negative below approximately

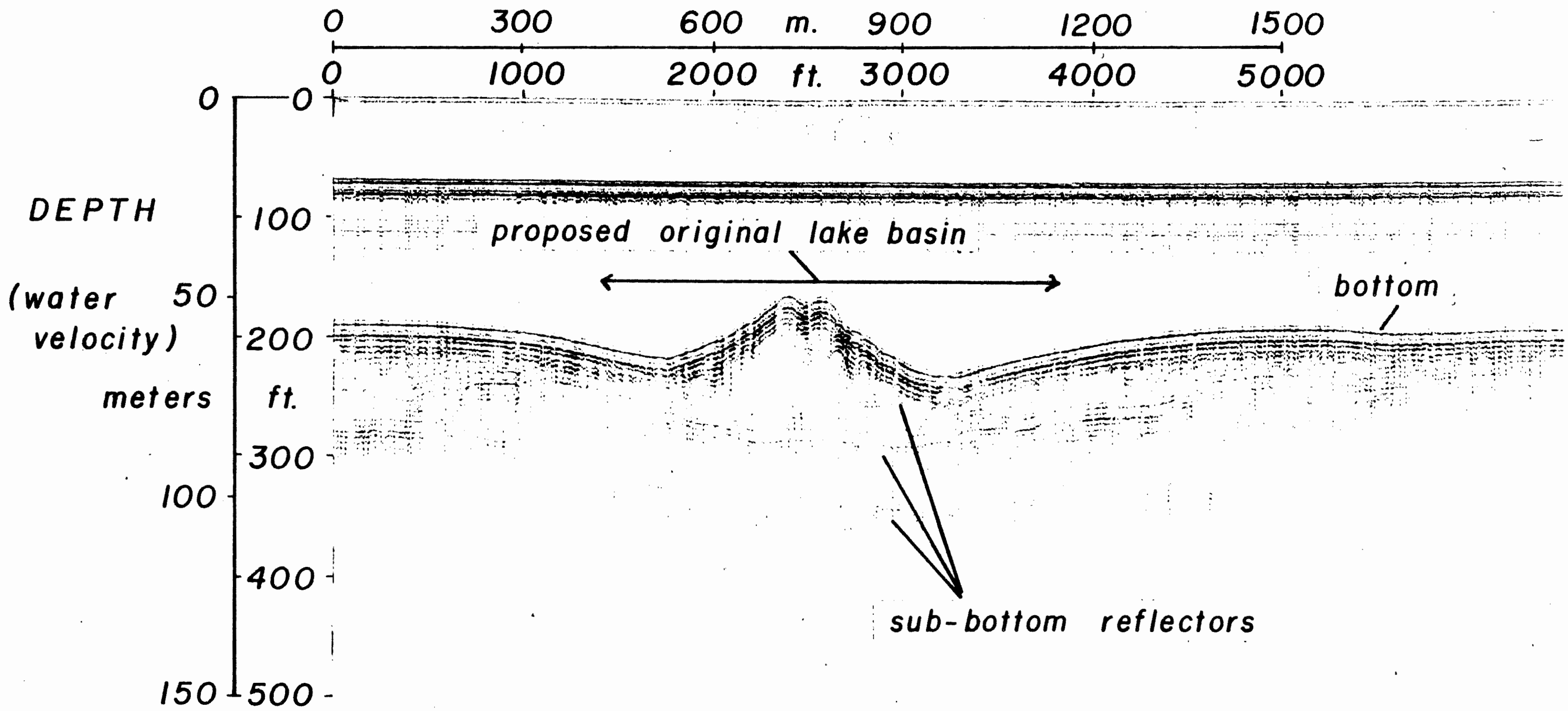


Fig. 6 PLF from Shearer et al. (1971)

20 metres water depth), causing the $0^{o}C$ isotherm to migrate downward into the deeper and relatively fresh water lacustrine and sub-lacustrine sediments.

4) Freezing of these interstitial waters occurs resulting in an increase in pore pressure and upheaval of the overlying sediments to form a PLF.

As more data were collected (1971-80), acoustic records over these features indicated that not all PLFs exhibited characteristics similar to the pingos on Tuktoyuktuk Peninsula and it became apparent that not all were formed by the above mechanism.

A study was undertaken (Shearer, 1980) to classify and discuss the probable origin of these features, as well as attempt to estimate the distribution of as yet undiscovered PLFs in the Beaufort Sea. Shearer identified four main morphological types:

Type A - Diapiric features that occur mostly on Mackenzie Trough edges and the shelf edge (Fig. 7). These are 20 - 40 m high and have slopes of about 1:3. They may have formed by melting of entrapped ice causing collapse of overlying sediments. The entrapped ice could be relict permafrost or relict glacial ice.

Type B - Shelf Edge slump features (Fig. 8) found in water depths greater than 100 m, along the shelf edge and slope. Relief of Type B features is believed to be a result of movements such as folding and block faulting associated with slumping on unstable slopes. The three dimensional shape of Type B features is probably not conical but ridge-like.

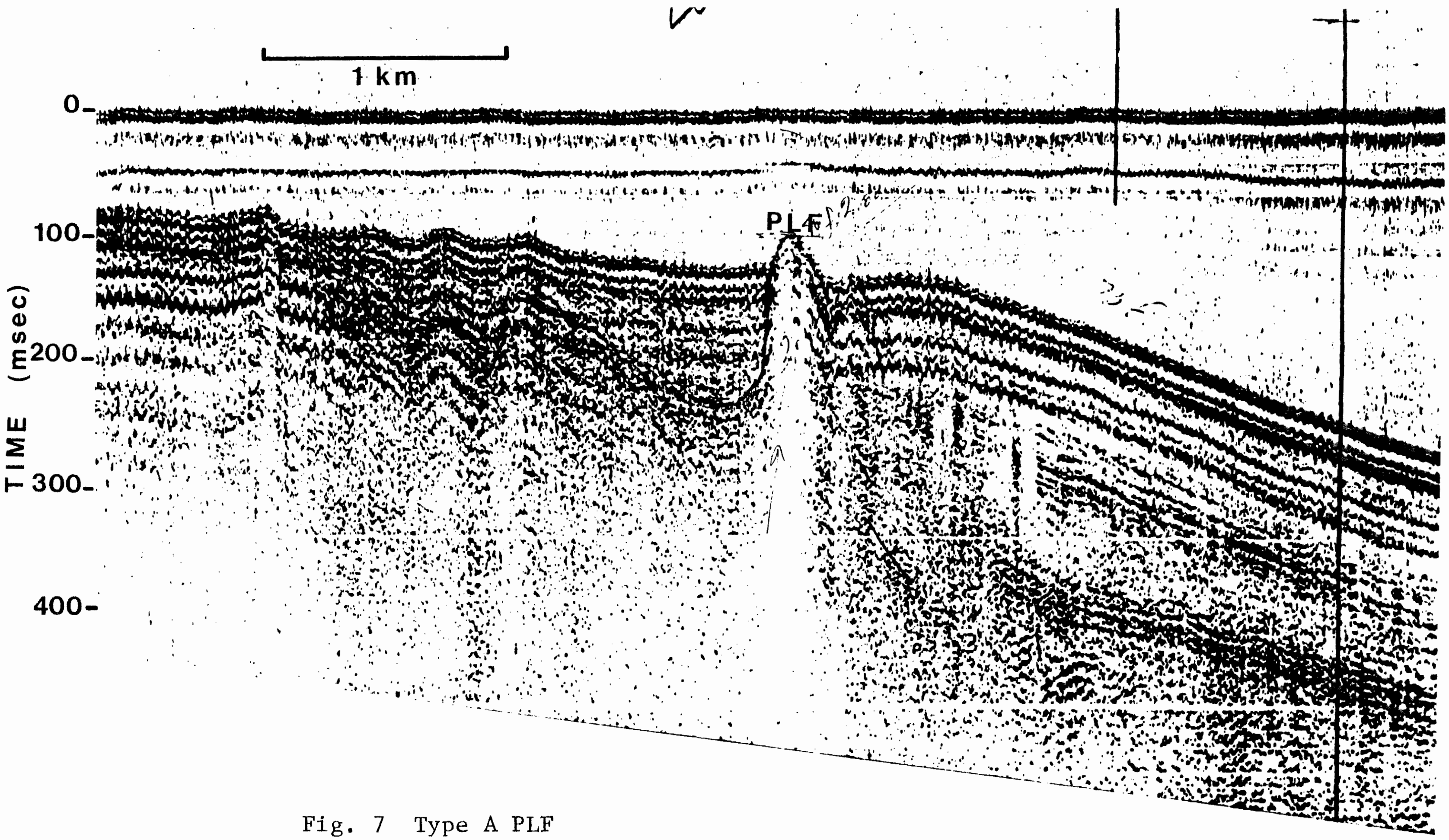


Fig. 7 Type A PLF

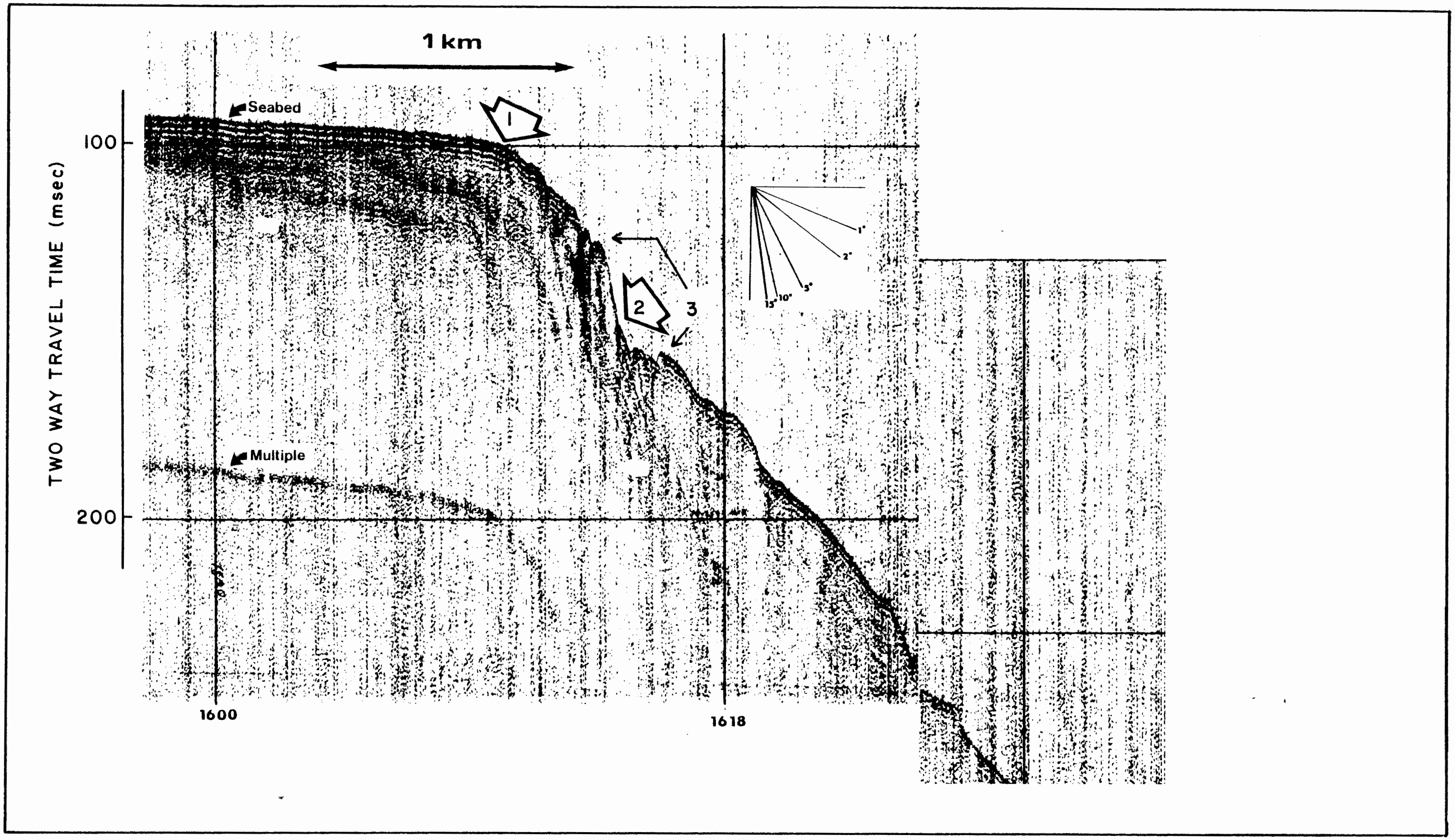


Fig. 8 Type B PLF 1. Shelf Break 2. Echelon Faulting 3. PLFs

Type C - Ice origin features that occur in groups in 30 - 75 m water depth on the shelf east of 136^{o} W. There are two C types: (Fig. 9). C1 are pingos formed in the subsea environment within old lake basins as described above. C2 form similarly but originate beneath ancient lake sediments and seem genetically tied to C1 features.

Type D - Relict and/or littoral zone sedimentation structures. (Fig. 10) Several relict positive-relief features occur on the shelf and include scour mounds, offshor bars, and irregularly eroded highs of old land surface (Unit C). Maximum relief of these is about 10 m. Many of these may have a 3D expression which is not conical.

1.6 CHARACTERISTICS OF MUD VOLCANOES AND MUDLUMPS

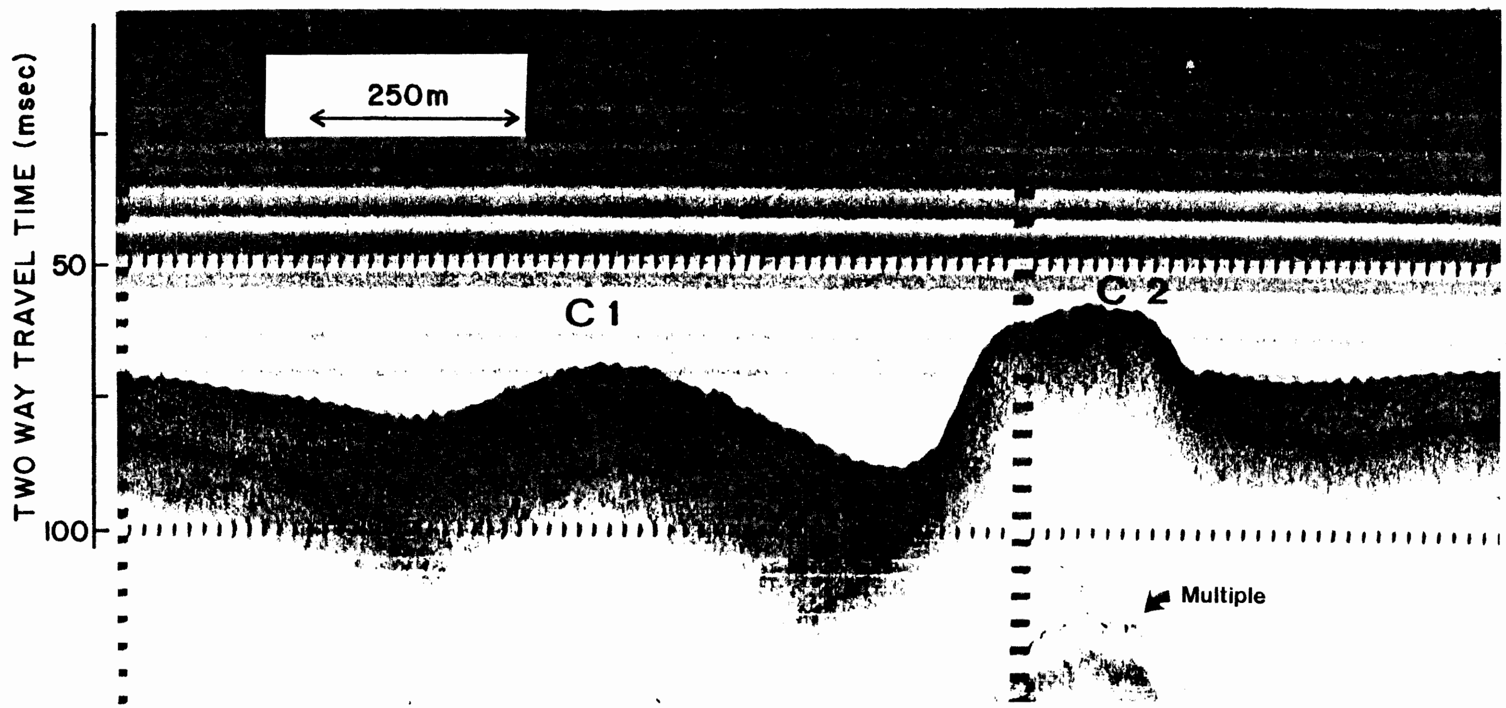
1.6.1 MUD VOLCANOES

It is believed that some PLFs may be mudlumps or mud volcanoes. Following is a generalized summary of the characteristics of mud volcanoes and mudlumps for later comparison with offshore PLFs and in particular the Kopanoar PLF.

Mud Volcanoes are found in many places in the world, including offshore Trinidad, Mississippi Delta, Caspian Sea, Iran and the Georgia region of the USSR. These positive-relief features form on land and on the seabed by the extrusion of viscous mud originating from deeper in the section (Fig. 11).

Based on articles from a literature search, (Newton,1980; Yakabov 1971; Morgan et al., 1968), several characteristics can be listed which are common to many mud volcanoes throughout the world:

1) Mud volcanoes are commonly found in groups.
2) Relief on land is up to 500 m with basal diameters 500-3000 m.



GSC – 12 kHz SOUNDER SECTION TYPES Cl and C2 PLF's

Fig. 9 Type C PLFs

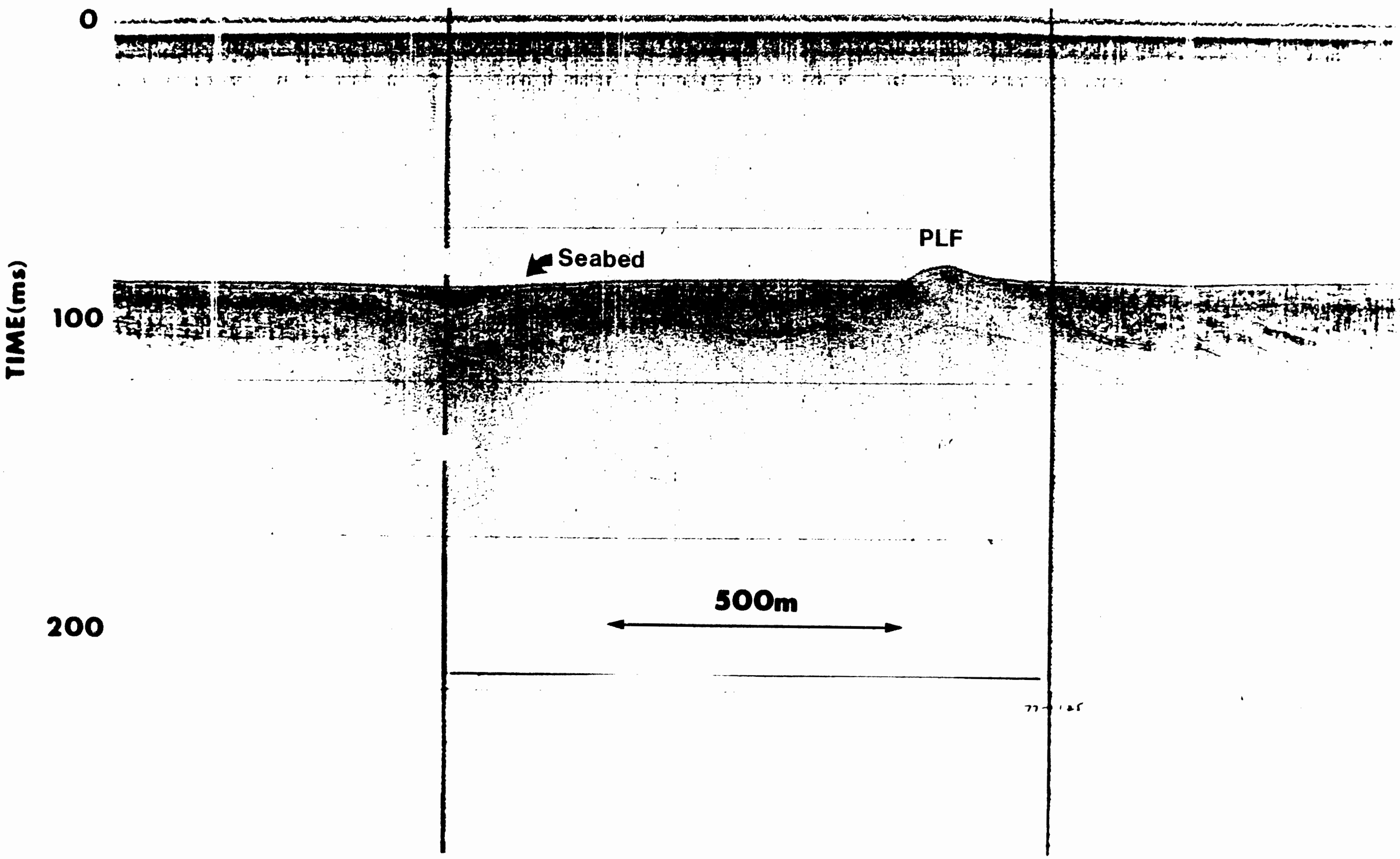


Fig. 10 Type D PLF

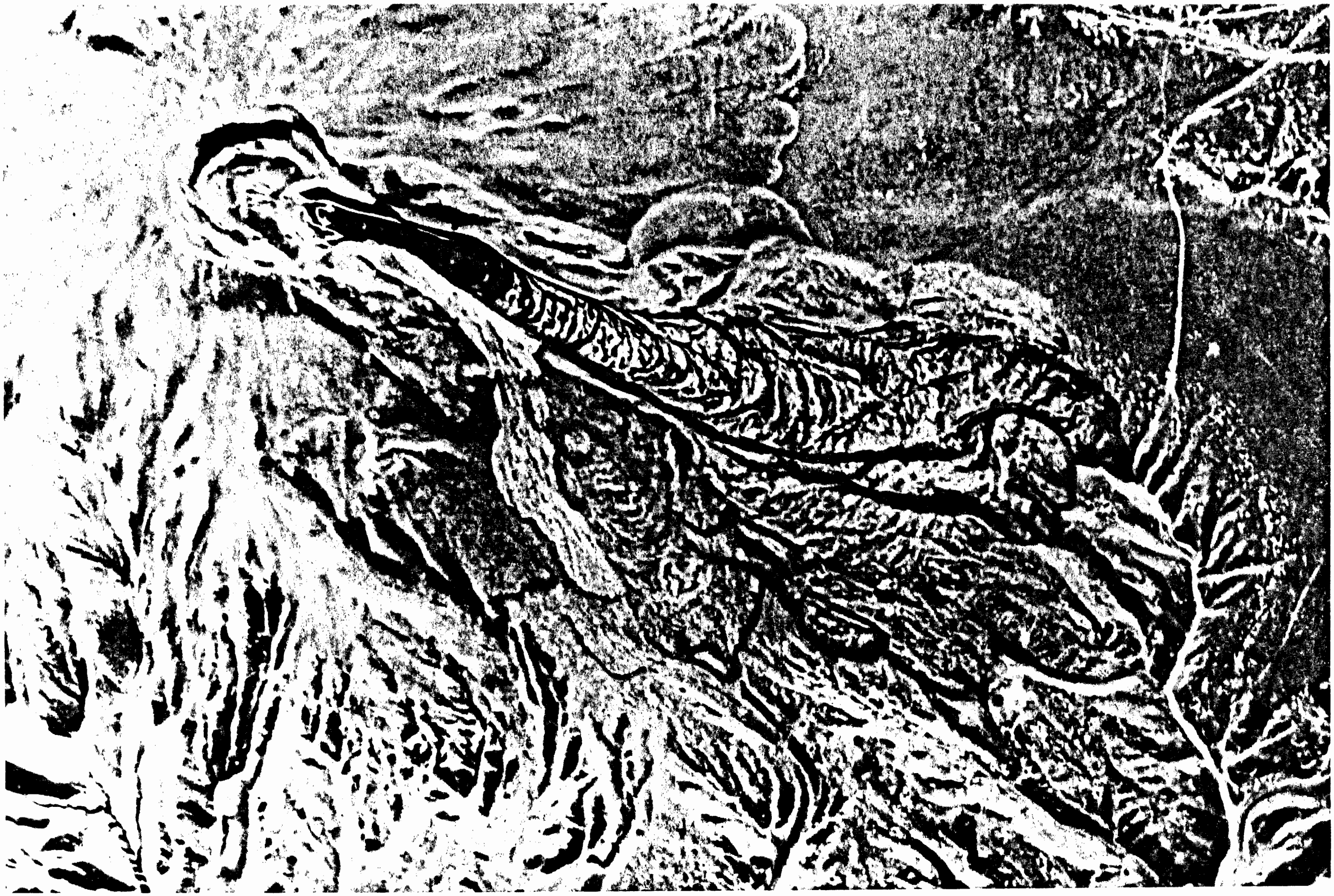


Fig. 11 A Mud Volcano in Russia. Note Road for Scale.

3) Marine versions have a similar shape but lower relief.
4) The cones are usually peaked or truncated.
5) A raised mass of mud surrounds a vent.
6) A broad synclinal basin usually surround them which get filled by sediment.
7) Marine mud volcanoes are always associated structurally with anticlinal folds or faults.
8) The extruded material is viscous mud.
9) Rock fragments up to 2 m in diameter are commonly found in the extruded material
10) Flows of mud breccia are often superimposed.
11) Parasitic mud cones, similar to the main mud volanco but smaller, are commonly associated. These are usually devoid of breccia and have clearly defined vents (Morgan 1968). They exhibit slopes of 1:1 or 1:2 on land.
12) Recurring stages of extrusion are often evident, cycles of which are usually of short duration.
13) Size and slope depend on the frequency of eruption and character of the materials erupted.
14) Gases, connate waters and sometimes traces of oil are almost always present.
15) The gases are up to 98% methane (CH_4) with heavier hydrocarbons and sometimes carbon dioxide (CO_2) nitrogen gas (N_2) hydrogen gas (H_2), hydrogen sulphide gas (H_2S), heavy saturated and unsaturated hydrocarbons and rare light gases.

1.6.2 MUDLUMPS

Mudlumps are the surface expression of diapiric clay masses usually caused by overpressured clay from deeper in the section intruding overlying denser material.

Morgan et. al. (1968) describe the mechanisms by which mudlumps form in prodelta sediments. Though intrusive masses sometimes reach the surface by protruding through overlying sediments, the vertical force is not sufficient to cause eruption, (unlike mud volcanoes). As overpressured mud moves up toward the surface, overlying sediments are raised and basins usually develop laterally where subsidence occurs in response to movement of the material from depth. The raised material is often eroded, infilling the basins.

Though the surface expression of mudlumps mud volcanoes and pingos are similar each forms by a different mechanism and exhibits some unique characteristics which can be compared with those of pingo-like-features.

CHAPTER 2 THE KOPANOAR PLF

In 1980 and 1981 data were collected in an attempt to determine the origin of the Kopanoar PLF. Seven acoustic lines were run over the feature, and two sediment cores were collected, one from the peak and one from the moat of the PLF. The geotechnical properties, biostratigraphy, gas content and pore water chemistry of the retrieved sediments were studied.

2.1 ACOUSTIC MORPHOLOGY AND STRATIGRAPHY

A detailed survey of the Kopanoar PLF was conducted in 1980 when seven passes were made of the PLF with side-scan sonar, 3.5 KH_z sub-bottom profiler and V-fin high resolution seismic system. V-fin Seismic data were obtained only on the last two passes. A trackplot of the seven passes (Fig. 12) can be referred to for the location of specific passes relative to the PLF.

The sub-bottom profile and V-fin seismic systems are both bottom penetrating, medium frequency sound sources which provide a vertical section of the acoustic stratigraphy. The slightly higher frequency of the sub-bottom profiler allows higher resolution but less penetration than the V-fin seismic system. The theory and applications of marine reflection seismic are discussed by Dobrin (1952).

Sidescan sonar utilizes the back scattering effect of high frequency sound waves. This sideways looking sonar essentially provides a plane view acoustic photograph of the seabed. Dark areas coincide with an area of high acoustic reflectivity which is a function of: a) Seabed slope, b) grain size and c) acoustic impedance of the material. Belderson et. al., (1972) present a comprehensive compilation of literature on the development and applications of sidescan sonar.

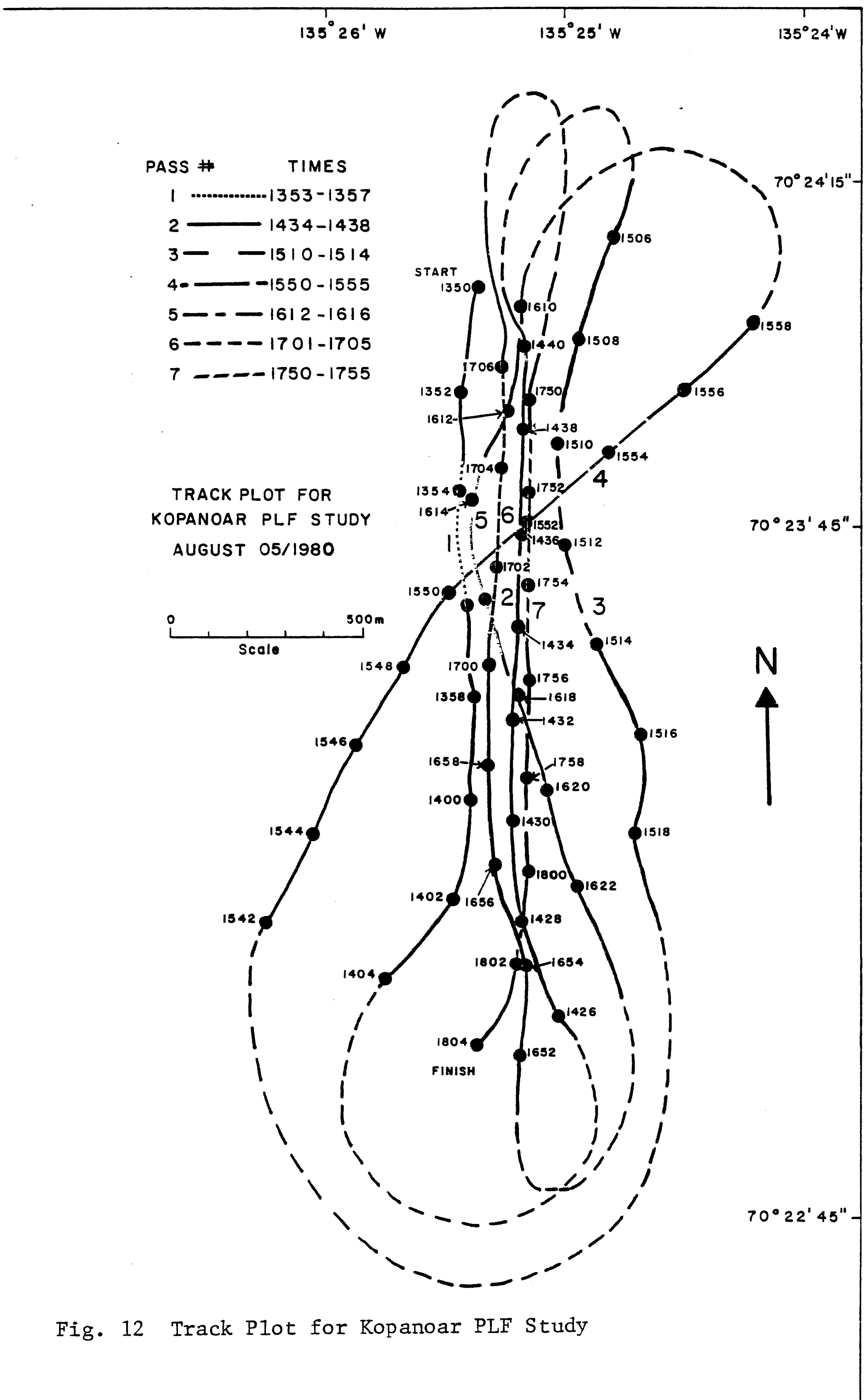


Fig. 12 Track Plot for Kopanoar PLF Study

2.1.1 MORPHOLOGY

Bathymetric profiles drawn from sub-bottom records are plotted on Figures 13 and 14, with north towards the right. The Kopanoar PLF is seen to be an asymmetric dome-shaped hill of about 500 m basal diameter. It is in 55 m (regional) water depth and is surrounded by an annular depression or moat of up to 11 m deep and 200 m across. The PLF rises 16 m from the seabed or 30 m from the deepest part of the moat. Maximum slopes encountered (pass #4) (Fig. 13) are 1:6 (10^{o}).

Side-scan sonar reveals that the slopes are in most places covered by superimposed lobe-shaped structures which resemble mud flows (Figs. 17 and 18) (Coleman and Prior, 1981). There is a widening channel which runs from the peak down the southwest side of the PLF. Flow material fills this channel and also partially infills the moat and scours (Fig. 18). The flow material appears to contain large blocks up to a few meters in diameter. The flows have distinct margins at the contact with the adjacent seabed (Fig. 16). Two small cone-like-features are also evident within this channel, one of which appears to have a distinct round depression in its peak (Figs. 16, 17, 19, and 20). Passes 2 and 7 cross directly over these cones (Figs. 13, 14, 16 and 21); which are 4 and 6 m high with maximum slopes of 1:6 (10^{o}).

From the sidescan data (Figs. 15-21), it is apparent that the area is heavily scoured by ice though the scours do not appear fresh (J.M. Shearer, pers. comm., 1982). The probable water depths below which active scouring only rarely occurs is about 50 m (Shearer, pers. comm., 1982). Though no scouring is evident on the peak of this feature, there is a suggestion of possible scouring on the lower slopes (Fig. 16). At depths shallower than 50 metres from the sea surface some ice scouring on the crest would be expected if this feature had existed for some time.

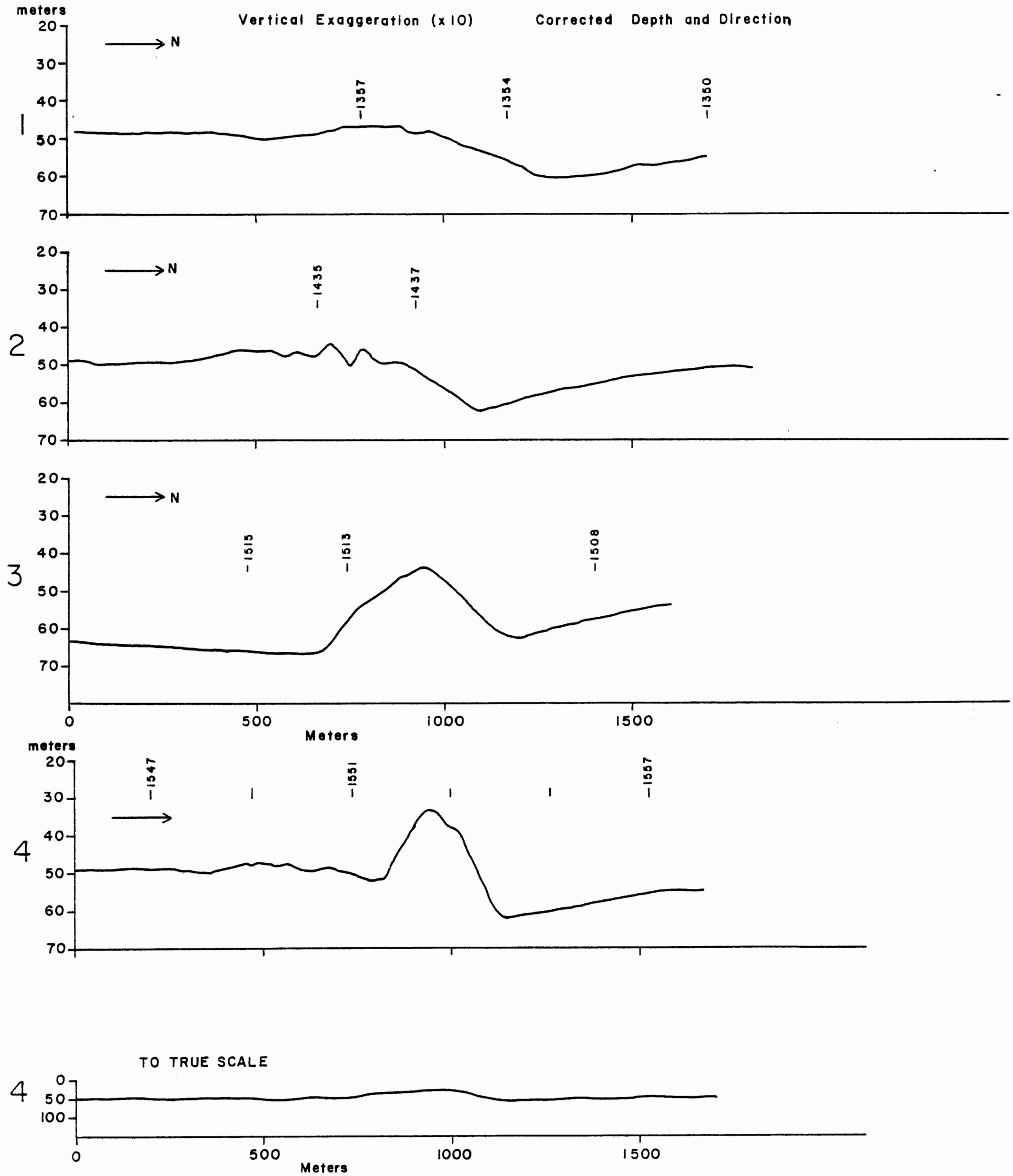


Fig. 13 Bathymetric Profiles of Kopanoar PLF from Passes 1 to 4 (See Fig. 12 for positions of passes relative to the PLF)

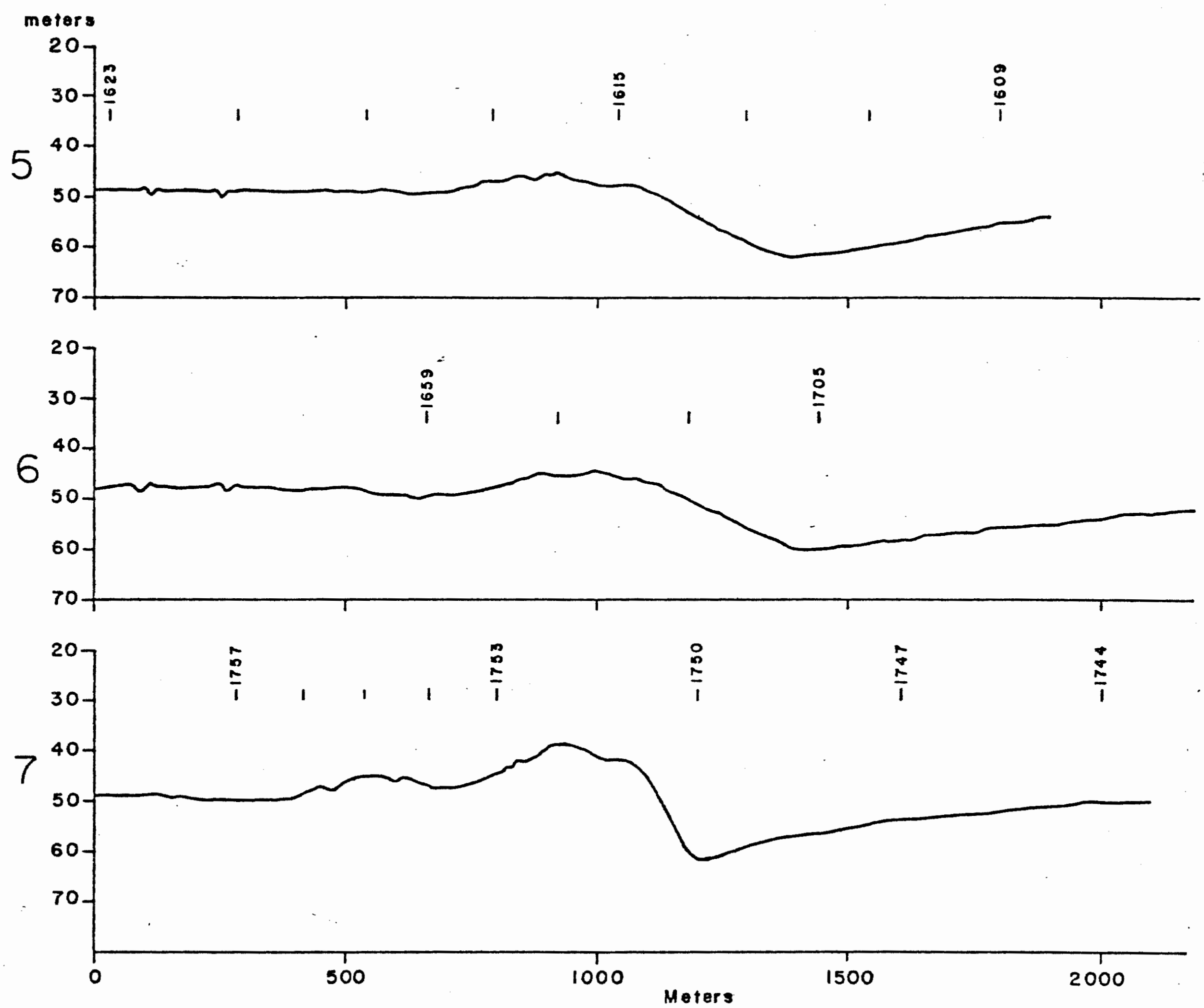


Fig. 14 Bathymetric Profiles of Kopanoar PLF from Passes 5 to 7 (See Fig. 12 for positions of passes relative to the PLF)

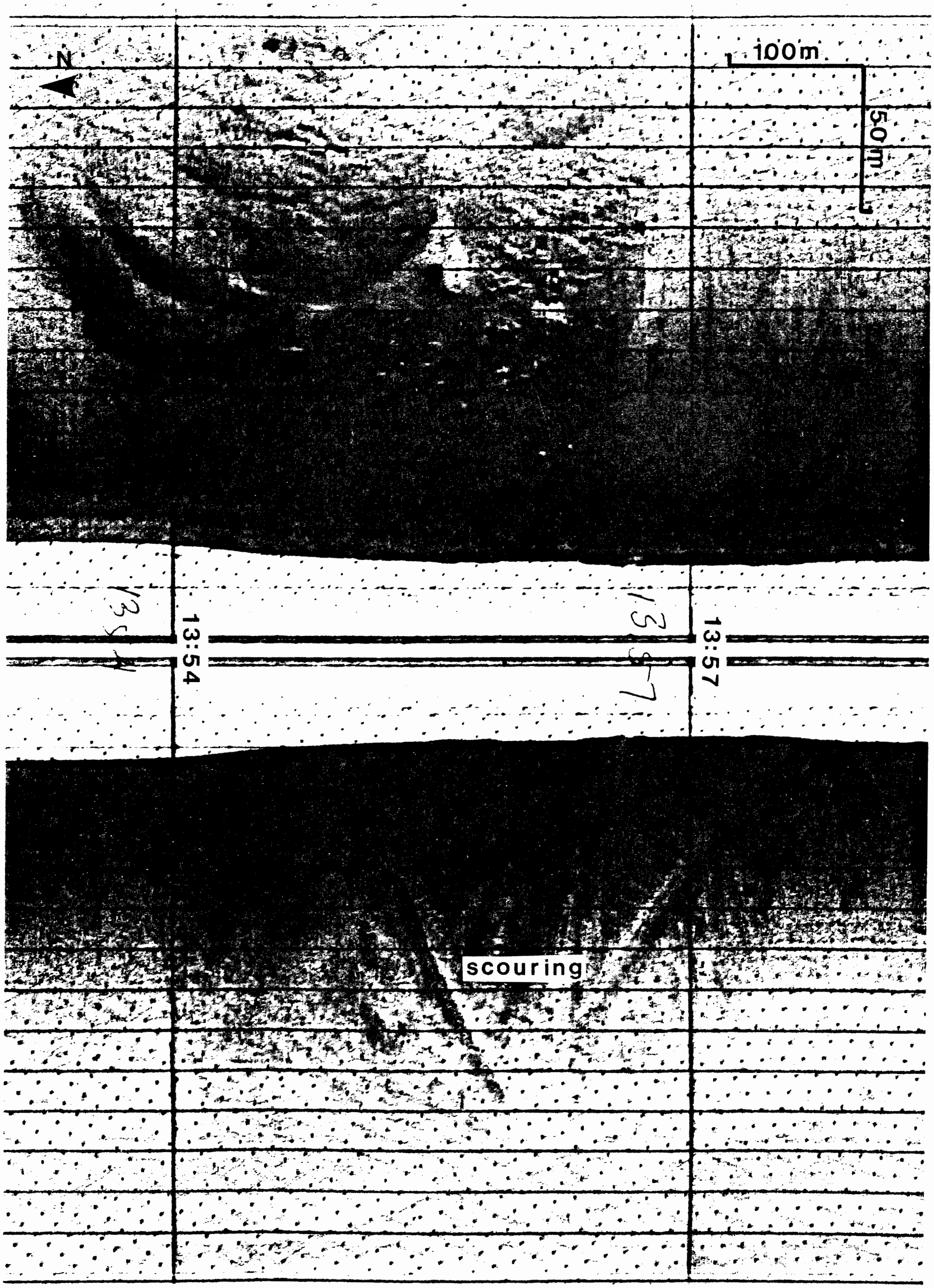


FIG. 15 PASS 1

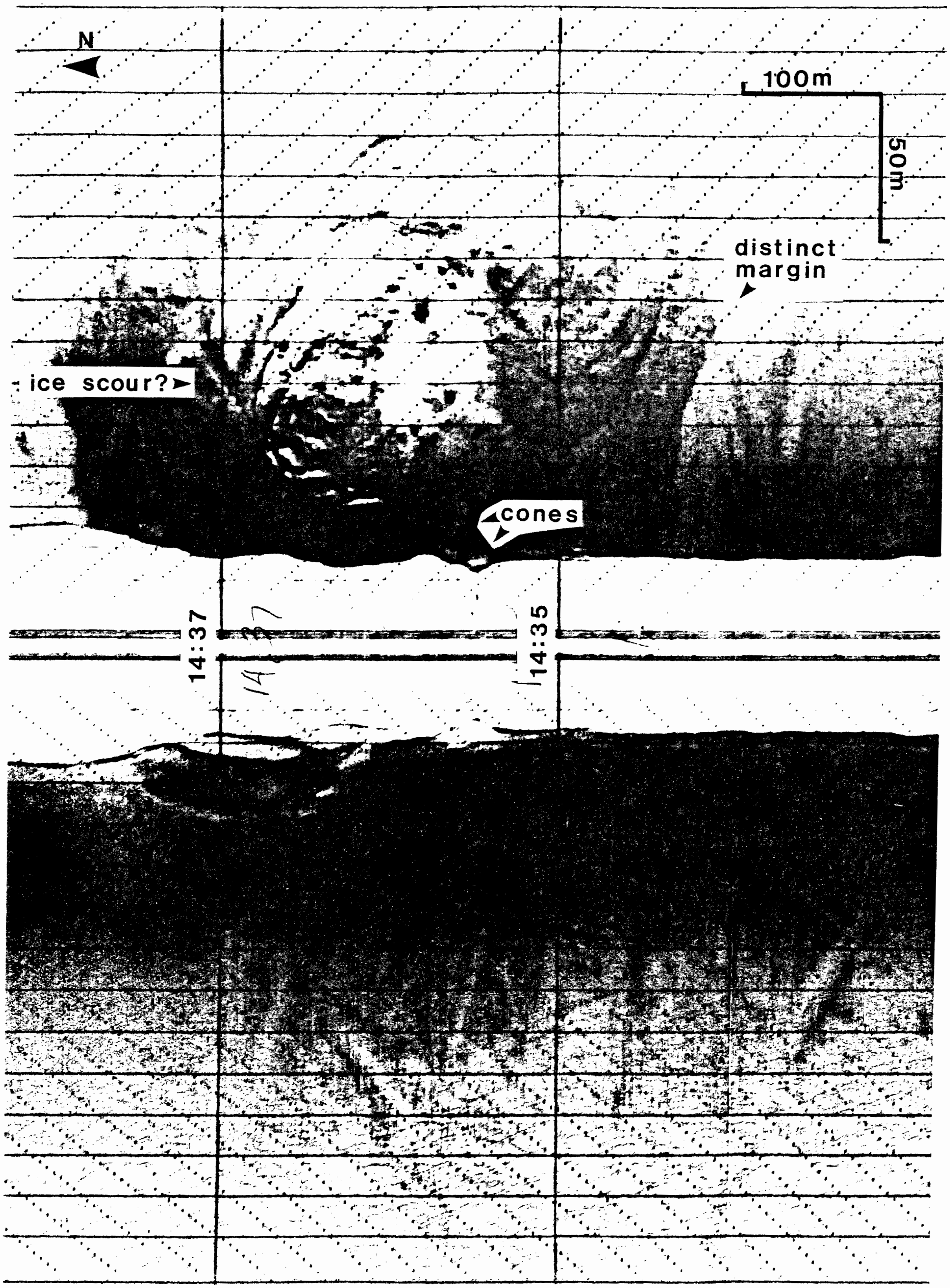


FIG. 16 PASS 2

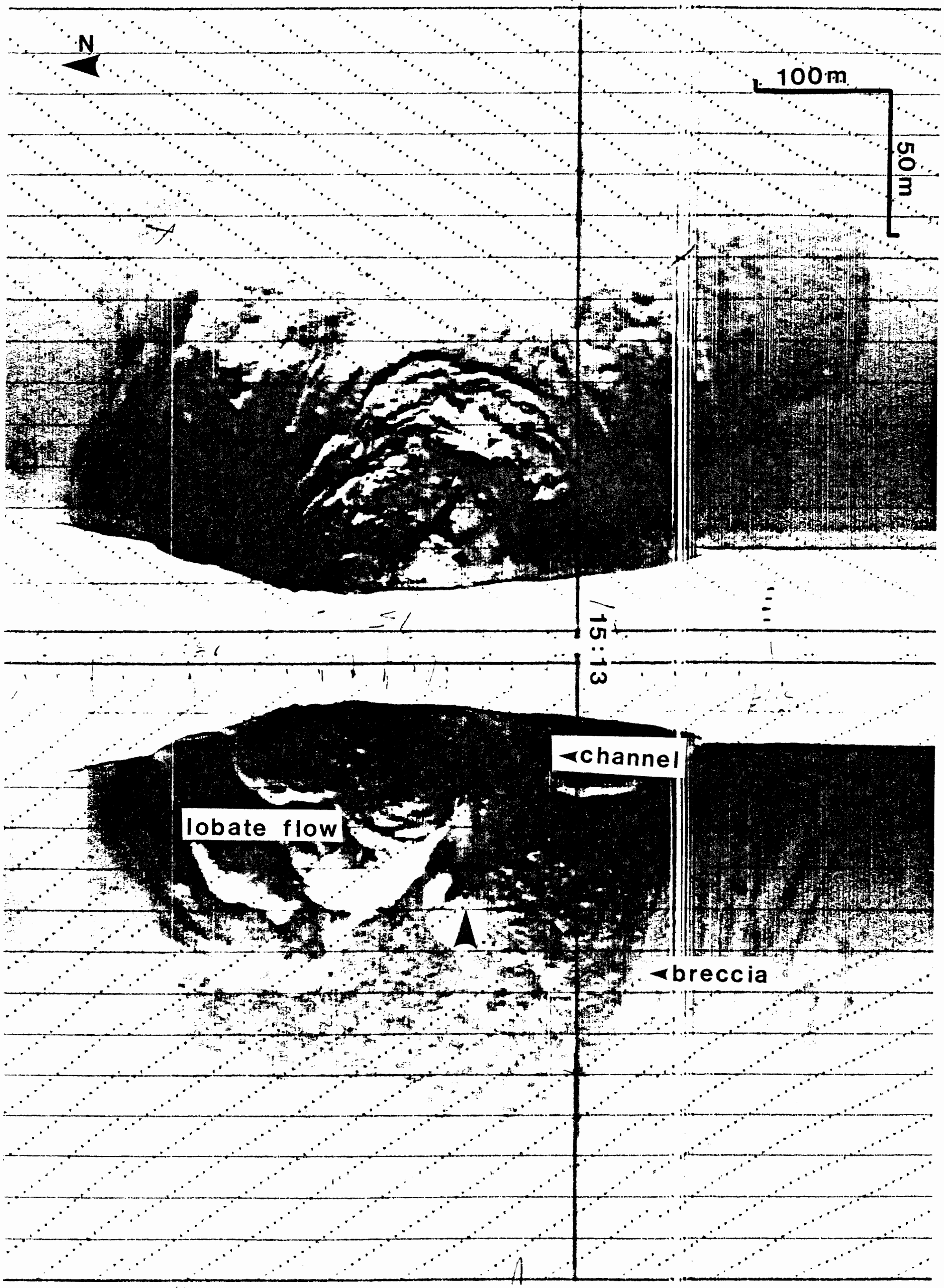


FIG. 17 PASS 3

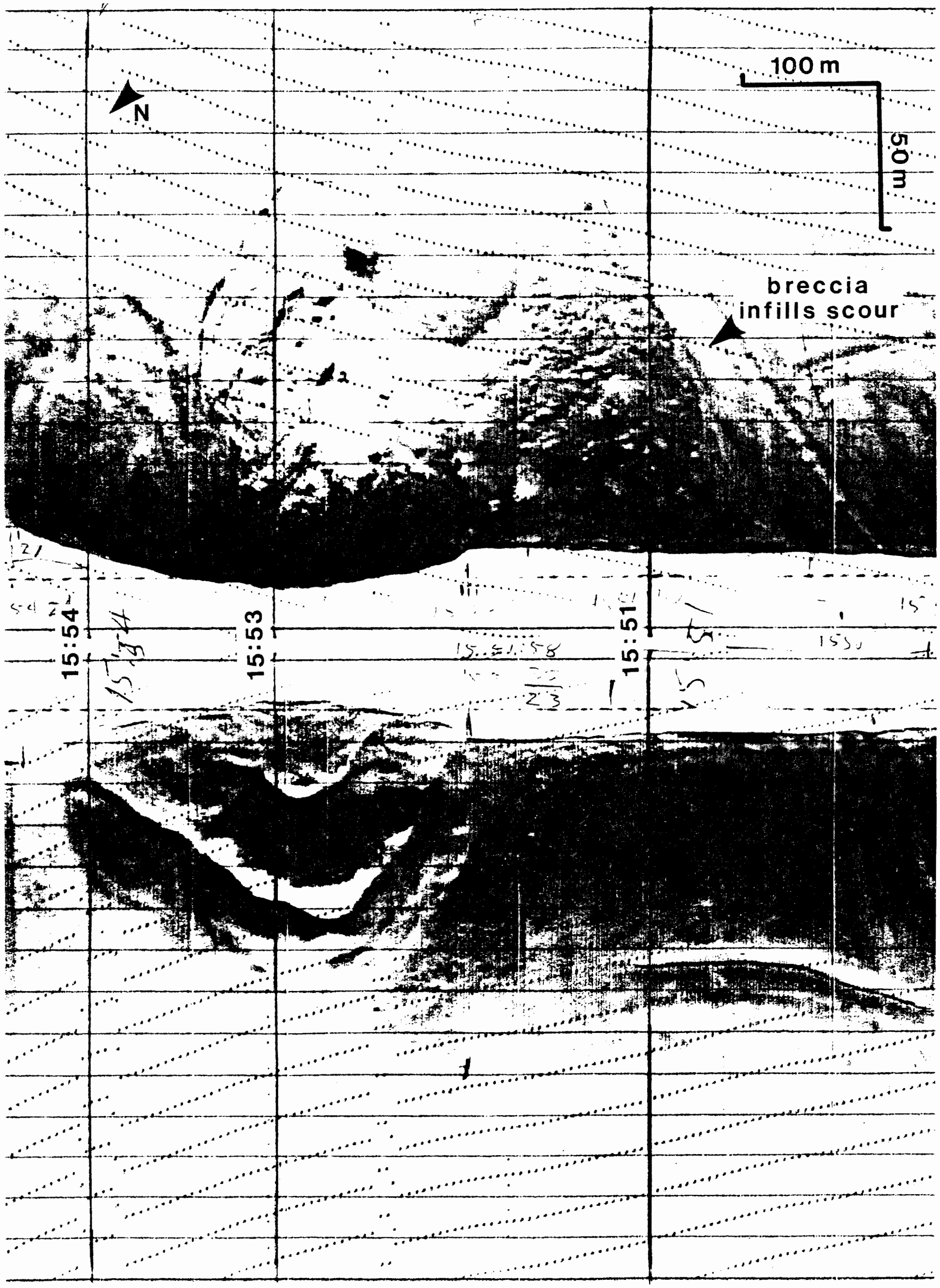


FIG. 18 PASS 4

FIG. 19 PASS 5

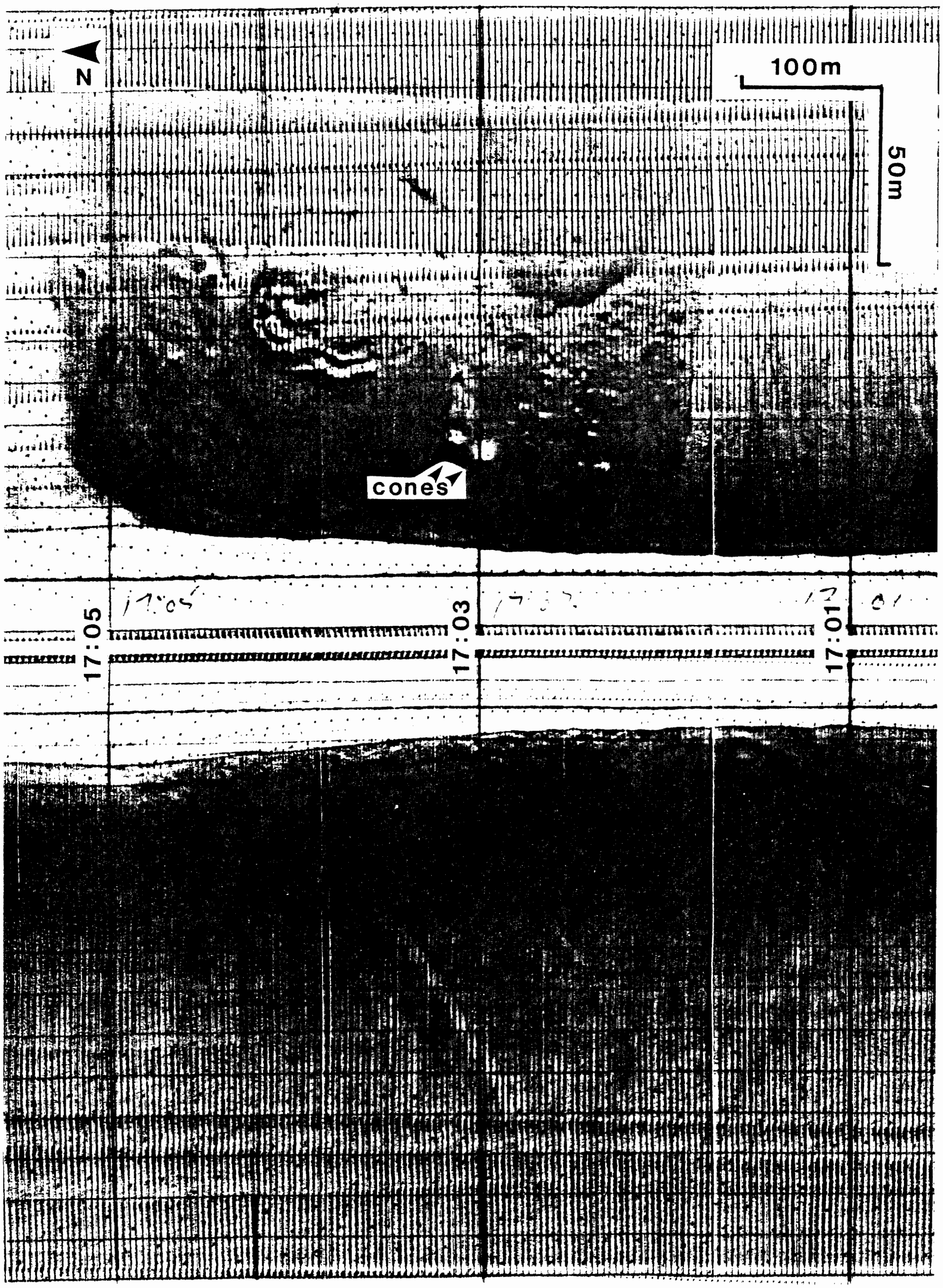


FIG. 20 PASS 6

FIG. 21 PASS 7

2.1.2 STRATIGRAPHY

The regional stratigraphy as outlined by O'Connor (1980) and described above (Fig. 3), is evident on the seismic records of passes 6 and 7 (Figs. 22 and 23). The stratified sediments of the moat are up to 75 m thick (using a velocity of sound in these sediments of 1500 m/s (MacAulay, pers. comm., 1982). They lie well above the unconformity within Unit B and reflectors within these sediments can be traced for several kilometers along the shelf. This contrasts with old lake basins where the sediments would lie directly within a depression in Unit C and any internal reflectors would terminate at the basin margins. In figures 21 and 22 reflectors appear to thicken inward and dip towards the PLF and are broken by multiple growth faults which are down thrown basinwards toward the PLF. The top two reflectors appear to turn up onto the flanks of the feature although it is not clear whether this is a real or an acoustic effect. The lack of acoustic reflectors within and below the peak is most likely due to the diffraction of acoustic energy by the steep slopes or possibly the presence of ice or gas in the core of the feature (O'Connor, 1981).

2.2 SEDIMENTS

Two cores were obtained from the sediments of the Kopanoar PLF: one Benthos gravity core (#8, 117 cm), from the peak of the feature; hereafter referred to as the 'peak' core, and one Benthos piston core (#7, 443 cm), with gravity trigger core (#7T, 150 cm), from the acoustically stratified sediments of the depression surrounding the PLF; hereafter referred to as the 'moat' cores. A plan view of the coring station is shown in Figure 24 and a schematic sketch of core positions in Figure 25.

Cores 7T and 8 were subsampled on board ship at approximately 50 cm

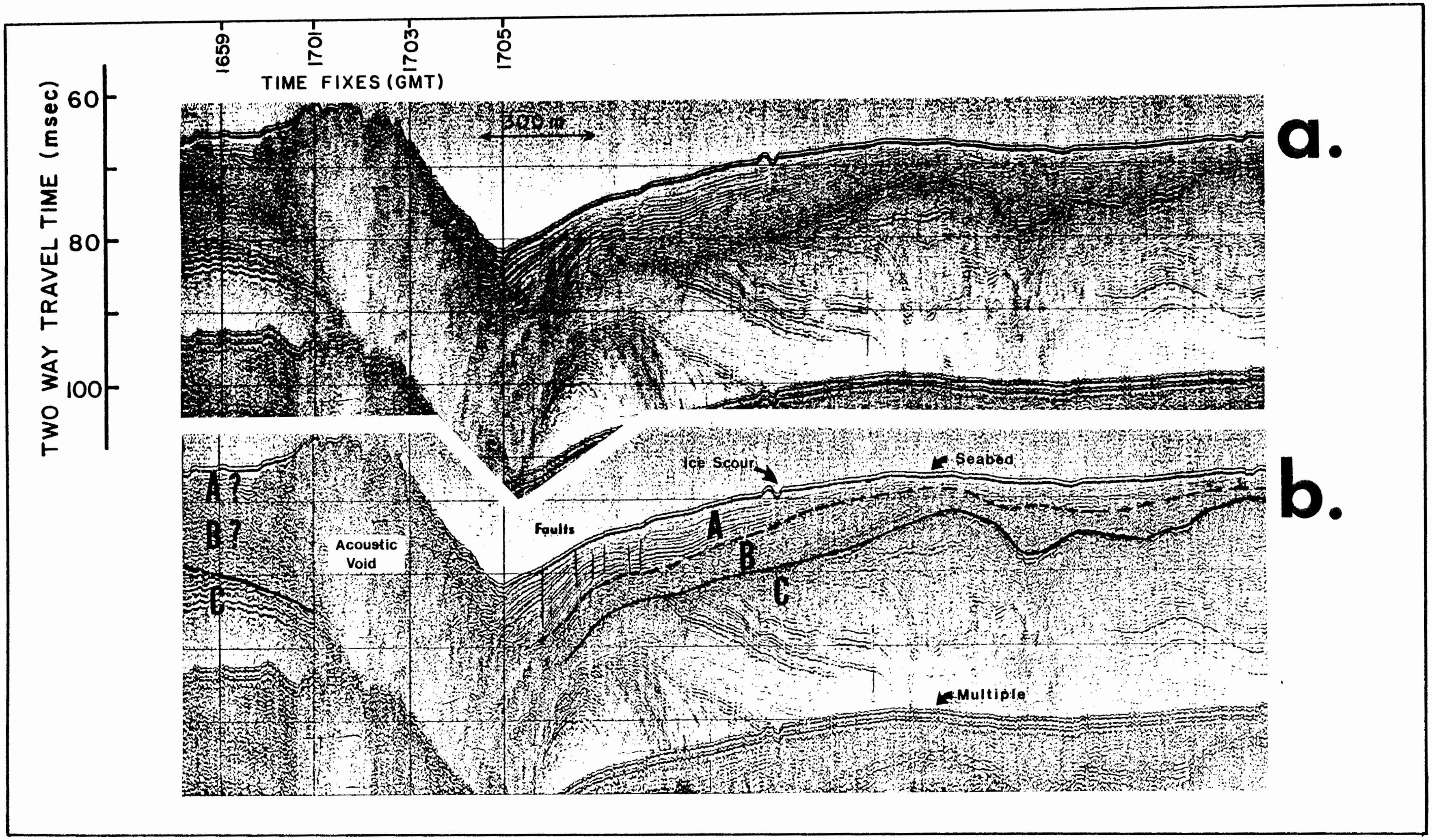


Fig. 22 Seismic Section of Pass 6: Kopanoar PLF a. original b. interpreted

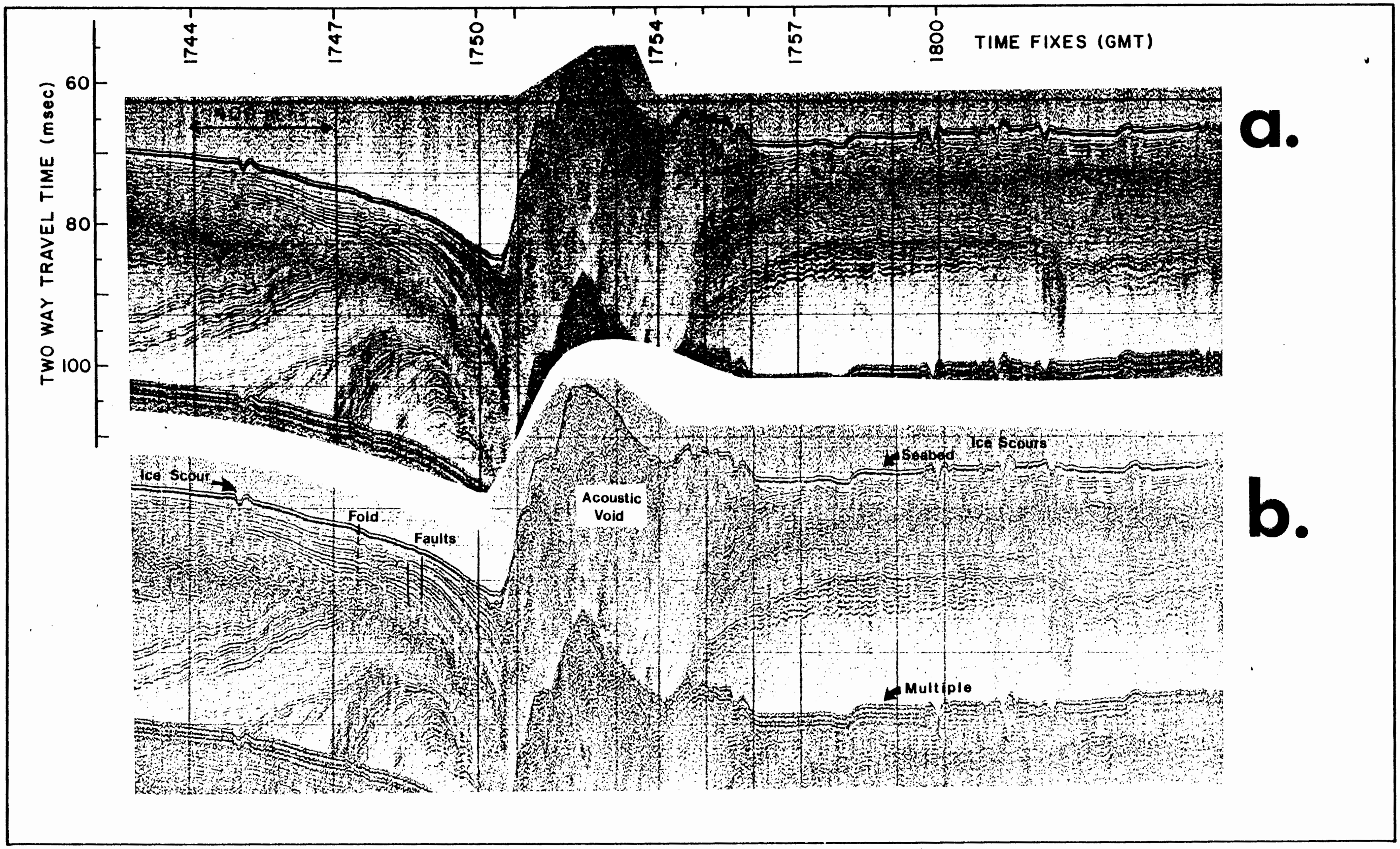


Fig. 23 Seismic Section of Pass 7 : Kopanoar PLF a. original b. interpreted

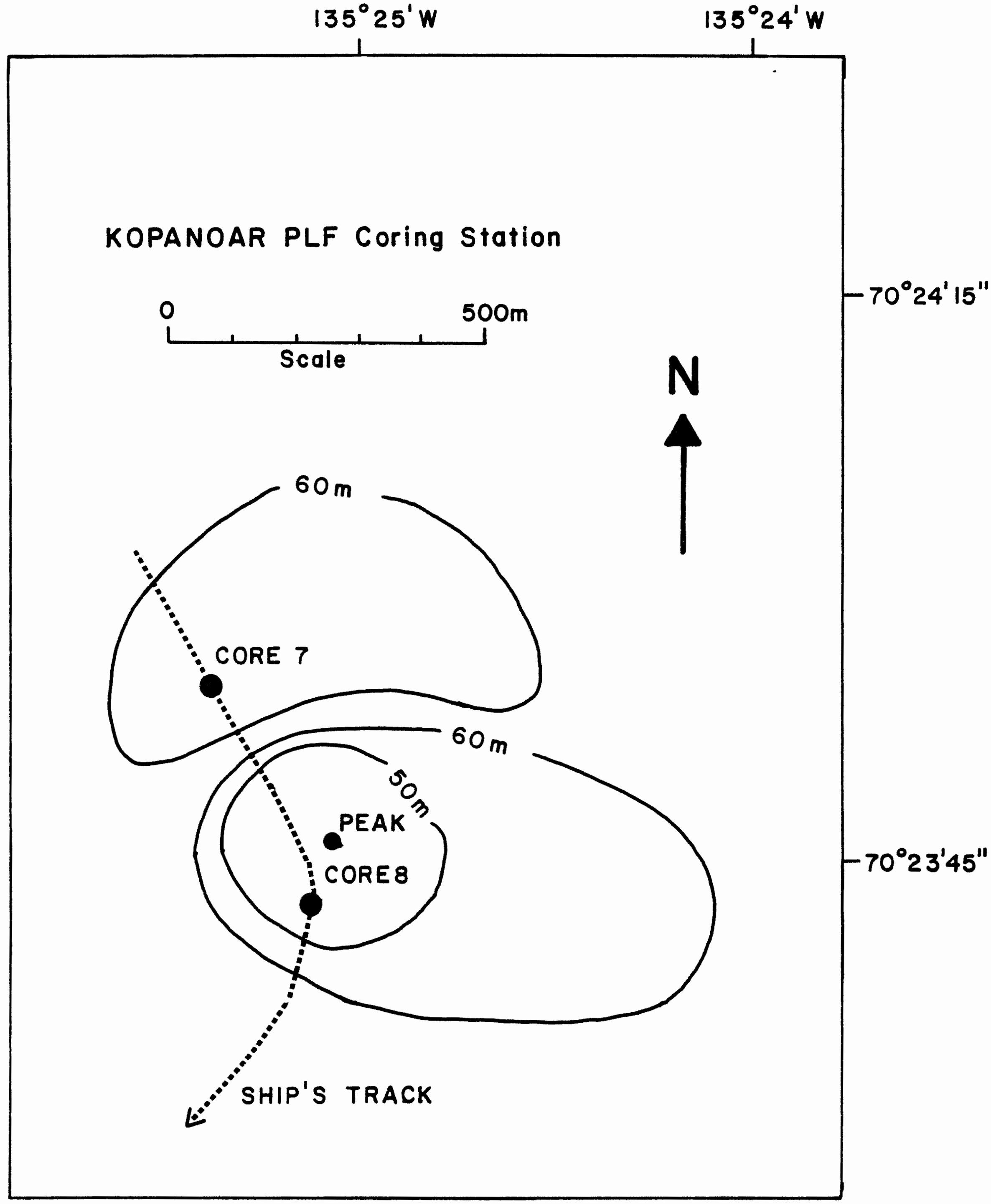


Fig. 24 Kopanoar PLF Coring Station

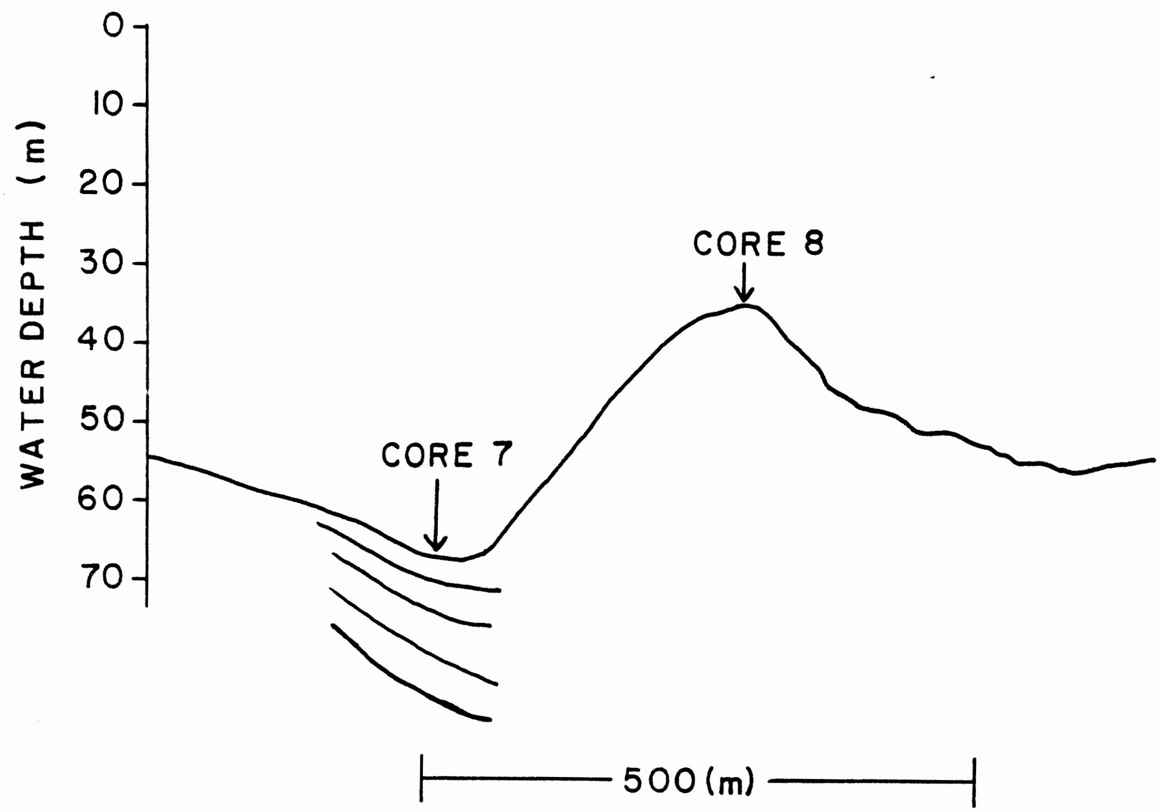


Fig. 25 Schematic Drawing of KOPANOAR PLF Coring Station

intervals for: a) gas analysis, b) ice analysis, c) water content and d) bulk density. At Bedford Institute the cores were split, described, photographed, x-rayed and tested for shear strength at 15 cm intervals. They were subsampled again for pollen, foraminifera, and dateable organic matter. As the samples that had been frozen on board for ice analysis had thawed, these were centrifuged. The pore waters were then extracted and analyzed for major ions.

Although each type of analysis was undertaken to answer specific questions, the more general problem of whether the sediment was deposited under marine or freshwater (lacustrine) conditions was assessed from these data.

2.2.1 CORES

The freshly split cores were photographed, x-rayed and described. Core logs, x-rays and photographs are available at the Atlantic Geoscience Centre, Dartmouth.

Both the peak and moat cores consist mostly of dark gray slightly silty clay.

The moat sediments are relatively undisturbed showing varying degrees of mottling throughout and distinct horizontal colour banding. (Figs. 26 and 27). Within a day of splitting the moat cores, the sediment oxidized and the dark banding was no longer evident. This banding was not generally associated with a lithological change though in some cases dark layers were found to be rich in organic carbon. A few discrete, thin (1-3 mm thick) lenses of graded silt and silty sand are present at irregular intervals throughout the moat cores. The main and trigger moat cores are of similar sediments, however neither the infrequent lenses nor the colour banding can be correlated between the two cores.

The peak sediments are highly disturbed and do not exhibit mottling

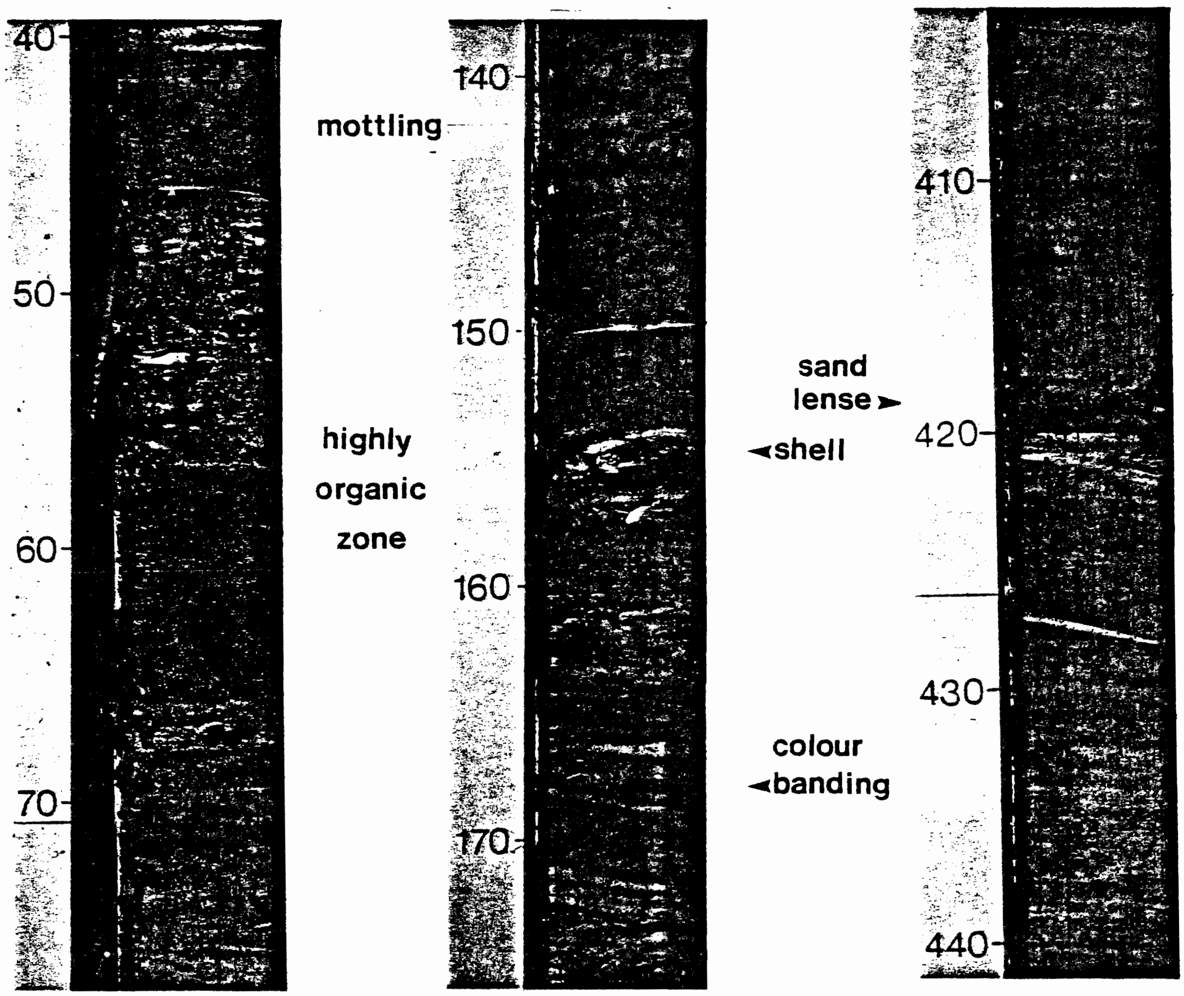


Fig. 26 Representative Photographs of Moat Core (7)

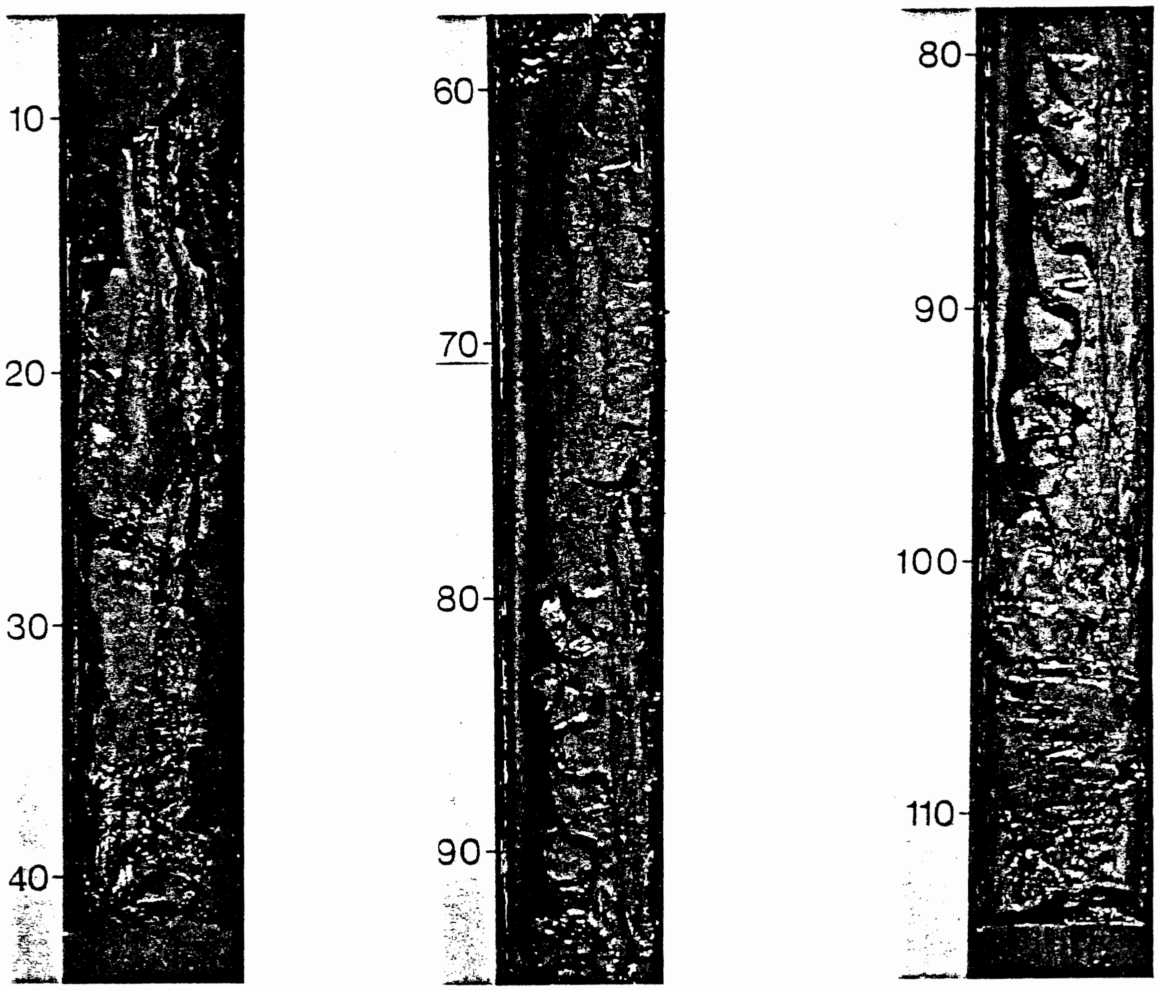


Fig. 27 Representative Photographs of Peak Core (8)

or colour banding (Fig. 27). They contained 30% ice (by volume) when recovered (visual estimate). The ice was in the form of discrete pure lumps about 1 to 2 cm in diameter throughout the core. The sediment contained many small, slightly stiffer, irregular clay balls about 0.25 to 0.5 cm in diameter. (Fig. 28).

2.2.2 CARBON-14 DATES

The moat core (#7) was subsampled at 3 levels for carbon-14 dating. Radiocarbon dating was performed by Beta Analytical Inc., Coral Gables, Florida. The radiocarbon dates were calculated using the Libby half-life of 5568 years. The quoted errors are one standard deviation based on the random nature of the disintegration process. B.P. stands for years before 1950 A.D. and ages were normalized to -25 per mil carbon-13. The results, which are consistent, are shown in Table 2 and Figure 29. Samples were estimated to contain 50-60% reworked carbon which was estimated from the pollen (Mudie, pers. comm., 1982). This would cause an error of about +6,000 yrs in the dates (Olsson, 1968) This results in dates of 3,990, 9,000, and 9,310 yrs B.P. The carbon dates indicate a mean sedimentation rate of 323 cm/1000 yr from 344 to 244 cm depth and 37 cm/1000 yr from 244 to 60 cm in the moat core. Vilks et al. (1979) estimated that sedimentation rates average 3 to 30 cm/1000 yr over most of the outer shelf for the late Wisconsinan and Holocene period.

2.2.3 GEOTECHNICAL ASPECTS

Shear strength, bulk density and water content were measured in the three cores to determine the sediments stress history and to compare these properties between these cores.

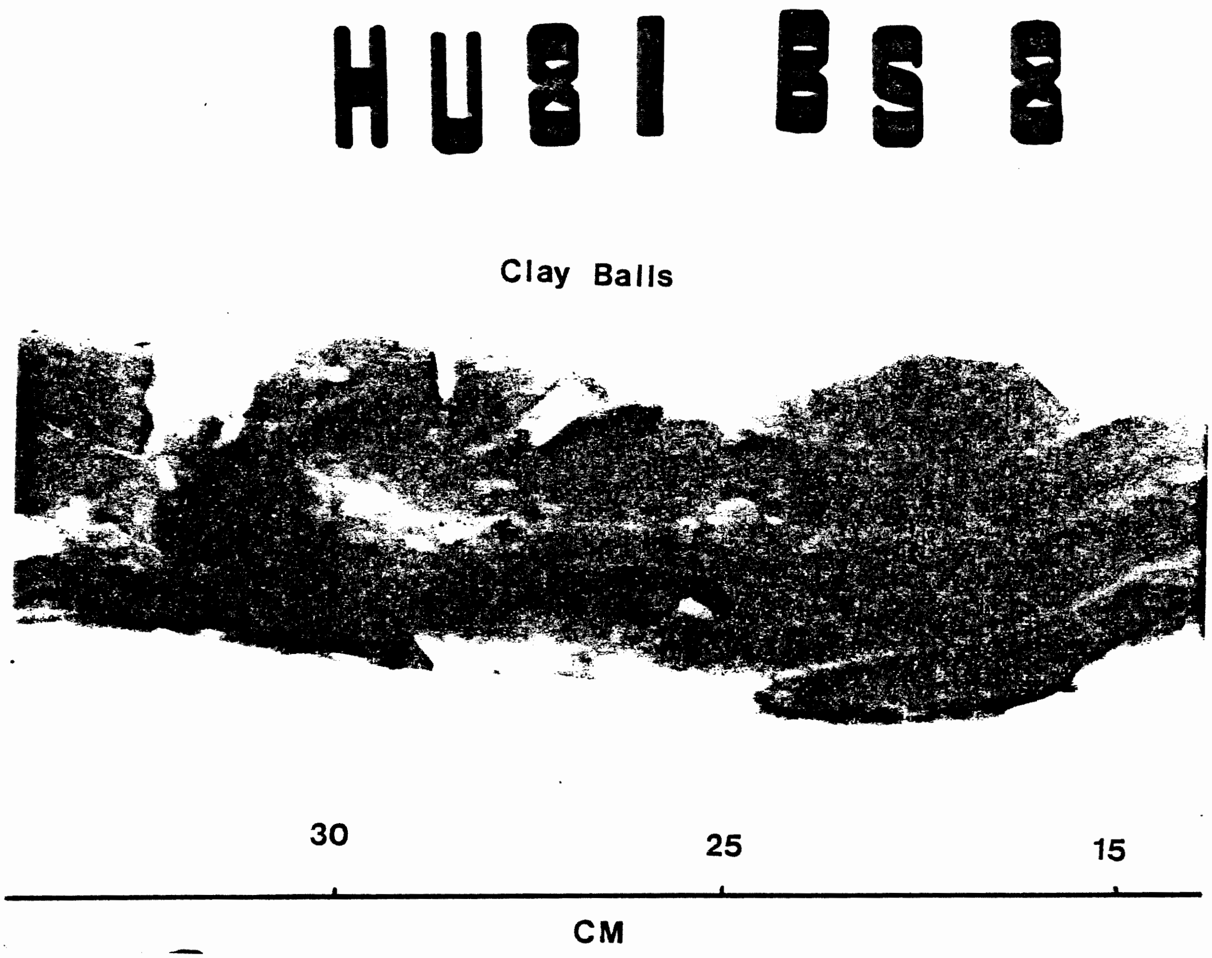


Fig. 28 Representative X-Rays of Peak Core (8)

TABLE 2

RADIOCARBON DATING ANALYSES OF MOAT CORE 7

LAB NUMBER	INTERVAL	C-14 AGE YEARS B.P.	C13/C12	C-13 ADJUSTED RADIOCARBON AGE	ADJUSTED AGE FOR REWORKING (after Olsson, 1968)
Beta-4040	55-65	10000 ± 140 B.P.	-25.57 0/00	9990 ± 140 B.P.	3990 ± 140 B.P.
Beta-4041	238-250	15010 ± 230 B.P.	-25.50 0/00	15000 ± 230 B.P.	9000 ± 230 B.P.
Beta-4042	338-350	15320 ± 210 B.P.	-25.98 0/00	15310 ± 210	9310 ± 210 B.P.

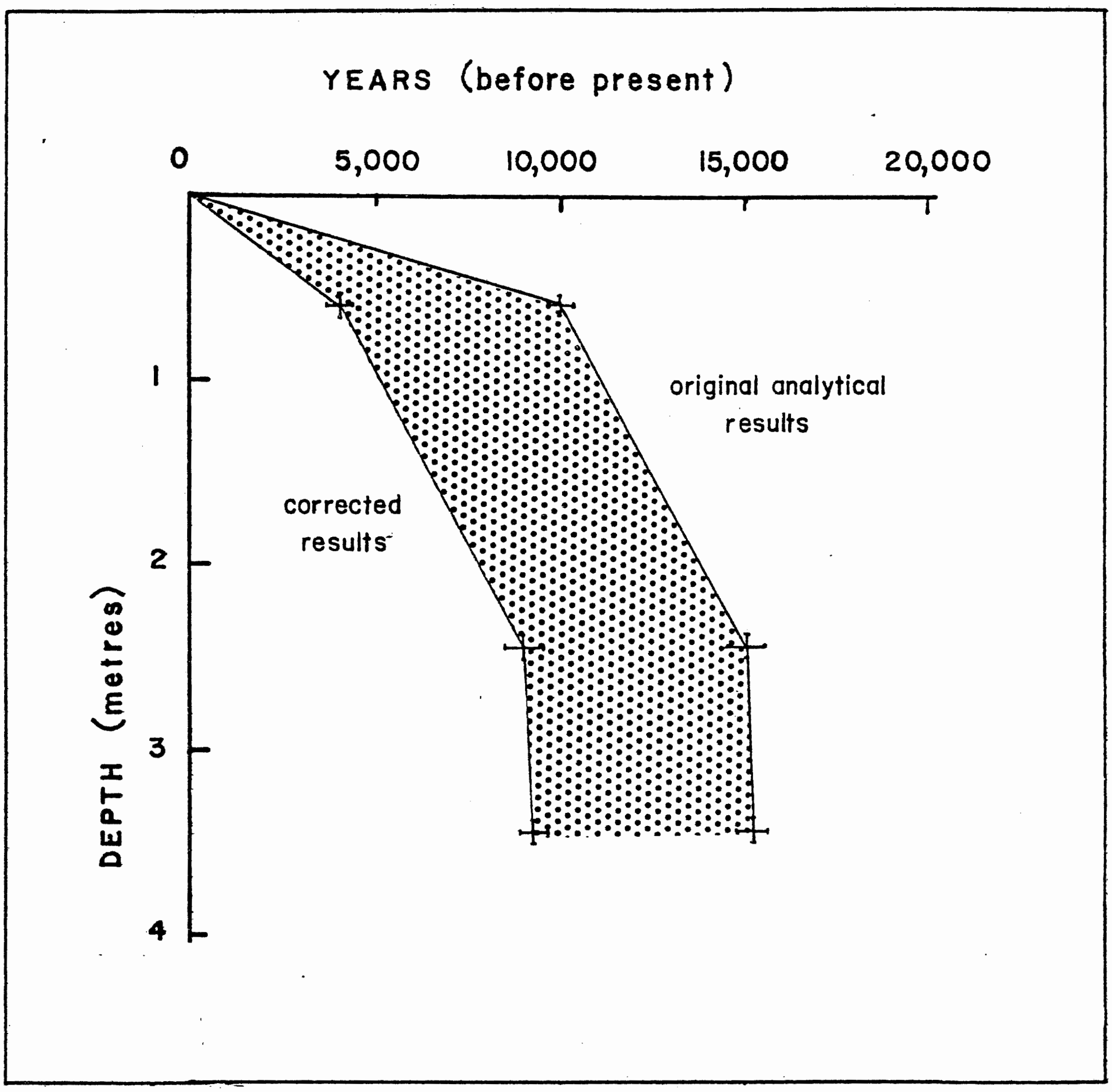


Fig. 29 Carbon Dates

Three samples were extracted by a calibrated sampler from approximately 50 cm intervals in the peak core (#8) and four from the moat core (#7T) at similar intervals on board ship. These were sealed in pre-weighed bottles. At Bedford Institute they were weighed before and after drying to determine bulk density and water content. As well, all three cores were tested at several levels by K. Moran (AGC), with a mini-vane shear testing device in the lab shortly after splitting. They were subsequently tested for water content at the same levels. To measure shear strength a vane was lowered vertically into the relatively undisturbed sediment and turned at a standard rate of .0262 rad/sec (90 deg/min) until the sediment failed. The torque that the sediment exerted on a calibrated spring in the vane shaft was measured and the shear strength determined from an established relationship (Craig, 1978):

$$T = \tau_f \left(\frac{d^2 h}{2} + \frac{d^3}{6} \right) \qquad \text{Eqn. 1}$$

where: T = torque at failure

d = overall vane width

h = vane height

τ_f = shear strength at maximum torque

The sediment was manually remoulded and then tested again in the same manner. The sensitivity of a clay is defined as the ratio of the undrained strength in the undisturbed state to the undrained strength, at the same water content, in the remoulded state (Craig, 1978). The sensitivity of most clays is between 1 and 4. A high sensitivity indicates loss of strength due to the natural structure being damaged or destroyed during remoulding. A low sensitivity may be due to a low undisturbed strength initially. The water content was calculated using equation 2 to correct for an assumed salt content of 35 ppt.

$$W(\%) = \frac{1.03(ww - dw)}{1.035 \times dw - .035 \times ww} \times 100 \qquad \text{Eqn. 2}$$

where: W = % water content
ww = wet weight of sediment
dw = dry weight of sediment

In a normally consolidated clay, bulk density and sensitivity increase while water content decreases with depth of burial. Results of these tests are in Table 3. Undisturbed shear strength (τ_u), remoulded shear strength (τ_r) and sensitivity (τ_u/τ_r) are plotted for cores 8, 7 and 7T in Figures 30 and 31. Bulk density for cores 8 and 7T and water content for all three cores are plotted in Figure 32. Considerable scatter is expected on τ vs. depth and water content vs. depth plots (Craig, 1978). The results show that:

1) Scatter in shear strengths is about $\pm$20 kPa.

2) In the moat core (#7), the bulk density, sensitivity and undisturbed shear strength increase while water content decreases down core as expected (Figs. 30 and 31).

3) In the peak core (#8), the water content increases slightly as bulk density decreases down core (Fig. 32), which is the reverse of that expected for normally consolidated clays.

4) The moat sediments have a generally higher undisturbed shear strength and possibly sensitivity than the two peak sediment tests yielded.

5) The peak core had lower bulk density and substantially lower water content than the moat cores.

6) The limited number of shear strength measurements on the peak

TABLE 3

SHEAR STRENGTH DATA

CORE	DEPTH (cm.)	τ_u SHEAR STRENGTH (kPa)	τ_r REMOULDED SHEAR STRENGTH (kPa)	τ_u / τ_r SENSITIVITY	WATER CONTENT
8	25	25.3	17.2	14.7	56.0
8	98	19.5	11.5	16.9	60.9
7	15				120.1
	40	29.9	11.5	26.0	110.2
	65	34.5	12.6	27.3	120.2
	80	52.9	29.9	17.7	92.5
	95	55.2	21.8	25.3	85.9
	110	39.1	12.6	31.0	93.3
	125	57.5	13.8	41.7	85.7
	150	60.9	10.3	59.1	91.5
	165	52.9	17.2	30.8	109.7
	180	69.0	39.1	17.6	88.0
	195	52.9	23.0	23.0	101.3
	220	64.4	33.3	19.3	91.5
	225	41.4	11.5	36.0	104.1
	248	48.3	14.9	32.4	103.0
	263	58.6	19.5	30.1	95.1
	278	57.5	17.2	33.4	100.8
	305	75.9	16.1	47.1	92.9
	320	85.1	63.2	13.5	87.0
	335	77.0	26.4	29.1	103.6
	350	89.7	27.6	32.5	94.1
	365	78.2	27.6	28.3	
	392	71.3	13.8	51.7	87.7
	407	71.3	34.5	20.7	83.1
	422	87.4	39.1	22.3	88.9
	437	82.8	29.9	27.7	83.5
7T	20	29.9	10.3	29.0	130.0
	35	62.1	27.6	22.5	96.2
	75	44.8	15.0	29.9	108.3
	85	36.8	18.4	20.0	125.5
	120	60.9	27.6	22.0	93.1
	135	25.3	16.1	15.7	116.1

FROM SHIPBOARD SAMPLES

CORE	DEPTH	BULK DENSITY (gms/cc)	WATER CONTENT (%)
8	6	1.68	53.5
	48	1.41	71.7
	113	.99	67.0
7T	6	1.26	139.8
	51	1.53	087.9
	101	1.38	116.6
	150	1.45	96.8

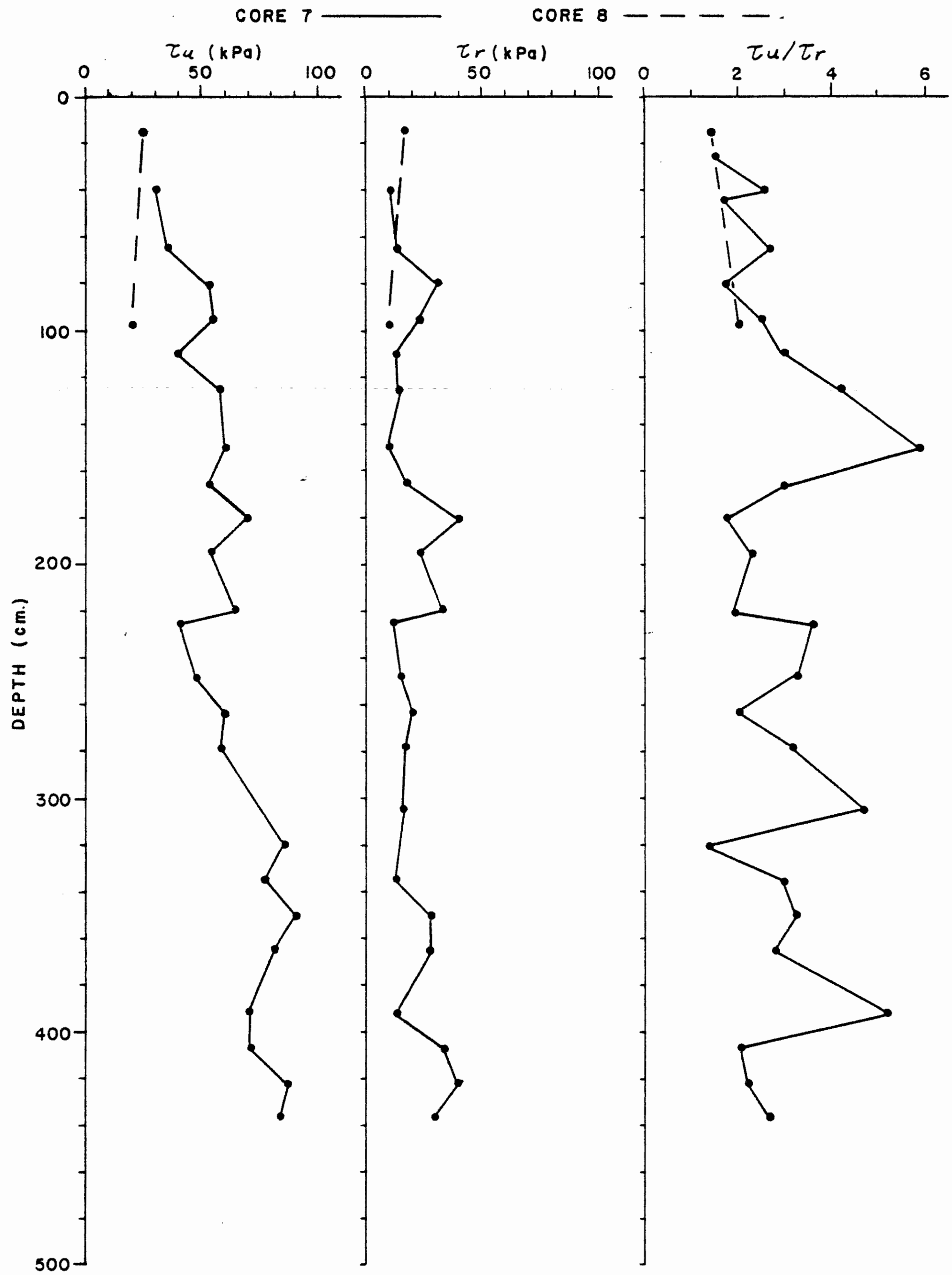


Fig. 30 Undisturbed Shear Strength, Remoulded Shear Strength and Sensitivity for Cores 7 and 8.

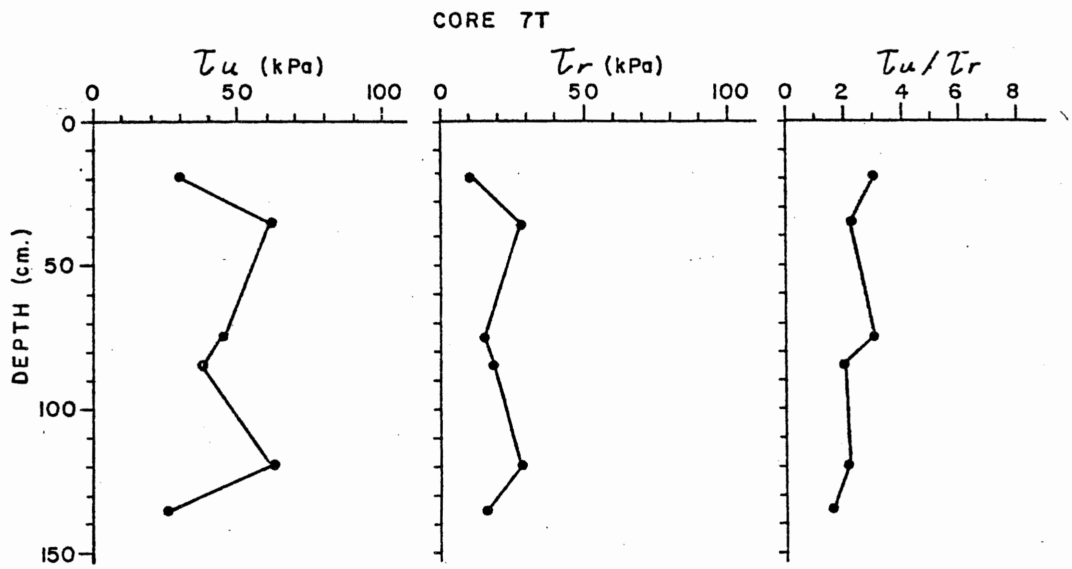


Fig. 31 Undisturbed Shear Strength, Remoulded Shear Strength and Sensitivity for Core 7T.

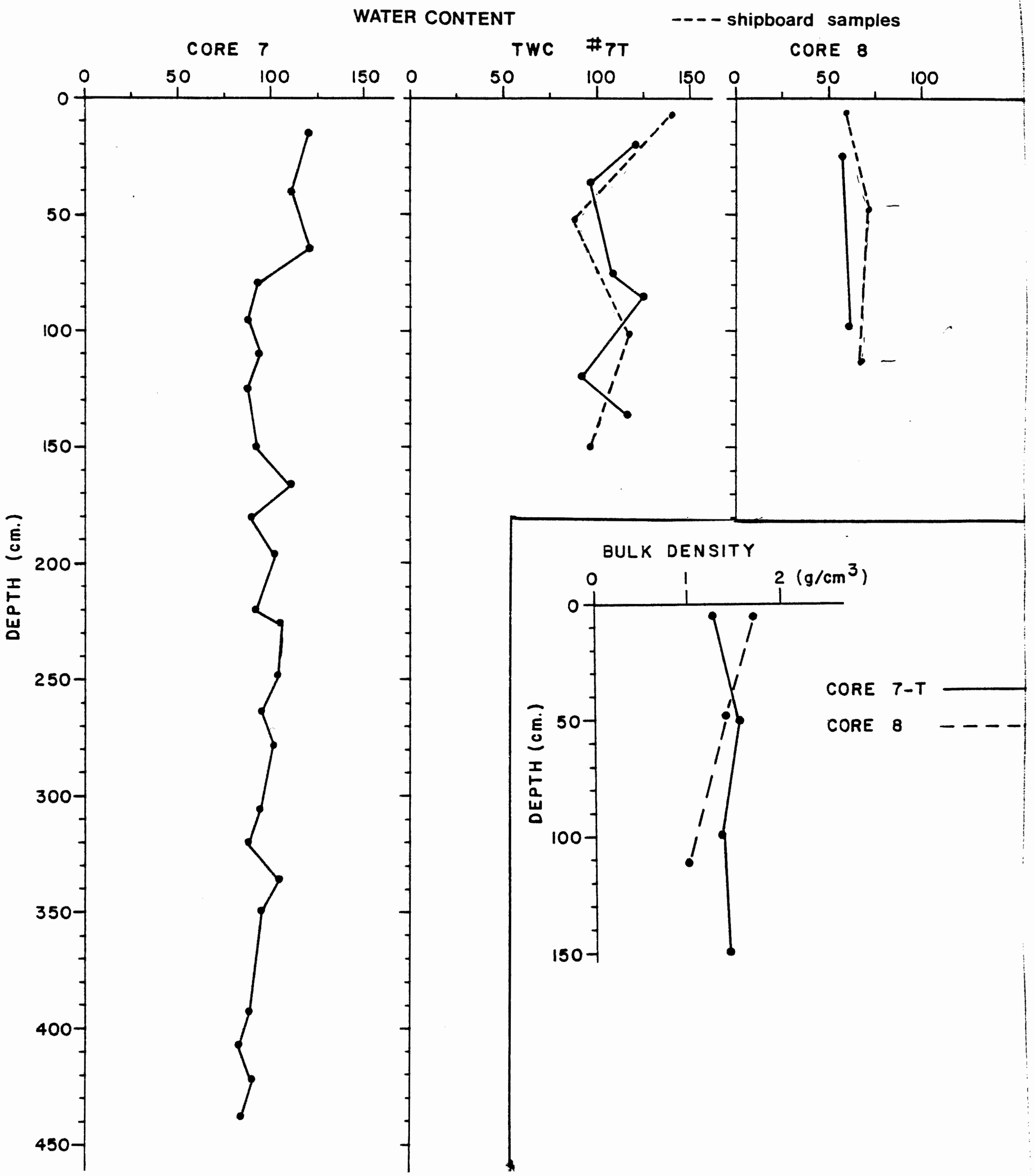


Fig. 32 Water Content and Bulk Density for Cores 7, 7T and 8

core (#8) and the scatter in shear strengths for core 7T defies specific interpretation. However, the rather inconsistent results obtained on core 8 should be noted. This may be reflecting the disturbed nature of the core as observed in section 2.2.1.

2.2.4 GEOCHEMISTRY

Sediment samples from moat and peak cores were extracted to analyze the ice and pore waters for major cation and gas concentrations. Fresh (low salinity), ice and pore waters might indicate a lacustrine or connate water source and the presence of petrogenic gases could suggest an association with thermally more mature sediment at depth.

2.2.4.1 POREWATER

Data from samples taken from three cores (#1,2, and 5) at a second PLF, (Fig. 33 and Station #1 on Fig. 2), are included in this section. These additional data are used to substantiate the interpretation of results at the Kopanoar PLF. Only the three samples from core 8 contained visible ice when retrieved from the sea bed. In these, the ice constituted 30% of the volume in the form of discrete pure lumps of 1 to 2 cm in diameter. Twelve of the fourteen samples were placed in a freezer immediately after being brought on board, the exceptions being the sample from core 7 and the cutter sediment of core 8. These two were simply bagged and stored in a fridge. The twelve frozen samples unfortunately thawed while en route to the lab. Time from thawing to centrifuging was only a few days.

Extracted pore waters were analyzed by R. Fitzgerald (AGC), for major cation concentrations of Sodium (Na^{+}), Potassium (K^{+}), Calcium (Ca^{++}) and Magnesium (Mg^{++}), by Atomic Absorption

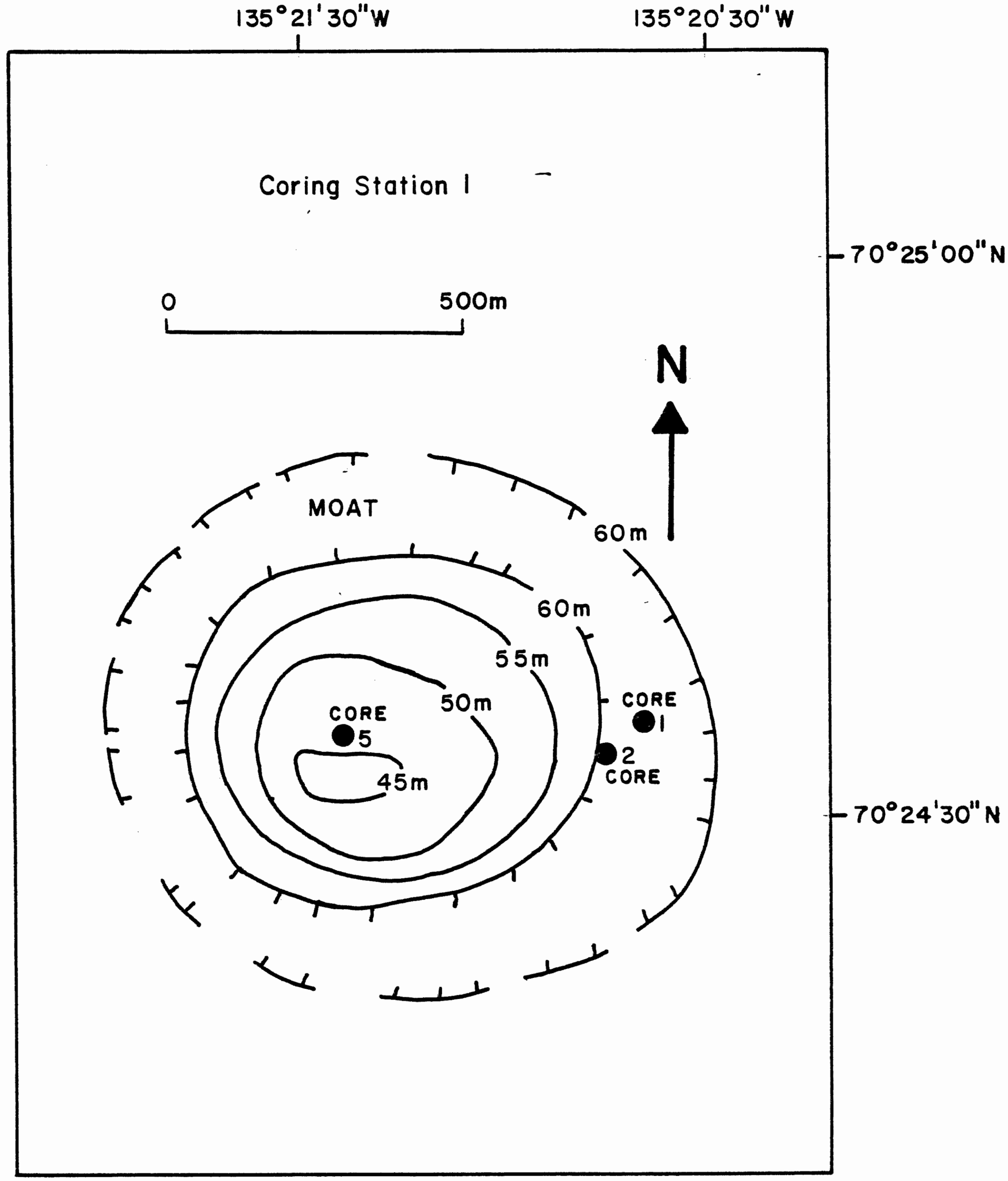


Fig. 33 Coring Station #1

Spectroscopy using one natural water standard in a method described by Cranston, (1974). The method of standard additions is used to determine accurately the major cation composition of Copenhagen seawater (CHSW). Different dilutions of this seawater can then be used as standards to analyze most marine and estuarine waters. By measuring the atomic absorption of the standards before and after that of a given sample, the concentration in the sample can be determined within a 95% confidence level. In seawater the relative proportions of different major cations (ie. Na/K, Mg/Ca, K/Mg, K/Cl) are found to be virtually constant, regardless of their absolute concentrations (Cranston, 1974).

Chemical data are listed in Table 4 and absolute concentrations of K^+, Na^+, Ca^{++} and Mg^+ are plotted in Figures 34 and 35. Note vertical lines at CHSW concentrations. The peak cores (#5 and #8) show significantly lower Na^+, Ca^{++} and Mg^{++} concentrations than their corresponding moat cores.

A standard method of comparing ion concentrations is by chlorinity ratios (ie. Na/Cl, Mg/Cl, K/Cl and Ca/Cl). As these remain fairly constant in seawater an unknown chlorine concentration is calculated from a known ion concentration in the same sample by equating the ratio to that known for a standard:

$$\frac{Na^+(\text{sample})}{Cl^-(\text{sample})} = \frac{Na^+(\text{CHSW})}{Cl^-(\text{CHSW})} \qquad \text{Eqn. 3}$$

where only Cl^- is unknown.

To make fewer assumptions here the sum of the known ion concentrations is used instead of that of a particular ion to calculate a chlorine concentration which is less sensitive to variations of individual ion concentrations:

TABLE 4 **Geochemistry Data**

MAJOR CATION ANALYSIS

CORE	DEPTH (cm)	CONCENTRATION (ppm) (PW)						CHLORINITY RATIOS				NORAMLIZED CHLORINITY RATIOS			
		Na	K	Ca	Mg	ions	Cl ( )	Na/Cl	K/Cl	Ca/Cl	Mg/Cl	Na/Cl	K/Cl	Ca/Cl	Mg/Cl
1	5-10	10200	405	422	1060	12087	18.36	.556	.0221	.0230	.0577	1.01	1.07	1.03	.91
1	95-100	11100	423	531	1190	13244	20.12	.552	.0210	.0269	.0591	1.00	1.02	1.18	.93
1	145	11400	356	597	1210	13563	20.602	.553	.0173	.0290	.0587	1.00	.84	1.30	.93
1	150-154	11000	400	562	1160	13122	19.93	.552	.0201	.0282	.0582	1.00	.98	1.26	.92
1	245-250	11300	352	59.4	1190	12901	19.60	.577	.0180	.0303	.0607	1.05	.87	1.35	.96
1	296-303	11300	324	629	1120	13373	20.31	.556	.0160	.0310	.0551	1.01	.78	1.38	.87
2	117	10300	408	465	1130	12303	18.69	.551	.0218	.0249	.0605	.998	1.06	1.11	.95
2	117 (cutter)	10200	437	425	1040	12102	18.38	.555	.0238	.0231	.0566	1.01	1.15	1.03	.89
5	4-8	8300	378	241	560	9479	14.40	.576	.0263	.0167	.0389	1.05	1.30	.75	.61
5	10-16	9360	449	325	789	10.923	16.60	.564	.0270	.0196	.0475	1.02	1.31	.88	.61
7	443	9120	416	368	965	10869	16.50	.553	.0252	.0223	.0585	1.00	1.22	1.00	.98
8	5-10	8180	254	243	608	9285	14.10	.580	.0180	.0172	.0431	1.05	.87	.77	.68
8	117	5380	147	133	312	5972	9.07	.593	.0162	.0141	.0344	1.07	.79	.66	.54
8	117 (cutter)	5690	149	163	359	6361	9.66	.589	.0154	.0169	.0372	1.06	.75	.75	.59
CHSW		10700	400	435	1230	12765	19.39	.552	.0206	.0234	.0634	1.00	1.00	1.00	1.00
RECALCULATED															
8	117	9576	262	237	555	10630	16.15	.593	.0162	.0147	.0344	1.07	.79	.66	.54

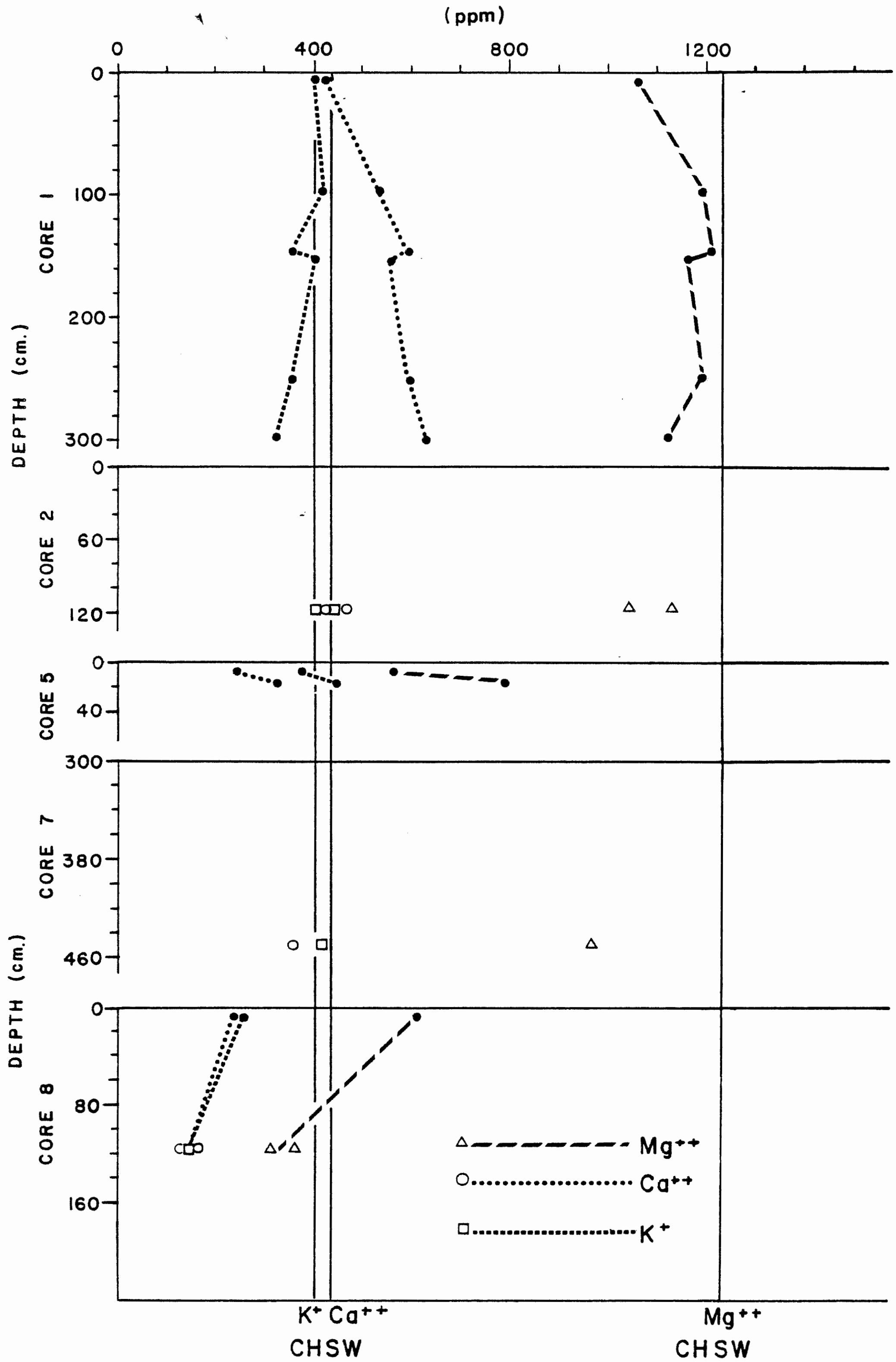


Fig. 34 Pore Water Data (K^+, Ca^{++} and Mg^{++})

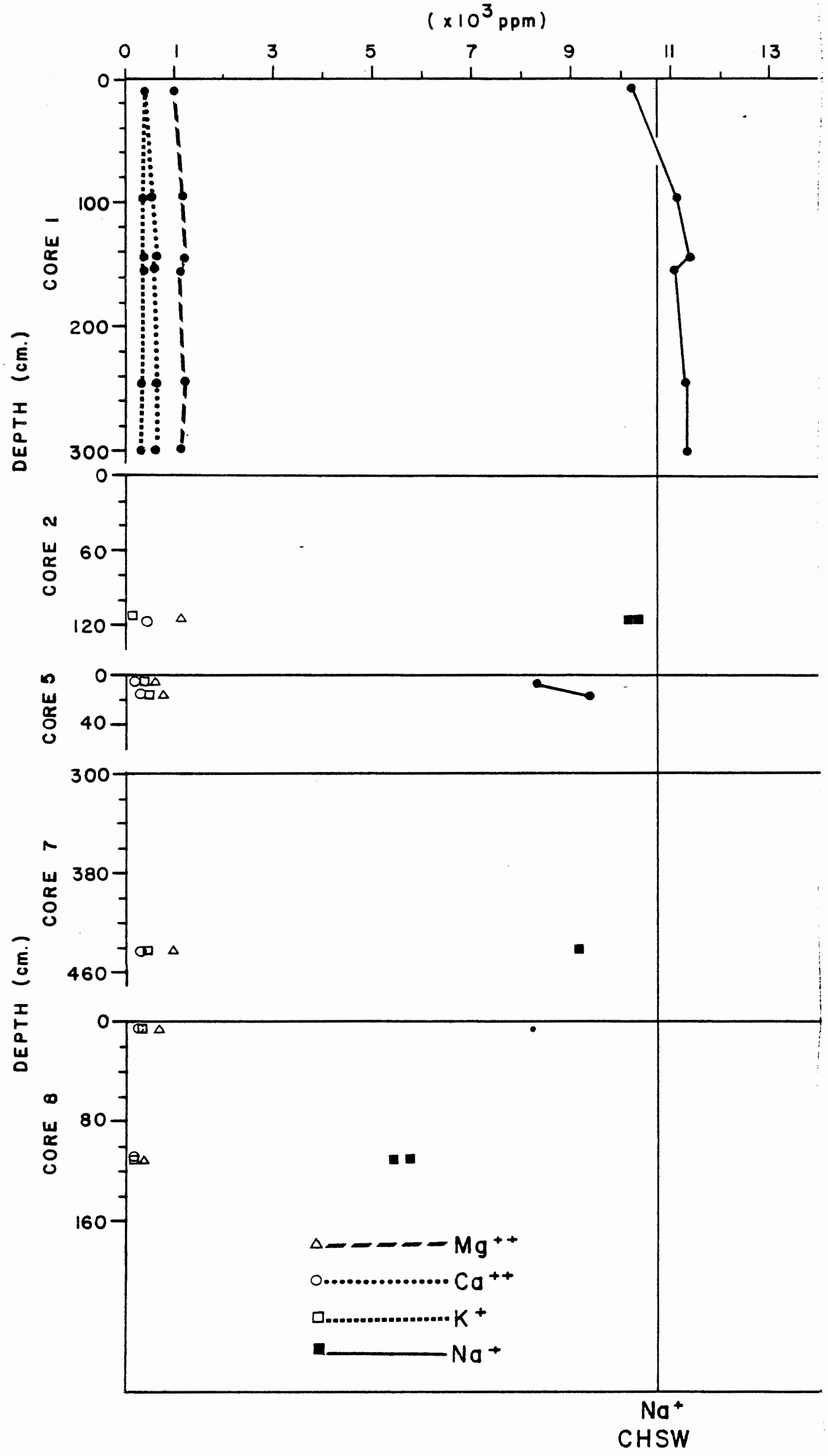


Fig. 35 Pore Water Data (K^+, Na^+, Mg^{++} and Ca^{++})

$$\frac{Na^{+} + K^{+} + Ca^{++} + Mg^{++}\ (CHSW)}{Cl^{-}\ (CHSW)} = \frac{Na^{+} + K^{+} + Ca^{++} + Mg^{++}\ (PW)}{Cl^{-}\ (PW)}$$

where: CHSW = Copenhagen Seawater
PW = Porewater
and only Cl^{-} (PW) is unkown

Cl^{-}(PW) is then used for each sample to calculate chlorinity ratios (Na/Cl etc.). These are normalized by CHSW chlorinity ratios from the literature (Horne, 1969) . Results are listed in Table 4

1) Normalized chlorinity ratios for Ca^{++}, Na^{+} and Mg^{++} from the three peak core 8 samples are 13 to 46% lower than CHSW.
2) In peak core 5 the normalized Mg^{++} and Ca^{++} chlorinity ratios are also anomalously low though the K^{+} ratio is 30% high.
3) The bottom two samples of moat core 1 have low K^{+} and high Ca^{++} ratios.
4) The cutter sample from 117 cm in core 8 was never frozen and yielded close normalized ratios to the other sample from 117 cm of core 8 which had been frozen. This would suggest that the freezing and subsequent thawing of most of the samples has had little or no effect on the relative cation ratios.

During the pore waters residence time in the sediment significant alterations from original chlorinity ratios can be caused by several mechanisms (D. Buckley, pers. comm., 1982):

1) Contamination reactions taking place within sediments such as reduction of organics by bacteria to form gypsum which

dissociates easily to raise the Ca^{++} concentration in the water. This usually takes weeks to years to become significant

2) Concentration of some ions by freezing and possibly subsequent migration or diffusion of this brine away.

3) Mixing with fresher water (from deeper in the section?) having different cation ratios.

4) Influence of gas within the sediments on cation concentrations (Hesse, 1981).

Using the facts that the ice constituted 30% of the total volume and that the space occupied by the ice decreases 9% in volume when it melts (A. Judge, pers. comm., 1982), it can be calculated that of the total water extracted 44% was from melted ice and 56% was interstitial pore water. Concentrations and chlorinity ratios can then be recalculated assuming there were no cations present in the ice. There is no change in the ratios of course but absolute concentrations can still be seen to be much lower than those of the moat pore waters (Table 4).

2.2.4.2 GAS ANALYSIS AND ORGANIC CARBON

Immediately on recovery, moat core (#7T) and peak core (#8) were subsampled at approximately 50 cm intervals. A 5 cm section of the core was placed with plastic core barrel liner into a can, covered with fresh water to 2 cm from the top and sealed. Cans were then stored in a fridge on board ship. Upon return to Bedford Institute they were sent to Carbon Systems Inc. to be analyzed by gas chromatography for methane (CH_4), ethane (C_2H_6), propane (C_3H_8), iso-butane and n-butane (C_4H_{10}) and the undersaturated forms of butane which are ethene and propene. Two holes were punched in each can and the head space displaced with helium. The can was then shaken for 10 minutes to liberate gases from the water and sediments in to the head space. The heavies (C_2 - C_4 gases) and the methane were then analyzed separately by direct injection into the gas chromatograph. All methane samples and a few of the samples run for heavier hydrocarbons were run in duplicate. Standards were also run daily to recalibrate the chromatograph.

Figure 36 is a schematic illustration of the temperature ranges in which various gases form. In marine sediments gases are produced by the decomposition of organic matter. At shallow depths this is largely accomplished by bacterial action and the gases which are produced are methane, carbon dioxide and hydrogen sulphide. With increasing depth of burial, the temperature rises and spontaneous chemical decomposition of organic matter quickly becomes the dominant method of gas generation while bacterial action decreases and eventually ceases at depth due to the higher temperatures and increased compactness of the rock. Gases produced thermochemically are carbon dioxide(CO_2), carbon monoxide(CO), nitrogen(N_2), hydrogen(H_2), hydrogen sulphide (H_2S), and the heavier hydrocarbon gases (C_2H_6, C_3H_8 and C_4H_{10}). The presence of thermochemically produced gases in surficial sediments would indicated that either the sediments were at one time more deeply buried or the gases originated at depth.

The results of gas analysis of peak core (#8) and moat core (#7) are shown in Table 5. There are several important observations to be made:

1) Methane and thermogenic gas concentrations are significantly higher in the peak core than the moat core. The high concentrations in the peak core are anomalous, based on comparison with other data from the Beaufort Sea (Whelan pers. comm., 1981).
2) The maximum value of 5.4 ppm for heavies (C_2 to C_4) in core 7 is due mostly to a high propane concentration. As thermogenically produced gases normally have progressively decreasing amounts of C_1, C_2, C_3, and C_4 hydrocarbons (as in core 8) this value is thought to be due to contamination.
3) Ethene and propene (undersaturated gases) are normally biogenically produced and their similar concentrations in the two cores indicates that the background biogenic activity is

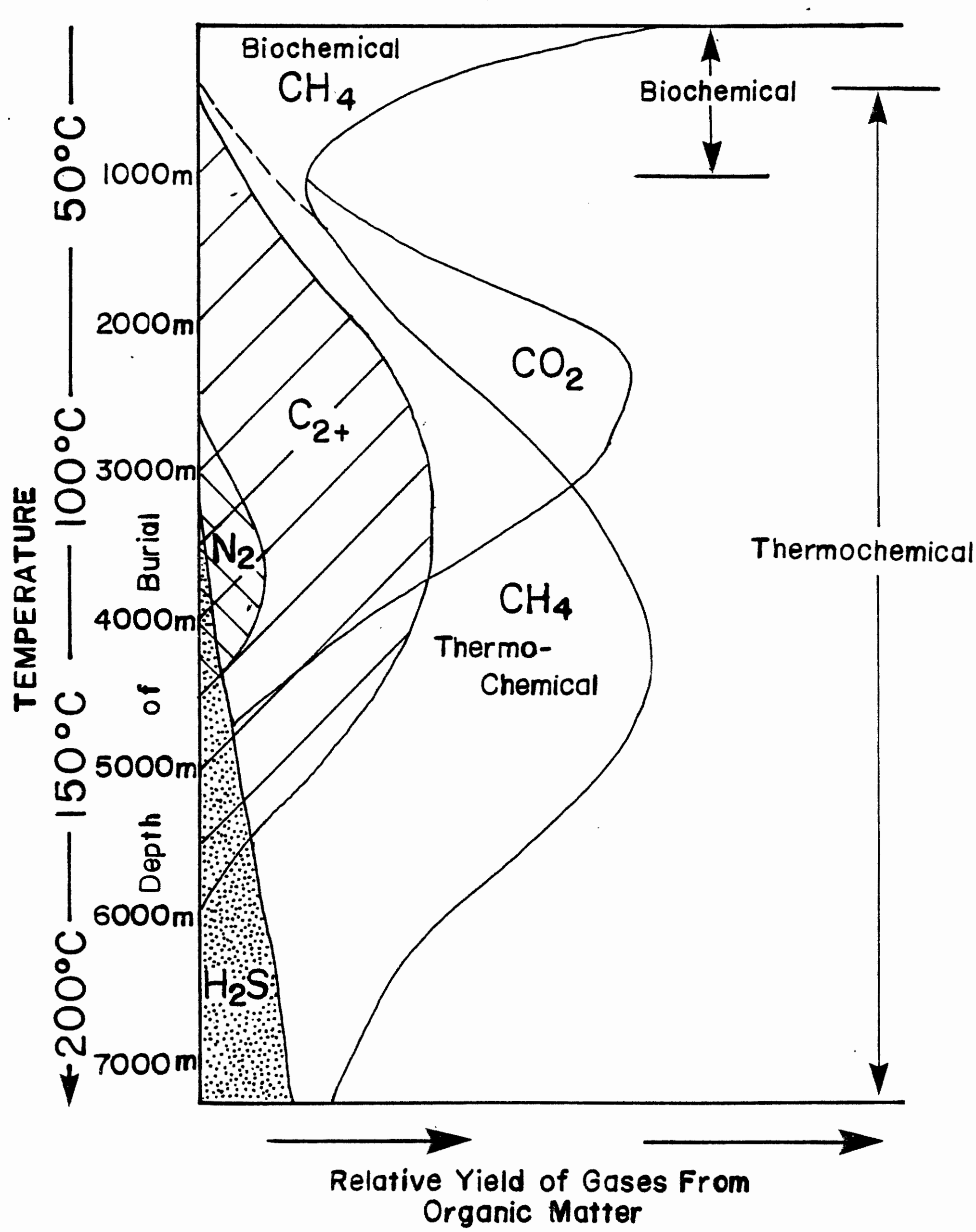


Fig. 36 Generation of Gases form Organic Matter combined from Hunt (1979) and Hedberg (1979)

TABLE 5

SEDIMENT GAS CONCENTRATION IN PPM (V/V)

Core	Depth	Methane	Ethene	Ethane	Propene	Propane	Iso-Butane	n-Butane	Sum of Heavies C_2-C_4
8	0.5	4905.0	0.1	2.5	0.1	0.7	0.2	0.2	3.6
8	44.50	15400.0	3.3	7.5	0.2	1.7	0.6	0.2	10.0
8	114-117	1852.0	0.3	12.1	0.3	4.3	0.8	0.5	17.7
7T	0-5	840.0	0.0	0.3	0.2	0.4	0.0	0.0	0.7
7T	50-55	755.0	0.3	0.2	0.2	1.0	0.0	0.0	1.2
7T	100-105	40.0	0.7	0.5	1.0	4.9	0.0	0.0	5.4
7T	152-157	1384.0	0.6	0.3	0.3	1.0	0.0	0.1	1.4

consistent. The local abundances of methane and thermogenic gases are not likely to reflect increased biogenic activity at shallow depth.

4) The increase in gas concentration towards the surface in core 8 is unusual and further information is required to explain this.

The two cores were also sub-sampled for organic carbon analysis at or adjacent to those intervals analyzed for gas concentrations. Analysis was performed using the total combustion method with a Leco model W12 analyzer by B. LeBlanc (AGC). The results (Table 6) indicate a higher level of in situ organic carbon in the moat sediments (core 7) than in the peak (core 8). This may support the conclusion drawn from the similar ethene and propene values in the two cores, that higher methane values in core 8 are not due to increased biogenic activity unless the carbon has been changed into hydrocarbons.

2.2.5 BIOSTRATIGRAPHY

Half of each of the moat and peak cores (7 and 8) were subsampled at approximately 25 cm intervals. They were examined for foraminifera by G. Vilks (AGC), for Quaternary pollen and diatoms independently by both J.C. Ritchie (University of Toronto) and P.J. Mudie (AGC) and for dinoflagellate populations and reworked spore assemblages by J. Bujak (AGC).

One mollusc was found in the moat core (7) at 155 cm. It was identified as Macoma calcarea (Gmelina) by F.Wagner (AGC) and is a cold water bivalve common in the Beaufort Sea in water depths less than 50 m. The single valve was found with dense organic matter adjacent to it which was overlain by a thin layer of irregularly shaped calcareous particles (Fig. 27). These could be the remains of an Ophiuroid (D. Peer, pers comm. 1982) which are predators of bivalves and are common in the Beaufort Sea.

TABLE 6

ORGANIC CARBON

Core	Depth (cm)	DVM Read	Normalized (X4)
8	17-20	.250	1.00
8	17-20	.242	0.91
8	39.40	.305	1.22
8	107-110	.269	1.08
8	107-110	.275	1.10
7T	05-07	.464	1.86
7T	49-50	.363	1.45
7T	100-101	.375	1.50
7T	150-152	.329	1.32
7T	150-152	.328	1.31

2.2.5.1 FORAMINIFERA

Counts of major species of foraminifera per 204 ml sample were compared with Beaufort Sea environment-species relationships established by G. Vilks et al. (1979). Water temperatures and salinity are believed to be the main factors controlling the present day water bottom distributions of foraminifera in the Beaufort Sea. Islandiella helenae (teretis) is primarily a deep water species which cannot survive well in low salinity water (Fig. 37). Conversely, Elphidium excavatum (clavatum) prefers brackish water habitats which are found in shallower waters near the Mackenzie Delta (Fig 38). Relative counts of these two species at a given level in a sedimentary section then give some indication of the general environment at the time that sediment was being deposited.

Counts of major foraminiferal species are shown in Table 7 as a percent of total count. Several important points are worth noting:

1) The only species found in substantial numbers in the peak cores are presently living in shallow water.
2) The deeper water I. helenae is present only in very small amounts at the top of the PLF peak core.
3) The lower part of the peak core is practically barren of faunas.
4) Faunas in the moat sediments are more diverse than those from the peak.
5) Moat sediment forams are abundant, well preserved and commonly pyrite encrusted.
6) The species content in the moat core is similar to the endemic fauna of the area.

The peak core is from 35 m and the moat core from 67 m water depth. The fresh water plume from the Mackenzie Delta is believed to have little influence on salinities at these depths in the area of the Kopanoar PLF. Figure 39 shows the expected relationship of salinity to depth at this station. It is extrapolated from water column samples

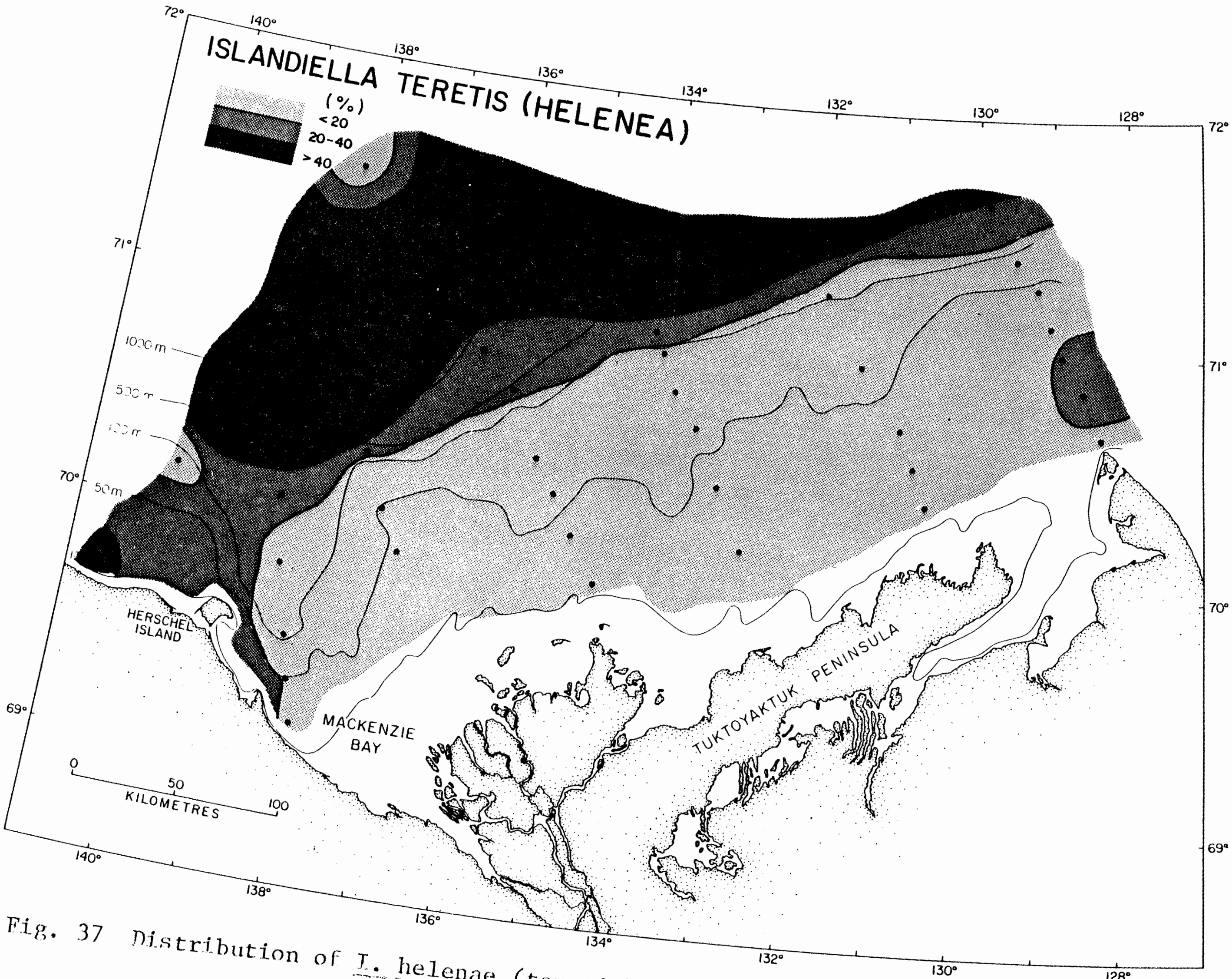


Fig. 37 Distribution of I. helenae (teretis) in the Beaufort Sea from Vilks et al. (1979)

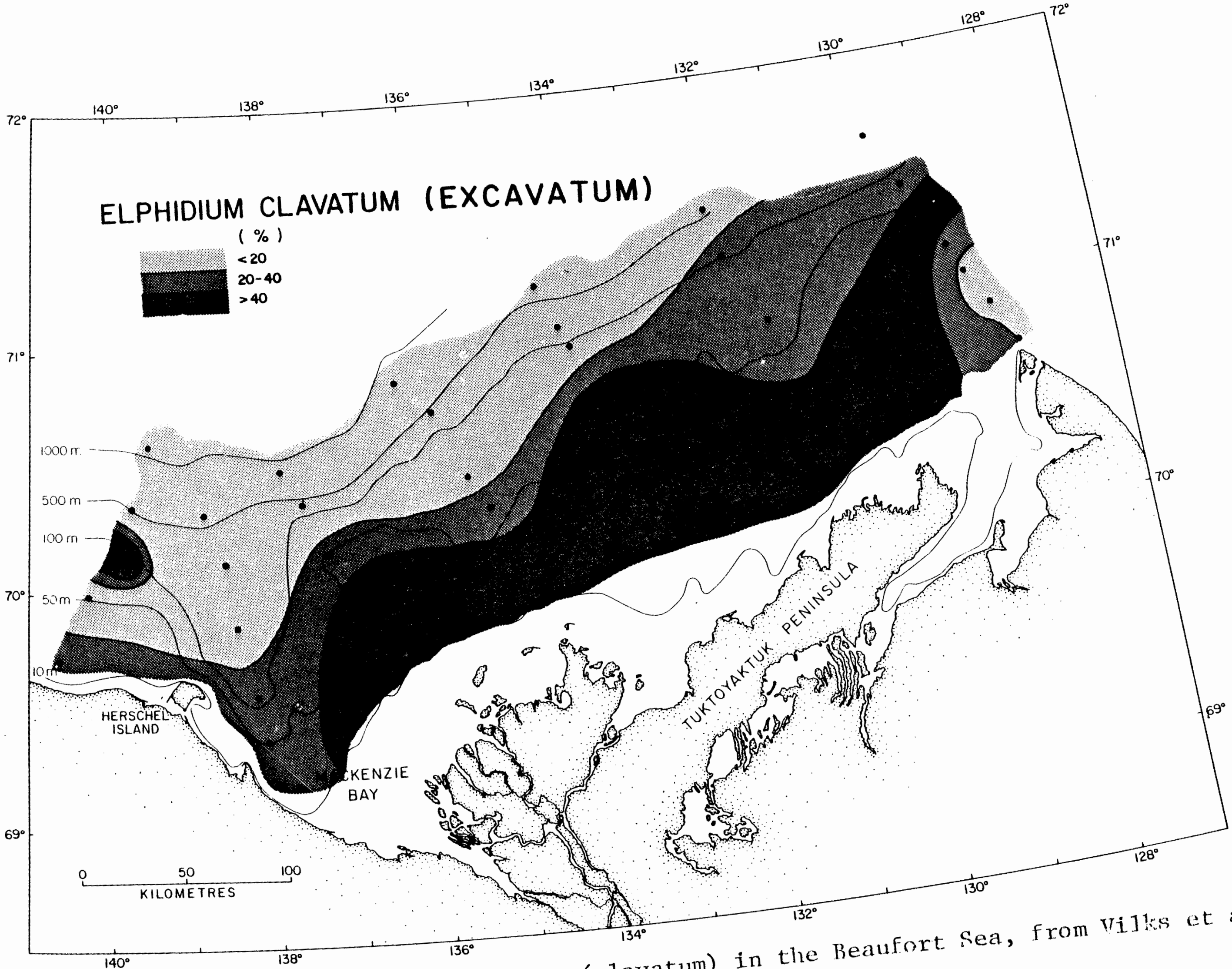


Fig. 33 Distribution of E. excavatum (clavatum) in the Beaufort Sea, from Vilks et al. (1979)

TABLE 7

PERCENT OF MAJOR SPECIES

	Core 8 (peak core)					Core 7 (moat core)															
Interval (cm +5)	10	25	60	75	100	0	25	67	93	125	150	175	200	225	250	275	300	325	350	375	419
I. helenae (teretis)	2					11	18	11	19			17		14		17	9				34
V. fusiformis													6	34				14	11		
E. excavatum (clavatum)	46	37				13	35	53	40	33	34	36	45	15		17	27	24	22		23
S. biformis									9	11								14			
C. reniforme	30	39				12	19		15	17	33	19	11	7		37	39	31	24		21
C. crassimargo						25		11													
Total Forams	249	227	21	3	16	138	175	508	193	229	150	262	339	59	20	342	137	288	177	17	1968

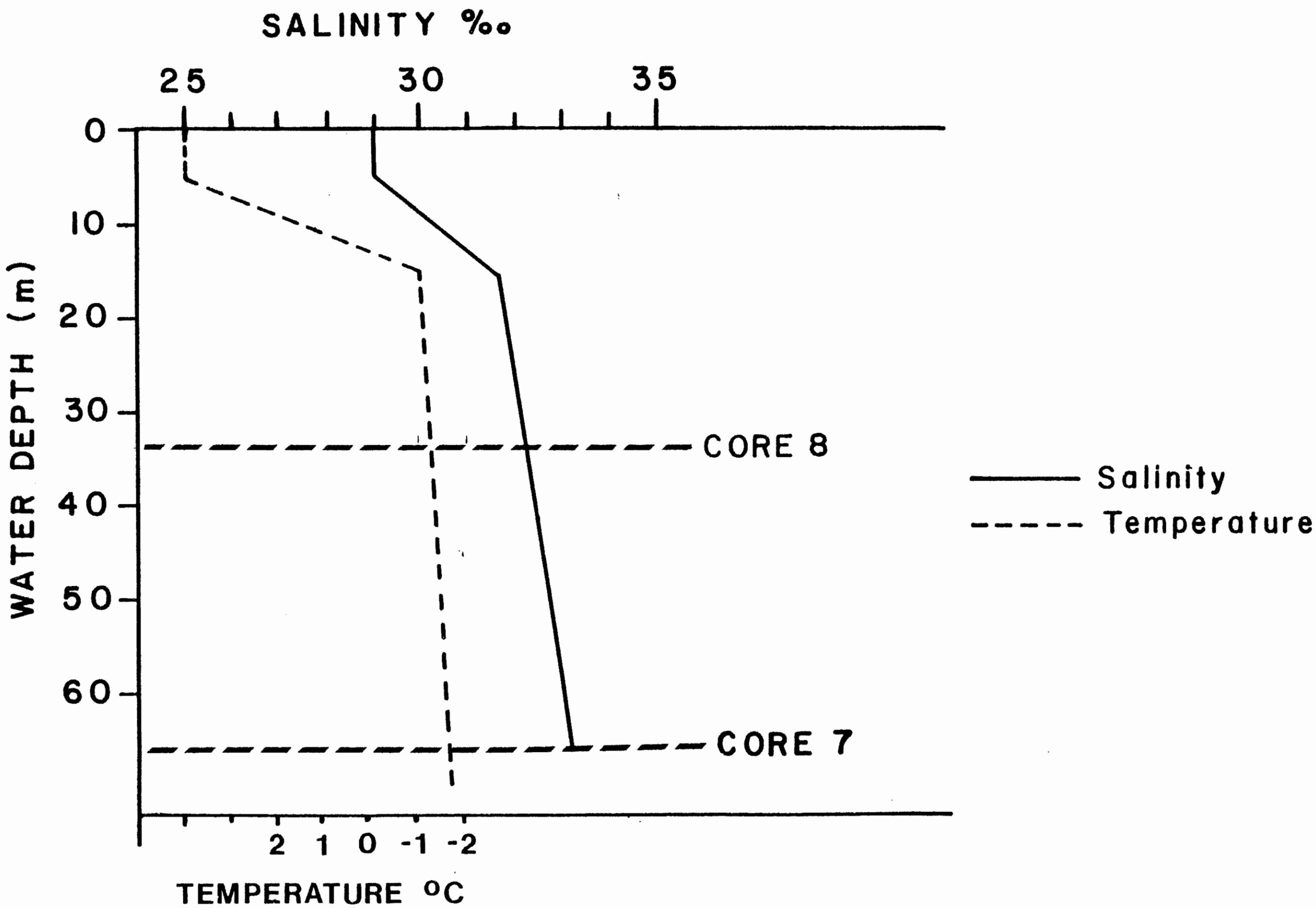


Fig. 39 Salinities and Temperatures vs. Water Depth Near the Kopanoar PLF from Vilks et al. (1979)

taken near the Kopanoar PLF in 1972 and shows little difference in salinity between 35 and 67 m water depth in this area.

2.2.5.2 PALYNOMORPHS

Samples from the two cores were first examined for palynomorphs by J.C. Ritchie after processing by the standard methods (Faegri and Iverson,1975; Cwynar et al.,1979). By adding a known concentration of an exotic pollen type to each sample, the pollen concentrations were then determined. Pollen data were compared with an onshore pollen stratigraphy established from lakes on the Tuktoyaktuk Peninsula by J.C. Ritchie and F.K. Hare (1971) (Fig. 40). This stratigraphy is also associated with pingos on the peninsula (Fig. 41). The pollen data are shown in diagrammatic form in Figures 42 and 43. They show a spruce (Picea) predominance with minor amounts of birch (Betula) and alder (Alnus). This spectrum type does not resemble any of those pollen zones established on land. Correlation with onshore zones cannot be made with a great deal of confidence without further analysis due to the low concentration of pollen in the marine cores (Ritchie pers. comm., 1981).. P.J. Mudie (AGC) re-examined some of the slide preparations with larger counts to try to overcome this concentration problem.

Several further facts emerge:

1) Pollen concentrations are much lower in both cores than is generally found in Beaufort Sea cores.
2) Quaternary pollen are present in both the moat and peak cores.
3) There is an order of magnitude more Tertiary pollen in the peak than the moat cores and these are also better preserved in the peak sediments.
4) Total counts in the peak core are higher than the moat core (sometimes double), mostly due to higher Tertiary pollen counts.

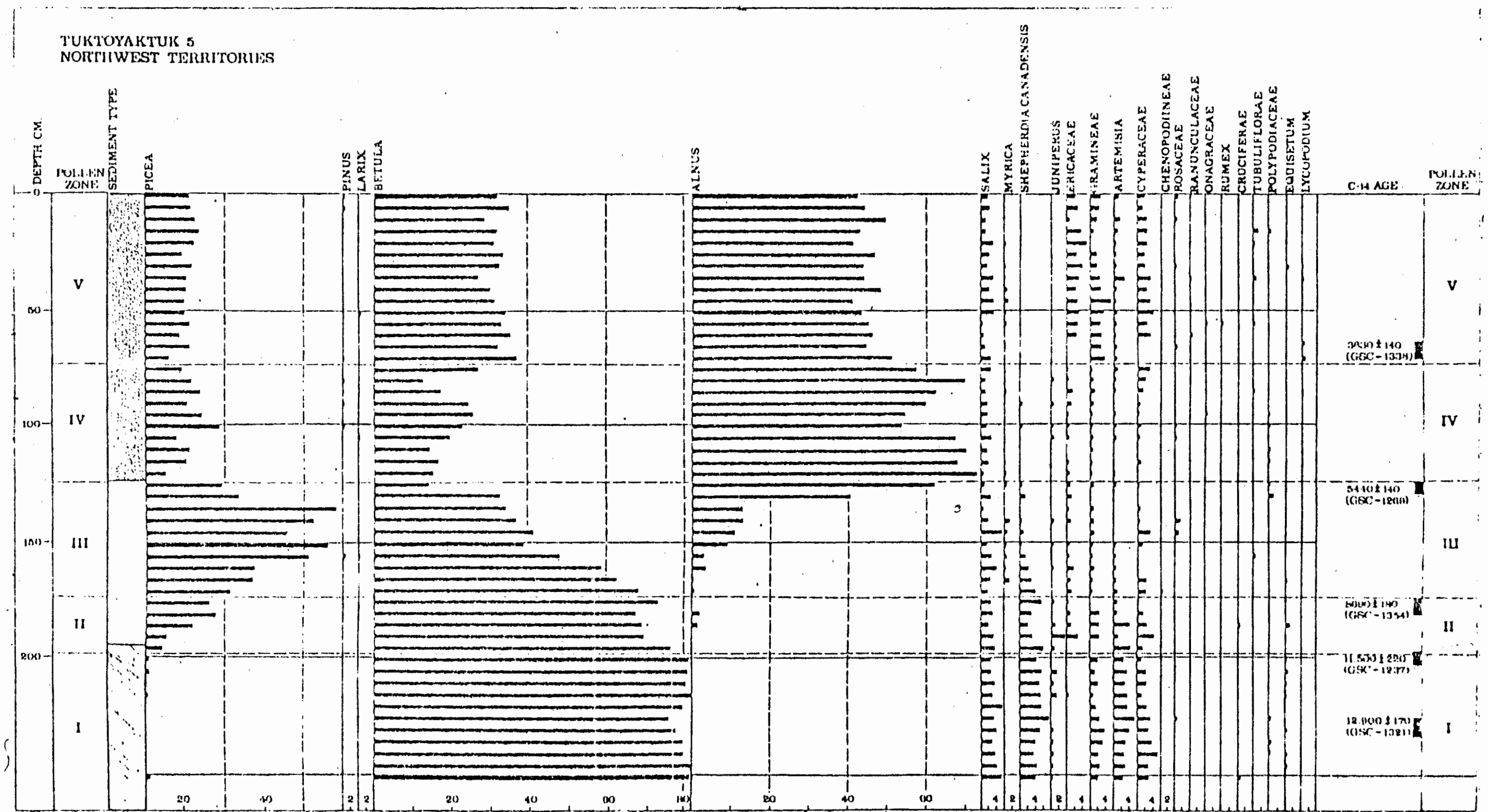


Fig. 40 Relative Pollen Stratigraphy From a Lake on Tuktoyaktuk Peninsula from Ritchie and Hare (1971)

ESKIMO LAKES - WAVE-CUT PINGO

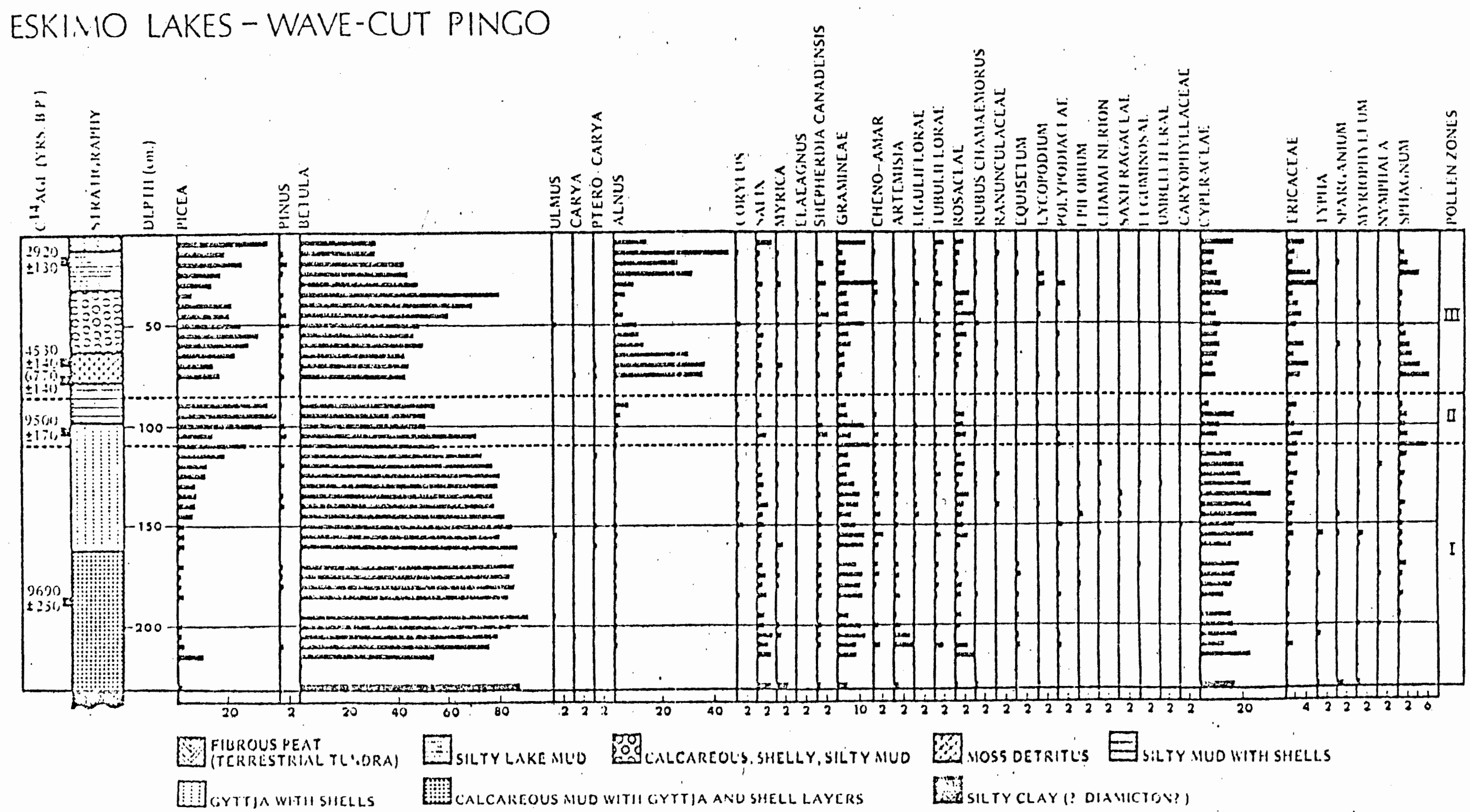


Fig. 41 Eskimo Lakes Wave Cut Pingo - Pollen Stratigraphy from Hyvarinen and Ritchie (1975)

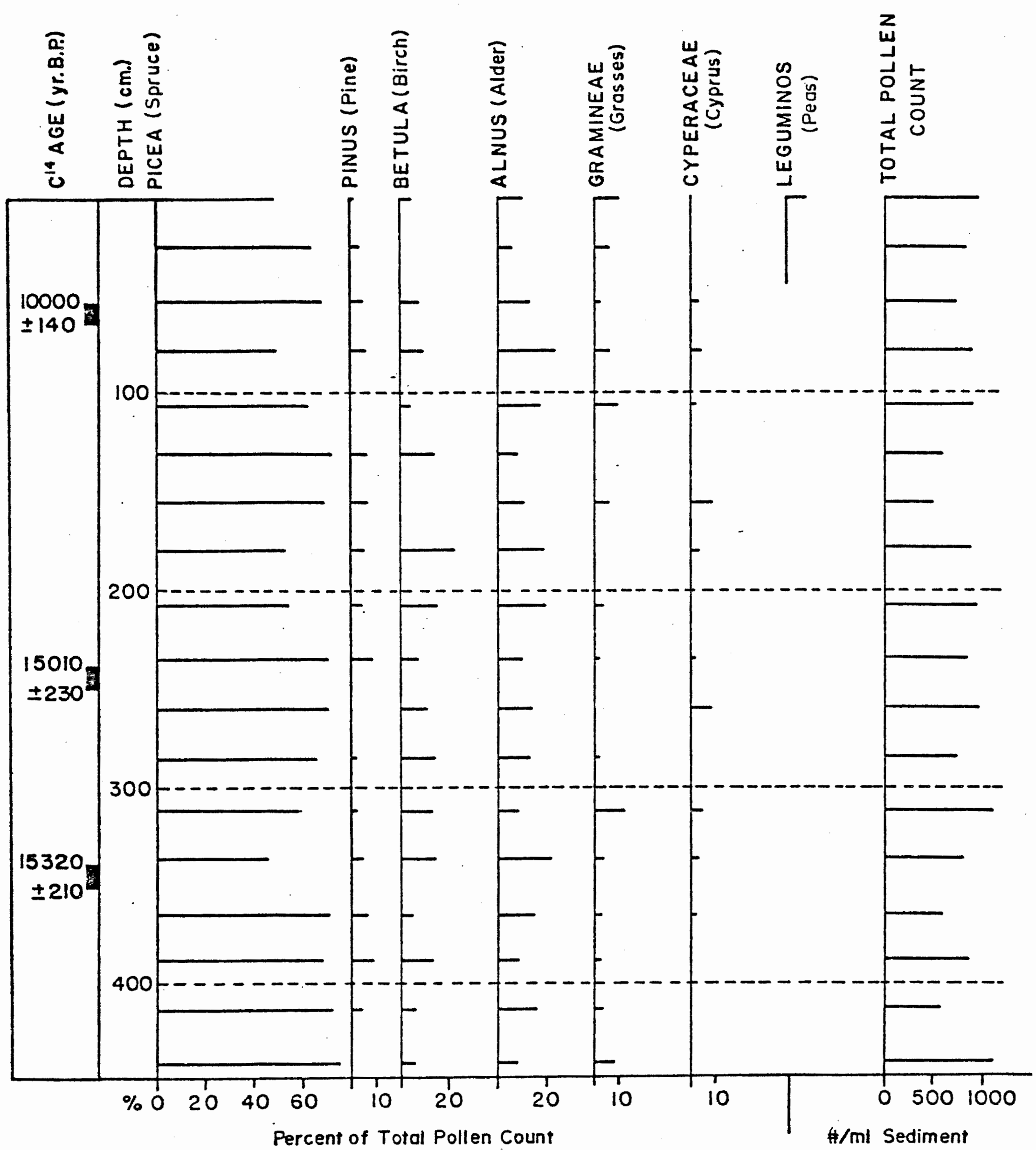


Fig. 42 Pollen Data for Moat Core (7)

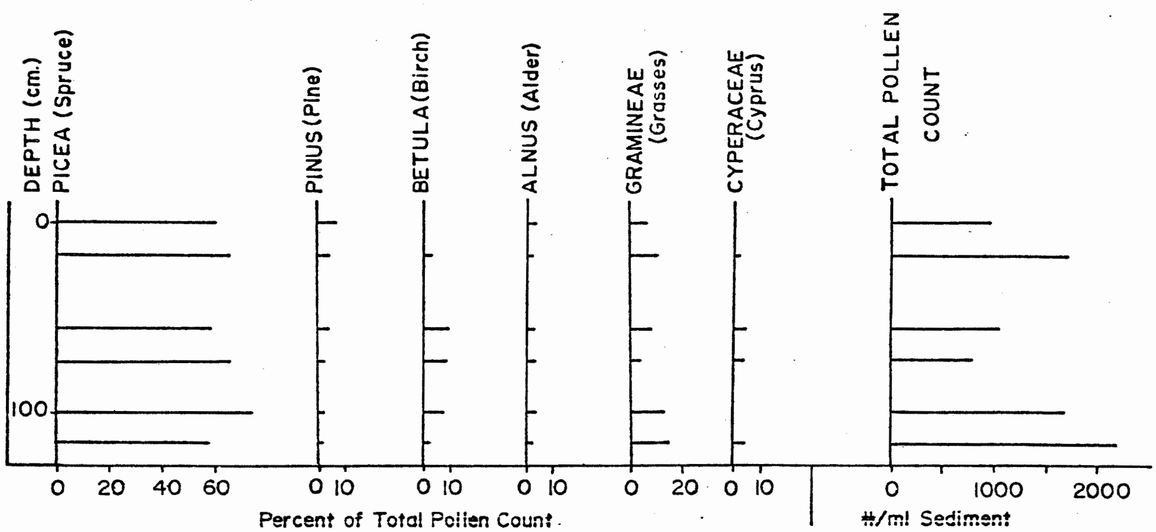


Fig. 43 Pollen Data for Peak Core (8)

5) Mesozoic and Paleozoic palynomorphs are common in the moat core and rarer in the peak core.
6) Layers barren of foraminifera in the peak core (below 25 cm) contain fewer alder (Alnus) pollen than above 25 cm. and less marine, more brackish water dinoflagellates.

J.C. Ritchie briefly examined the slide preparations for diatoms as well at levels 0, 50, 104, 312, 390 and 442 cm in the moat core. He found only marine and brackish water taxa (pers. comm. 1981).

Several factors must be considered when correlating pollen counts between marine and onshore sediments. For example, birch pollen is heavier and is less easily transported to the submarine environment than is spruce, (P.J. Mudie pers. comm., 1981). This could be the cause of the high birch/spruce ratio in zones 4 and 5 of Figure 40 to be reduced in the same zones offshore. Spruce pollen is carried easily by winds and thus predominates providing a high consistent background level in the PLF sediments.

A second group of samples were taken at approximately 25 cm intervals and prepared for examination of dinoflagellate populations plus reworked spore assemblages by J. Bujak (AGC). He also observed the biological florescence of palynomorphs under UV-illumination to aid in determining the ages of taxa. This technique is called flourescence microphotometry and is discussed in detail by van Gijzel (1971). It is based on the principle that as gradual decomposition of various substances in the walls of palynomorphs continues during geological time, the colour spectrum of florescent illumination changes. Easily soluble components which are responsible for the higher frequency blue-green emmissions disappear first and more resistant components which produce a longer wavelength yellow-orange colour remain over a longer geological time. The intensity, colour and spectrum of illumination are a complex function of; a) the chemical composition of various types of palynomorphs, b) their decomposition through time depending on the resistance of chemical constituents to corrosion and coalification, c) their thermal history and d) the properties of measuring equipment. Generally Holocene-Pleistocene specimens exhibit short wavelength blue-green emmissions whereas Mesozoic palynomorph emmissions are more towards the long wavelength yellow-orange end of the spectrum.

Semi-quantitative data from Bujak analyses are listed in Table 7. The upper part of the moat core (down to about 338 cm) contains abundant marine dinoflagellates which are well preserved and exhibit blue-green florescence. In this upper section there are rare Carboniferous spores and early and late Cretaceous dinoflagellates and spores. From 338 to 364 cm in the core is a transition to below 363 cm where Quaternary dinoflagellates are very rare and reworked Carboniferous and Cretaceous palynomorphs are common. These older taxa exhibit yellow to yellow-orange flourescence. Dinoflagellates younger than Cretaceous are extremely rare in the peak core. In this core the palynomorphs are mainly Cretaceous with some Carboniferous taxa present. The peak core and lower part (below 364 cm) have similar assemblages of predominantly reworked Cretaceous palynomorphs with Carboniferous taxa present. These taxa are typical of assemblages from the Beaufort Sea, Mackenzie Delta and Richardson Mountains area (Bujak pers. comm., 1982).

TABLE 8

CORE 7

SAMPLE HORIZONS (cm)	INDIGENOUS DINOFLAGELLATE: OPERCULODINIUM SPP	INDIGENOUS DINOFLAGELLATE: BRIGANTEDINIUM SPP.	INDIGENOUS DINOFLAGELLATE: ROTT. AMPHICAVATA	REWORKED PALYNOMORPHS: LATE CRETACEOUS	REWORKED PALYNOMORPHS: EARLY CRETACEOUS	REWORKED PALYNOMORPHS: CARBONIFEROUS
26	C	.		.	.	
25	C	.				
78	C	.			.	
104	A	.			.	
130	C	.	.	.	.	
156	C	.	.	.	.	.
180	.	.			.	
208	C	.				.
234	.	.				.
260	.					
286	C	.				
312	A	.	.	C	.	.
338	C	.		C	C	.
364				C	.	.
390				.	C	
416				C	.	.
442	.	.			.	.

CORE 8

SAMPLE HORIZONS (cm)	INDIGENOUS DINOFLAGELLATES: BRIGANTEDINIUM SPP.	REWORKED PALYNOMORPHS: LATE CRETACEOUS	REWORKED PALYNOMORPHS: EARLY CRETACEOUS	REWORKED PALYNOMORPHS: CARBONIFEROUS
25		.	C	.
60		C	.	
75	.	.		
115		.	C	

. 1-5 Specimens

C 6-24 Specimens

A 25 Specimens

CHAPTER 3 SUMMARY OF IMPORTANT RESULTS

3.1 ACOUSTIC DATA

-feature is conical in shape with basal diameter of 500 m and a relief of 30 m from the deepest part of the moat.

-slopes are covered with lobate material.

-PLF is surrounded by an annular depression which is underlain by acoustically stratified sediments.

-these sediments thicken and dip towards the PLF, are broken by normal faults with down faulted block toward the PLF and are not confined at depth by the unconformity at Unit C.

-basin reflectors do not terminate at basin margins.

-a channel cuts down the southwest side of the PLF which is infilled by breccia which also infills part of the moat and and part of an ice scour mark.

-two cones are evident in the channel - one with a depression in its peak.

-brecciated acoustic character of channel fill is different from material comprising the slopes.

-no ice scours on peak, possible scour on lower slope.

-acoustic void below peak.

3.2 SEDIMENTS

-to depths sampled, sediments are marine, organic, slightly silty clay.

-peak and moat cores have different structures and geotechnical properties.

-peak sediments cored -show colour banding or mottling
-contain ice
-contain stiff clay balls
-have a low sensitivity to remoulding

-moat sediments cored -show colour banding and mottling
-have infrequent thin silty lenses
-contain no visible ice
-have an increasing sensitivity with depth

-seabed temperatures of -1.2 to -1.6 (estimate Fig. 39), are not low enough to freeze seawater.

-carbon-14 dates suggest mean sedimentation rates of 323cm/1000yr from 344 to 244 cm, and 37cm/1000yr from 244 to 60 cm in the moat core.

3.3 GEOCHEMISTRY

-significantly lower K^+,Ca^+, and Mg^+ (absolute concentrations and chlorinity ratios) in porewater of peak sediments than moat sediments, though Na^+ chlorinity ratios are similar.

-peak sediments have a higher methane concentration and contain thermogenic gases not found in the moat sediments.

-organic carbon concentrations are lower in peak than in moat sediments.

-undersaturated gas (ethene and propene) levels similar for both cores.

-increase in gas concentrations towards the surface.

3.4 BIOSTRATIGRAPHY

-distinctly different assemblages in peak vs. moat sediments.

-peak sediments have few forams, mostly just on top and mostly shallow water species.

-moat sediments have abundant diverse forams, well preserved and sometimes pyrite encrusted.

-shallow and deep water forams are present throughout the moat core

-pollen counts are lower in both cores than is normal for Beaufort Sea sediments.

-higher pollen counts in peak core than moat.

-no fresh water palynomorphs are present in either core.

-there is no evident correlation of pollen assemblages with an established on-shore stratigraphy.

-total counts in the peak core are much higher than in the moat core.

-an order of magnitude more Tertiary pollen in the peak than the moat core and these are also better preserved in the peak sediments

-upper part of the moat core (above approximately 338 cm) contains abundant marine Holocene-Pleistocene dinoflagellates and only rare older palynomorphs.

-below this, Recent taxa are rare while Cretaceous and Carboniferous dinoflagellates and spores are common.

-for entire peak core, dinoflagellate and spore assemblages are similar to the lower part of the moat core.

-these older taxa are typical of the Mackenzie Delta and Richardson Mountains areas.

CHAPTER 4 INTERPRETATION AND DISCUSSION

There are several structural and morphological characteristics which the Kopanoar PLF does not possess which one would expect to find if it had formed by a pingo 'C type' mechanism within ancient lake bed sediments. For example, if the moat of stratified sediments were of lacustrine origin at depth they would be expected to lie within a depression in Unit C and acoustic reflectors within the moat would terminate at the basin margins. Neither of these is the case (Figs. 22 and 23). Also, the peak core would have cored into either lacustrine sediments or recent marine sediments which had been deposited since the transgression. If the latter were the case the moat and peak cores would have similar gas concentrations as well as palynomorph and foraminifera assemblages. Many of the PLF characteristics are common to mud volcanoes but not pingos. The presence of the channel and its breccia fill (Figs. 15 to 21), parasitic cones in the channel (Figs. 17 and 19), the stiff clay balls (Fig. 28) and thermochemically produced gases in the peak sediments (Table 5), all are highly suggestive of an eruptive type origin.

The moat core sediments were found to have a higher shear strength, bulk density and water content than the peak core and their bulk density and sensitivity increased with depth as would be expected in a normally consolidated sediment. Shear strengths and sensitivities were very low in the peak core indicating the sediment had been disturbed such that the natural structure was damaged or destroyed.

As is often the case with mud volcanoes (Yakabov, 1971), PLFs tend to occur in groups (Fig. 1) and are often associated with faults (Fig. 44). The possibility exists that not only other C2 type PLFs but also Type A and many of the Type B and C1 features are mud volcanoes in which gas plays a significant role in formation. Faulting forms weak zones or conduits through which trapped gases and waters can travel to vent at the surface. On Figure 44 two PLFs can be seen to occur at the

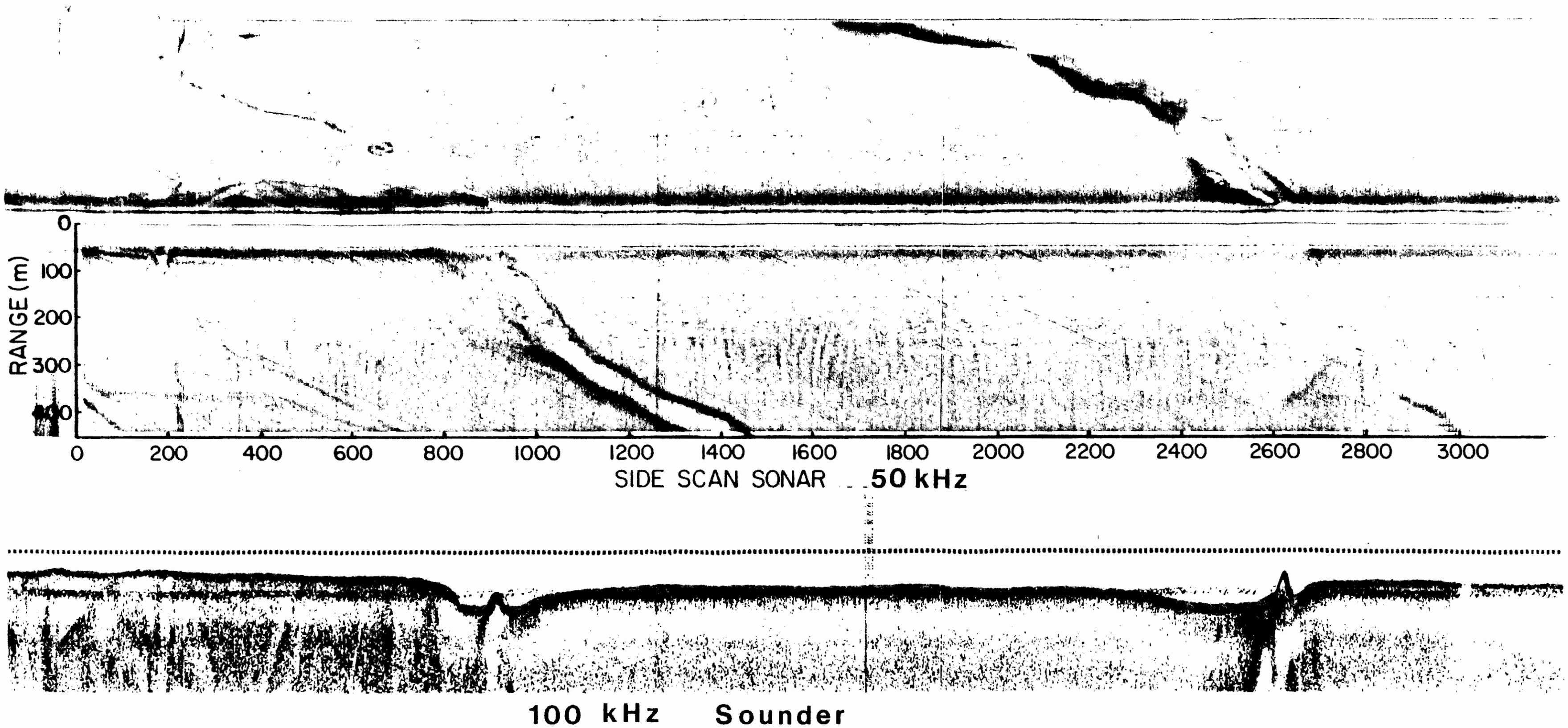


Fig. 44 PLFs Associated With Faults

margins of a down faulted block of the sea floor.

The presence of continuous reflectors below PLFs (Fig. 6), does not discount the possibility of a mud volcanic origin as the vent and centre of activity could be offset from the plane of the acoustic section. Where vents are clear and small and/or the source of material is at great depth, compensating subsidence would be distributed over a large area and little deformation would be seen in bedding even at a short distance from the vent.

There is much evidence on the Beaufort Sea shelf of gases migrating up through the sediments (Fig. 45). Gases were actually seen bubbling to the sea surface when an attempt was made in 1979 to core the Admirals Finger (the first PLF discovered by CCGS MacDonald), (Blasco pers. comm., 1980).

The heavier carbon gases found in the peak core required temperatures of about 70 to 150^{o}C (about 1000 to 5000 m depth) to be generated. As it is unlikely that these temperatures ever existed at the seabed the gases are more likely to originate at depth.

Forams present in the peak core are presently found in nearshore brackish water of the Beaufort Sea and the dominant species of the moat core sediments is presently a major deep water species. This suggests that the sediments of the peak were deposited shortly after the sea transgressed the Kopanoar PLF area (after the last glaciation) and are older than those of the moat which were deposited later when the sea had reached a depth where the deeper water species would survive.

The carbon dates have been plotted in Figure 46 along with a hypothesized sealevel curve for the Mackenzie Delta area (Forbes, 1980). The sealevel curve suggests the area of the PLF became submerged about 11,000 yrs ago. The water depth increased about 7 m/1000 yr until 5,000 yr ago after which it increased more slowly (about 2 m/1000 yr). Active ice scouring is believed to occur in the Beaufort Sea continental shelf between 10 and 50 m water depths (Lewis et al., 1976). Lack of scouring on the peak at 35 m and possible

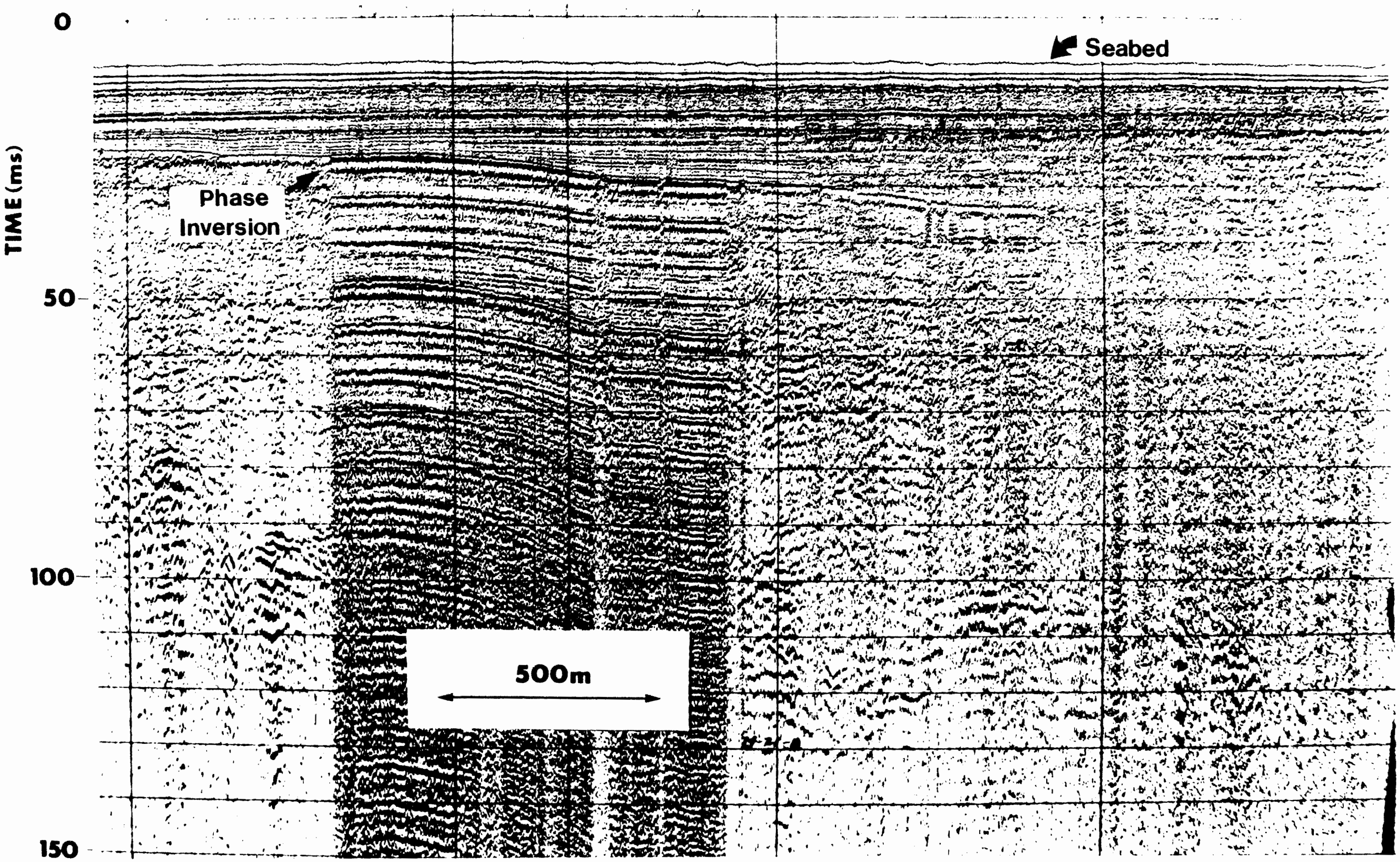


Fig. 45 Gas in the Sediments

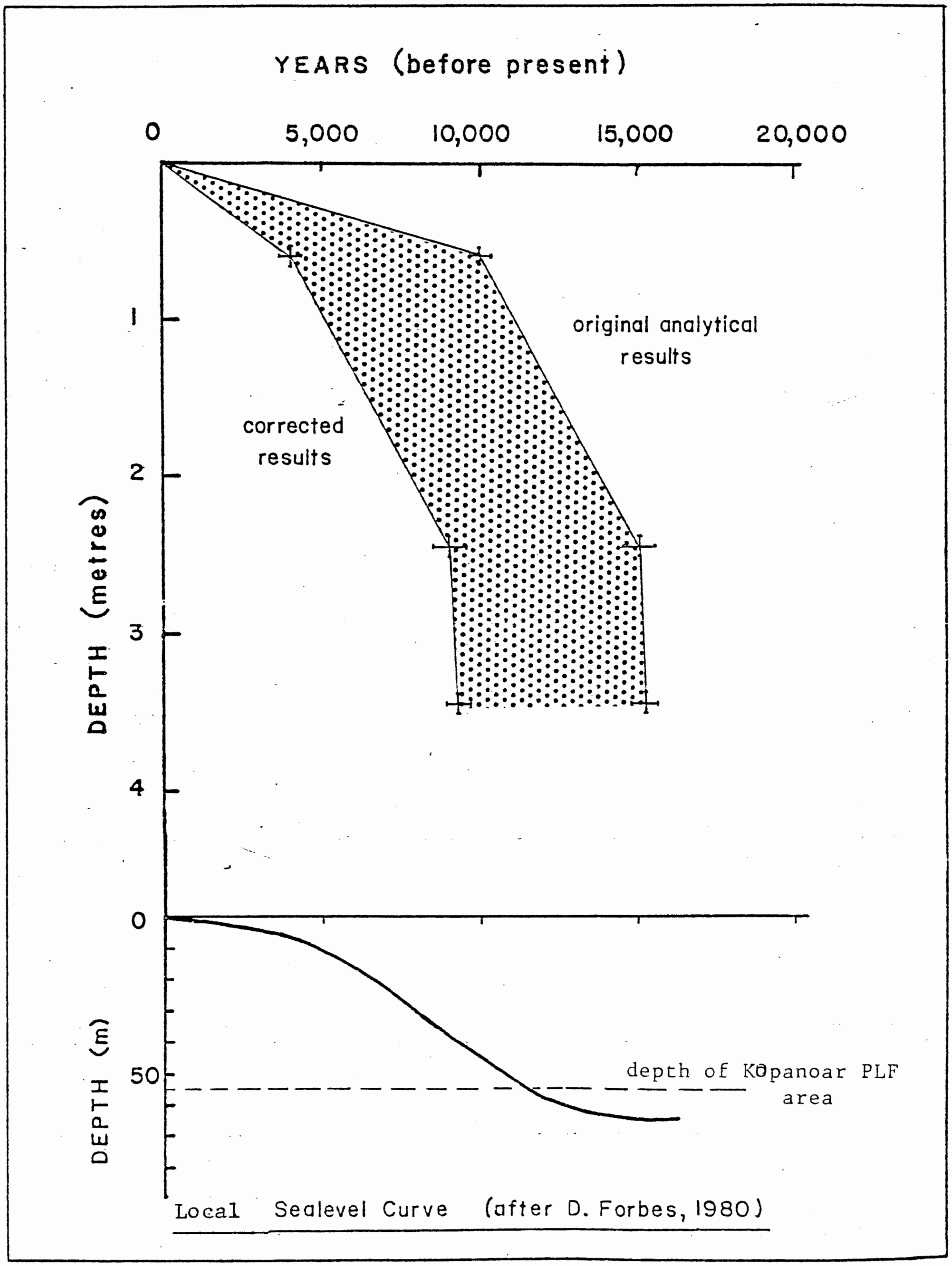


Fig. 46 Carbon Dates and Sealevel Curve

scouring on the lower slopes suggests either recent formation of the feature or a recent covering or remoulding of slope material possibly by slumping or an eruption. Forbes' sea level curve (Fig. 46) places the 50 m water depth in this area about 11,000 yrs ago which may indicate that the feature has been active as recently as this. The infilling of scours on the seabed by the breccia which infills the channel and moat also suggests a recent eruption, and the size of blocks in the flow give some indication of the violence of eruption. The difference in the rough acoustic texture of the channel fill compared to the smooth lobate material of the slopes and the possible presence of a scour on the lower slope may be explained by more than one stage of eruption. The main vent may have 'clogged' after eruption allowing pressure to build at depth to a point of secondary eruption through the main vent or possibly through secondary parasitic routes to the mud cones seen in the channel.

The mean sedimentation rate from the lower section of the core is at least 10 times higher than sedimentation rates suggested by Vilks et al.(1979). Acoustic reflectors within the moat suggest that layers thicken and dip towards the PLF and are broken by growth faults. This would also indicate a fast sedimentation rate possibly due to preferential infilling with synchronous basinal subsidence.

Major cation analysis of the peak and moat sediment pore waters showed significantly lower cation concentrations within peak sediments and lower chlorinity ratios than standard seawater or moat pore waters. If cation concentrations are recalculated assuming all cations were dissolved in the interstitial waters only and not the insitu ice (which constituted 30% by volume), the chlorinity ratios remain constant but the increased concentrations (K^{+}, Ca^{++}, and Mg^{++}) are still approximately 50% lower than in the moat pore waters. Water bottom temperatures (from Vilks et al., 1979) are about -1.2 to -1.6^{O}C and seawater freezes at -1.9 to -2.0^{O}C. If the source of the ice is seawater it seems unlikely that ice would form in the peak but not form in the moat sediments. As seawater freezes, major cations are almost totally rejected from the ice matrix (A. Judge pers. comm., 1981). A cation rich brine forms. Excess cations may stay near the ice or migrate away. In either case, cation concentrations in remaining porewater would probably be the same or higher than the original seawater which constituted the porewater from which the ice would have formed. As mentioned above, pore waters in samples that had contained ice were found to have significantly lower cation concentrations and chlorinity ratios than moat sediment pore waters. This could be the result of mixing of fresh water from depth (connate?) which would explain the low cation concentrations, chlorinity ratios and the presence of ice in the peak core.

Though PLFs of different origins may exist on the Beaufort Sea continental shelf, such as the types described by Shearer (1980), it is believed that at least the Kopanoar PLF and probably many others formed by a mud volcano type mechanism.

CHAPTER 5 CONCLUSIONS AND IMPLICATIONS

1) Evidence does not support a classic pingo or 'C type' origin of the Kopanoar PLF in lake basin sediments, rather the data give strong support to the hypothesis that the PLF is of mud volcanic origin triggered by gases and possibly waters migrating from depth to the seabed.

2) There may have been more than one incident of eruption.

3) Other PLFs on the Beaufort Sea continental shelf and slope may also be of mud volcanic origin.

4) More data are necessary to confirm this hypothesis on this and other PLFs.

5) As dynamic features, PLFs may be significant factors to consider during future hydrocarbon exploration and development.

CHAPTER 6 RECOMMENDATIONS

It is highly recommended that further studies be undertaken to confirm or refute the hypothesis that many pingo-like-features in the Beaufort Sea are mud volcanos. The increase in gas concentrations toward the surface needs to be explained and the marine vs. fresh water origin of the ice determined. Investigation of other PLFs would also determine if the Kopanoar PLF were truly representative of many others. Several suggestions follow that may produce more diagnostic data:

1) Further acoustic lines, particularly sidescan over the Kopanoar PLF to observe any changes in the morphology or other indications of activity since the last survey.

2) Manned dives on the PLF to map, photograph and specifically sample the breccia and small cones in the channel. Water samples could also be obtained directly above the vent and cones, to be analyzed for gas content.

3) Further gas analysis should include carbon isotope analysis (C^{12}/C^{13}) of the methane. When methane is formed biogenically it has a different carbon isotopic composition from that formed thermogenically. Methogenic bacteria form methane by reduction of CO_2, consuming the lignter $^{12}CO_2$ rather than the heavier $^{13}CO_2$. Determination of the C^{12}/C^{13} ratio might support the conclusion in this thesis of a thermogenic origin of the gases.

4) A transect of several cores along a vertical section through the feature from some distance off the feature to the peak. A 40 ft core could easily be obtained in the moat and a longer

core than already achieved might be possible in the peak with a heavier corer. This would allow the variation in the gas content, biostratigraphic assemblages and geotechnical properties to be determined across the feature.

5) Immediate subsampling on board ship to separate ice and pore waters in vials for oxygen isotope analysis. Unlike with major cations, the oxygen isotope ratios (O^{16}/O^{18}) of water changes very little when it freezes. As seawater and fresh water have distinctly different oxygen isotope ratios, the

measurement of them in the isolated ice may conclusively determine its origin.

6) Higher pollen counts and possibly to deeper intervals, would help to establish if a correlation with the onshore pollen stratigraphy (Section 2.2.5.2) does exist.

REFERENCES

Belderson, R.H. (1972). Sonographs of the Seafloor, Elsevier Publishing Co., Amsterdam, 185 pp.

Campbell, I. (1979). Study of the Pingo-Like-Features Detected in the Beaufort Sea, unpublished report by Coast Pilot Ltd., Sidney, B.C. for the Department of Fisheries and Oceans, Sidney, B.C., 12 pp.

Coleman, J.M. and D. Prior (1981). "Subaqueous Sediment Instabilities, the Offshore Mississippi Delta", Offshore Geologic Hazards, AAPG Short Course, OTC Education Note Series #18.

Craig, R.F. (1978). Soil Mechanics, Van Nostrand Reinhold Co. Ltd., Berkshire, England, 318 pp.

Cranston, R.E. (1974). Interactions Between Major Cations, pH, and Suspended Matter in Coastal Environments. MSc. Thesis, Dalhousie University, Halifax, Nova Scotia.

Cwynar, L.C., E. Burden and J.H. McAndrews (1979). Canadian Journal of Earth Sciences, 16, p.1115.

Dobrin, M.B. (1952). Introduction to Geophysical Prospecting, McGraw-Hill Book Co., 630 pp.

Faegri, K. and J. Iverson. Textbook of Pollen Analysis. Münksgaard, edition 3.

Forbes, D.L. (1980). Late Quaternary Sea Levels in the Southern Beaufort Sea, Current Research, Geological Survey of Canada, Paper 80-1B, pp. 75-87.

Harper, J.R. and S. Peland (1982). Beaufort Sea Sediment Dynamics, unpublished report, Woodward-Clyde Consultants, Victoria, B.C., for the Geological Survey of Canada, Dartmouth, N.S.

Hedberg, H.D. (1979). Methane Generation and Petroleum Migration, AAPG Studies in Geology Series #10, Problems in Petroleum Migration, pp. 179-206.

Hesse, R. and W.E. Harrison (1981). "Gas Hydrates (Clathrates) Causing Pore-Water Freshening and Oxygen Isotope Fractionation in Deep Water Sedimentary Sections of Terrigenous Continental Margins", Earth and Planetary Science Letters 55, Elsevier Publishing Co., Amsterdam, pp. 453-462.

Holmes, G.W., D.M. Hopkins and H.L. Foster (1968). "Pingos in Central Alaska", Washington, Geological Survey Bulletin, 1241-H, 40 pp.

Horne, R.A. (1969). Marine Chemistry, Wiley-Interscience, New York, pp. 151-155.

Hunt, J.M. (1979). Petroleum Geochemistry and Geology, W.H. Freeman press, San Francisco, 617 pp.

Hyvarinen, D. and J.C. Ritchie (1975). Arctic and Alpine Research 7, pp. 261-272.

Johnson, B.R. (1980). Final Report of Statistical Analysis of Pingo-Like-Features (PLF) in the Beaufort Sea, unpublished report, Barrodale Computing Services Ltd. for the Department of Fisheries and Oceans, Sidney, B.C.

Mackay, J.R. (1979). "Pingos of the Tuktoyaktuk Peninsula, North-west Territories",

Morgan, J.P., J.M. Coleman and S.M. Gagliano (1968). "Mudlumps: Diapiric Structures in Mississippi Delta Sediments", American Association of Petroleum Geologists, Mem. 8, pp. 1-9.

Newton, R.S., R.C. Cunningham and C.E. Schusert (1980). "Mud Volcanoes and Pockmarks: Seafloor Engineering Hazards or Geological Curiosities?", Paper #3729, Offshore Technology Conference, Houston, Texas.

O'Connor, M.J. (1980). Development of a Proposed Model to Account for the Surficial Geology of the Southern Beaufort Sea, report by M.J. O'Connor & Assoc. Ltd. for the Geological Survey of Canada, Dartmouth, N.S. Contract #OSC79-00212

O'Connor, M.J. (1981). Distribution of Shallow Acoustic Permafrost: A Report on the Southern Beaufort Sea, a report for the Geological Survey of Canada, Dartmouth, N.S., Contract #085C.23420-0-M531.

Olsson, I.U. (1968). "C-14/C-12 Ratio During the Last Several Thousand Years and the Reliability of C-14 Dates", Means of Correlation of Quaternary Successions, R.B. Morrison and H.E. Wright Jr., eds., Vol. 8, Proceedings of the VII Congress, International Association for Quaternary Research, pp. 241-252.

Pelletier, B.R. (1975). Sediment Dispersal in the Southern Beaufort Sea, Beaufort Sea Project, Technical Report 25a, Institute of Ocean Sciences, Sidney, B.C., 80 pp.

Ritchie, J.C. and F.K. Hare (1971). "Arctic Tree Line", Quaternary Research, Vol. 1, pp. 331-342.

Shearer, J.M. (1971). "Submarine Pingos in the Beaufort Sea", Science, Vol. 174, pp. 816-818.

Shearer, J.M. (1981). Pingo Correlation and Prediction Study, Contractor Report Series 81-3 for the Department of Fisheries and Oceans, Sidney, B.C.

Simpkin, P.G. (1980). Study on the Acoustic Target Strength of PLF's Found in the Beaufort Sea, unpublished report, Geomarine Assoc., St. John's, Nfld. for the Department of Fisheries and Oceans, Sidney, B.C.

van Gijzel, P. (1971). "Review of the UV-Fluorescence Microphotometry of Fresh and Fossil Exines and Exosporia", in Sporopollenin, ed. J. Brooks et al., Academic Press, London, New York. pp. 659-685.

Vilks, G., et al. (1979). The Holocene Marine Environment of the Beaufort Sea, Geological Survey Bulletin 303.

Yakabov, A.A., A.A. Ali-Zade and M.M. Zeinalor (1971). Gryazevye Vulkany Azerbaidzhanskoi SRR: Atlas, Mud Volcanoes of the Azervaijan SSR, Baku, USSR, 258 pp.