Development of a Proposed Model
to Account for
the Surficial Geology of
the Southern Beaufort Sea

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GEOLOGICAL SURVEY OF CANADA

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"Development of a Proposed Model to Account for the Surficial Geology of the Southern Beaufort Sea"

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SUMMARY

A generalized model of the surficial geology of the southern Beaufort Sea continental shelf has been developed from a review of recent scientific studies conducted mainly by the Geological Survey of Canada. The proposed model consists of three basic geologic units whose individual properties and thicknesses may vary over the shelf.

Unit A is a horizontal sequence of fine grained marine sediments which were deposited on the shelf following the last sea level rise. The base of Unit A grades into Unit B, a transgressive sequence of sand, silt and clay comprising deltaic, lagoonal and littoral sediments deposited in the complex transitional environment which existed during the last sea level rise. Unit B rests unconformably on Unit C, a much older sequence consisting primarily of coarse grained sediments derived from former continental (glacial, fluvial, eolian) and transitional (deltaic, littoral) environments. In some parts of the shelf the unconformity is thought to represent a significant period of subaerial exposure and erosion, resulting in the widespread occurrence of overconsolidated sediments and relic permafrost below this boundary.

An attempt was made to test the proposed model by examining seismic records collected by the GSC during the period 1970 to 1978. It was concluded that acoustic identification of specific geologic units appears to be possible, except where ice scouring, permafrost and/or the presence of shallow gas interfere with the acoustic stratigraphy. No acoustic evidence contradicting the model was encountered. The seismic review also resulted in the identification of glacial sediments, possible massive ice occurrences, relic thermokarst depressions and pingo-like features underlying the seafloor.

An examination of seismic information pertaining to the morphology of the shelf edge was also undertaken. It demonstrated that the shelf edge is presently stable east of 132° longitude, but that the stability decreases in a westerly direction to approximately 137°, where recent faulting or slumping of the shelf edge appears to have occurred. The western (Mackenzie Canyon) edge is also unstable, but the responsible geologic mechanisms along this boundary are somewhat different.

The acoustic evidence suggests that the submarine environment may be every bit as complex as the adjacent permafrost-affected land. If such is the case, then a thorough knowledge of the active and potentially active geologic processes is warranted before extensive resource development can be undertaken safely.

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1.0 THE PROPOSED GEOLOGIC MODEL

As a starting point for future discussion, we propose a generalized surficial geologic model of the continental shelf which consists of three basic stratigraphic units:

Unit A - a horizontal sequence of recent marine sediments deposited on the shelf following the last sea level rise, the base of which grades into:

Unit B - a transgressive sequence which includes deltaic, lagoonal and littoral sediments deposited in a complex transitional environment which existed during the last sea level rise. Unit B rests unconformably on:

Unit C - an underlying, much older sequence whose original depositional environment is presently unknown, but which probably contains sediments derived from former continental (glacial, fluvial and eolian) and transitional (deltaic, littoral) environments. Since the upper boundary of this unit is believed to be an unconformity surface representing a significant period of subaerial exposure and possible erosion, the occurrence of relic permafrost within this sequence is probably widespread.

Subsequent to deposition, the original character of some or all of these units has been modified by such processes as ice scouring, permafrost aggradation or degradation, glacial ice thrusting, slope instability, differential compaction and shallow gas migration.

In the report which follows, evidence is presented to support the generalized model and the relationship of the model to secondary geologic processes is discussed. Acoustic evidence is used to illustrate the subsurface conditions wherever possible.

2.0 SCIENTIFIC STUDIES RELATING TO THE GEOLOGIC MODEL

2.1 Borehole Investigations

Since 1973, hundreds of boreholes have been drilled in the southern Beaufort Sea, mostly in support of geotechnical studies relating to the development of offshore natural resources. O'Connor et al (1979) present a synthesis of much of the borehole data available along three corridors underlying the shallow (0-20 m) environment between Garry Island and Kugmallit Bay. According to their descriptions, the 3 stratigraphic units in the present geologic model have the following characteristics:

Unit A

The recent marine sequence, Unit A, consists of grey to black, soft to firm (rarely stiff) clays or silty clays, usually containing traces of fine sand and organics, often in the form of fine laminations. The clays grade shoreward into grey, loose to very loose silts. Unit A may exhibit a complete range of plasticity, depending on the type and quantity of clay present. Coarse materials (sands and gravels) have also been identified within this unit at isolated locations, but are believed to be the result of ice-rafting.

Unit B

Unit B underlies the marine sequence over part of the shelf. It is composed of a discontinuous and highly variable sequence of sands, silts and clays deposited in the transitional environment which accompanied the last sea level rise. In some areas and at some depths a record of the original depositional environment (deltaic, lagoonal or littoral) has been preserved in the stratigraphy. In other places the original stratigraphy has been destroyed by a phase of the advancing sea which reworked previously deposited sediments, including those of Unit C, below. Macleod (1979 pers. comm.) reports that Unit B may also contain some organic rich and/or heterogeneous stoney clay layers as channel fill near the base of the sequence, but no published information is available to confirm this theory.

Unit C

The transgressive sequence rests unconformably on an old erosional surface which cuts into Unit C. In the nearshore zones between Garry Island and Toker Point, Unit C consists predominantly of fine to medium grained, grey, brown or yellow sand. It normally contains a trace to some silt and only minor organics, but clay, silt and gravel layers have also been encountered in some areas. Consistency of this sand varied from loose to very dense.

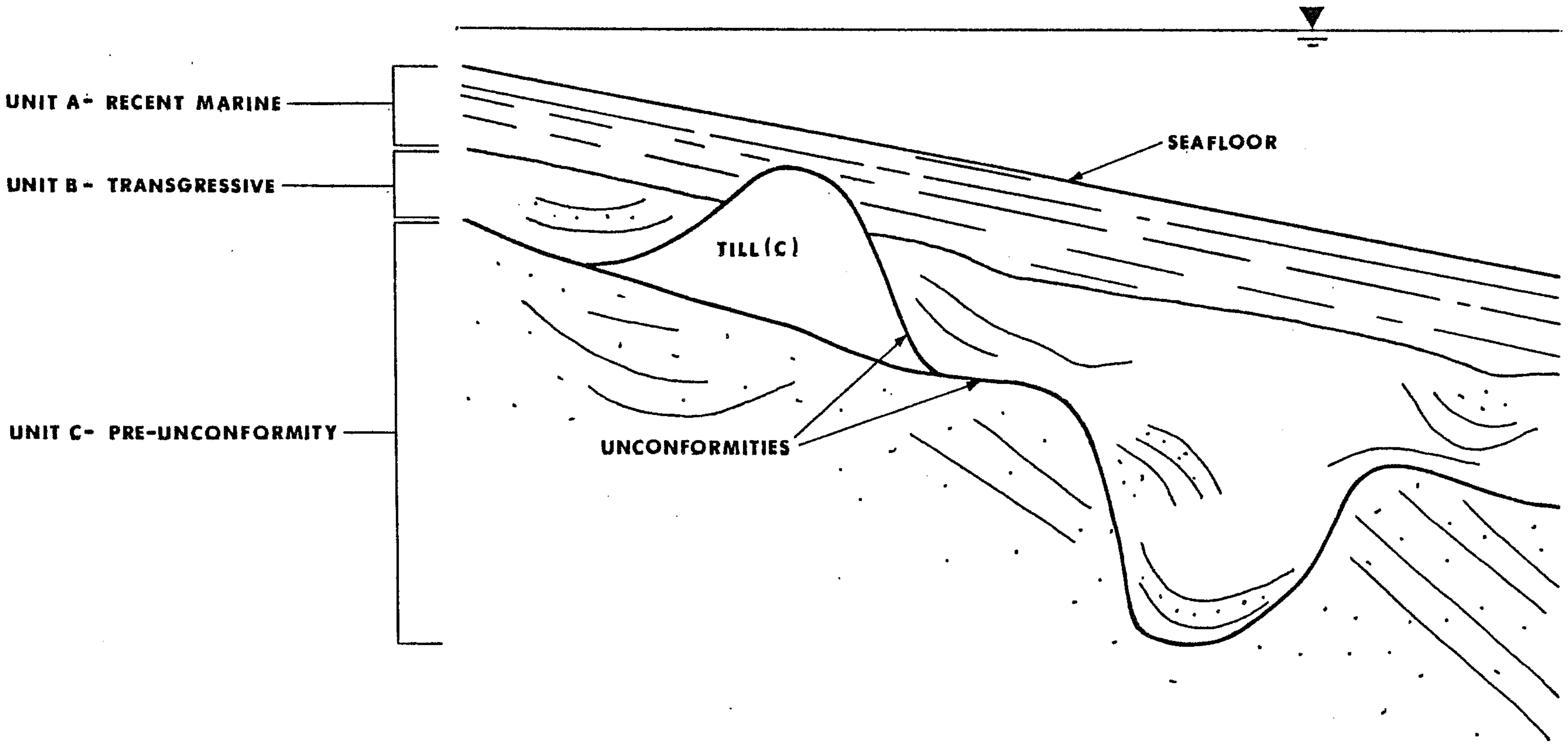
The origin of the sandy sediments which comprise Unit C are not clearly understood at this time. Some authors consider the sands to be "old delta", ie. part of a deltaic or littoral sequence deposited sometime prior to Wisconsin glaciation. A suggestion has also been made that the sands may represent periglacial deposits of about the same age. (Henry, 1976, pers. comm.)

In some places Unit C may include an upper complex sequence of silty, fine sand interbedded with grey to black stoney clay. It is reported that stratification of the coarser material and apparent horizontal shear planes were evident in some of the borehole samples recovered from this unit, and that the stiff to hard consistency observed gave this stratum a till-like appearance. Underlying this upper sequence is a medium plastic, silt-clay containing abundant salt-stained fissures in the upper few metres. Liquidity indices at this horizon are negative or close to zero. The apparent desiccation of the top of the silt-clay stratum is consistent with the geologic model's hypothesis regarding subaerial exposure of this unit and adds supporting evidence to the theory that the stoney clay may be part of a glacial till or morainal deposit which was deposited on the old unconformity surface and then partially buried during subsequent deposition of the more recent sediments.

Drawing No. 2-1 shows a schematic cross section illustrating the proposed relationship between the three units which make up the geologic model. The actual thickness of each unit is known to be highly variable across the shelf. In fact, Units A and/or B may be absent in some areas, so that the actual stratigraphy encountered at any one location may bear little resemblence to that shown on the drawing. For purposes of the model, Unit C includes all sediments deposited prior to the major unconformity which exists at the base of the transgressive sequence. As the borehole evidence indicates, however, Unit C probably contains both continental (glacial) and transitional (deltaic, littoral) sediments which are themselves separated by an unconformity of unknown duration. Since the lower unconformity is usually difficult to recognize without the benefit of excellent borehole samples, no stratigraphic distinction between the glacially derived and underlying sediments is made in the current model.

2.2 Ice Scouring

Of all the post-depositional processes which influence the subbottom



THE PROPOSED
GEOLOGIC MODEL

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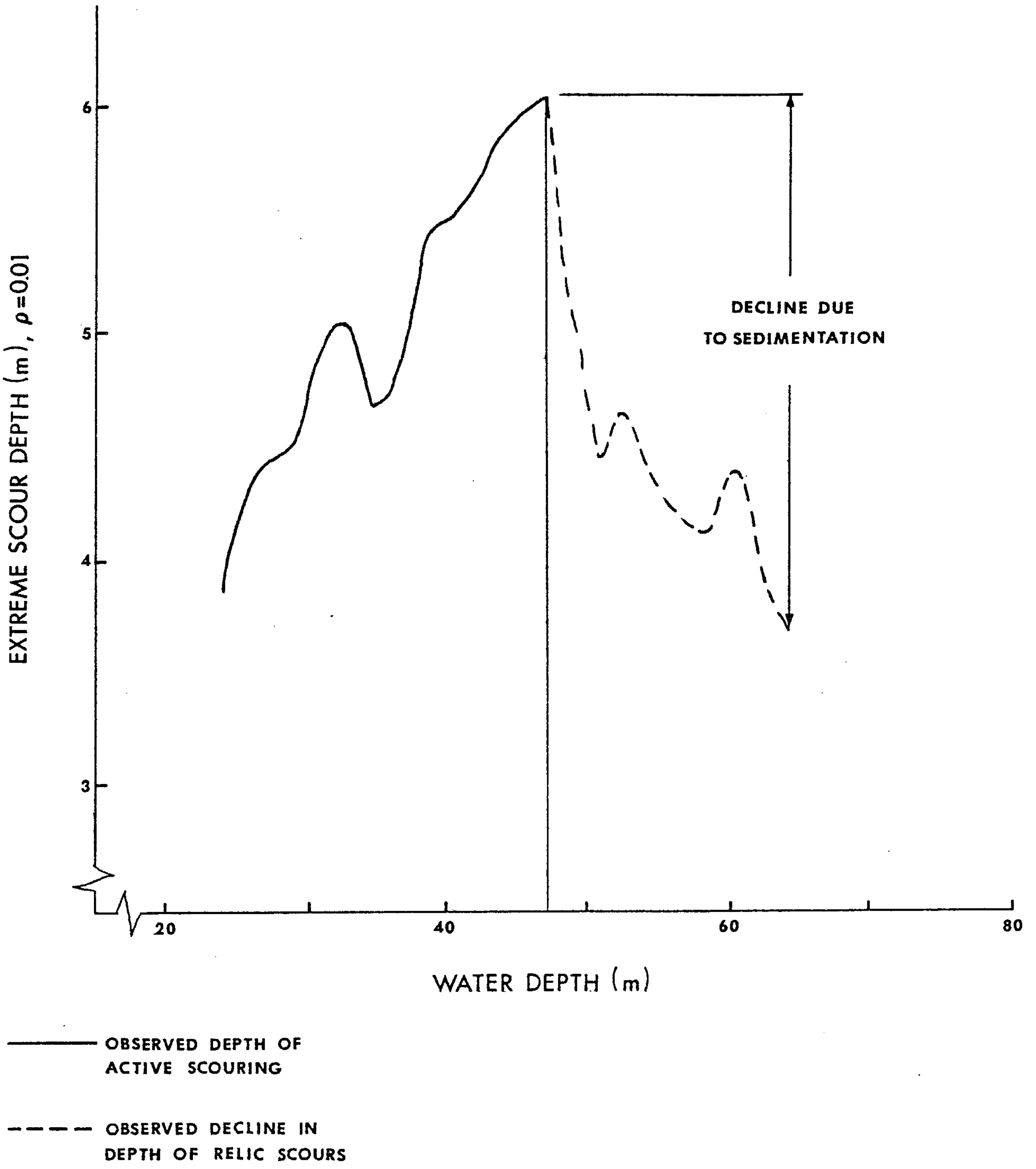
stratigraphy of the Beaufort shelf, ice scouring is probably the most significant. The frequency of scour occurrence observed on the present seafloor is highest between the 10 m and 50 m isobaths. It rapidly diminishes in both shallower and deeper waters, being practically negligible beyond the 80 m contour.

The direction and depth of scouring is influenced not only by topographic features such as embayments or other depressions on the seafloor, but also by the nature of the soil unit which is being scoured. Normally, scours are deepest and best preserved where the surficial sediments are soft and cohesive, as in Unit A, the recent marine sequence. Deep scours may also occur in areas of loose sands and non-cohesive silts, but may be smoothed out by seasonal wave and current processes. Stiff, over-consolidated clay (till), dense sand, and/or frozen seabed material offers considerably more resistance to erosion by keels of drifting ice, and thus the depth of scouring observed in such materials is greatly reduced.

Almost all scours mapped on the present seafloor are less than 2 m deep, but some 6 to 7 m deep scours have also been observed, mostly in areas where adjacent deep water provides ample opportunity for winds to build up the momentum of the ice without being slowed down by groundings en route.

According to Lewis et al (1976) the depth of active scouring is believed to increase as a function of water depth to about the 47 m isobath (Drawing No. 2-2). Beyond this depth all the observed scours are believed to be relic, ie. formed in shallower waters when the sea level was much lower. The observed decrease in scour depth beyond the 47 m isobath is thought to be due to natural erosion of the scour embankments and progressive



EXPLANATION OF SCOUR DEPTH
DECLINE BY SEDIMENTATION
(after Lewis et al, 1976)

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infilling by recent sedimentation.

The thickness of existing subbottom sediments affected by ice scouring is not limited to the present maximum depth of scouring observed on the shelf. Deeper sediments, which were closer to the seafloor in the past, may also have been scoured as they passed through water depths where active scouring was occurring. If the scouring was intense, then the ploughing action of the massive ice keels may have completely destroyed the original stratigraphy, leaving behind a zone where the bedding is so highly disturbed that older strata now rest on top of, adjacent to, and perhaps under younger beds in a completely random manner. If the scouring was not intense, then individual relic scours may be wholly or partly preserved in the stratigraphic record.

A stratigraphic zone characterized by the presence of these relic or paleoscours is believed to be present over much of the continental shelf east of Mackenzie Bay and probably includes to some degree all three units in the geologic model. Offshore, in deep water beyond the limit of both active scouring and those relic scours which have not yet been infilled by recent sedimentation, a thick paleoscour zone is believed to occur at depth beneath the seafloor. In shallower waters the paleoscour zone may be considerably thinner, its upper surface being coincident with the present seafloor and the depth of its lower surface being controlled by the depth of present scouring, which in turn is a function of both the magnitude of the present ice keels and the nature of the subbottom sediments.

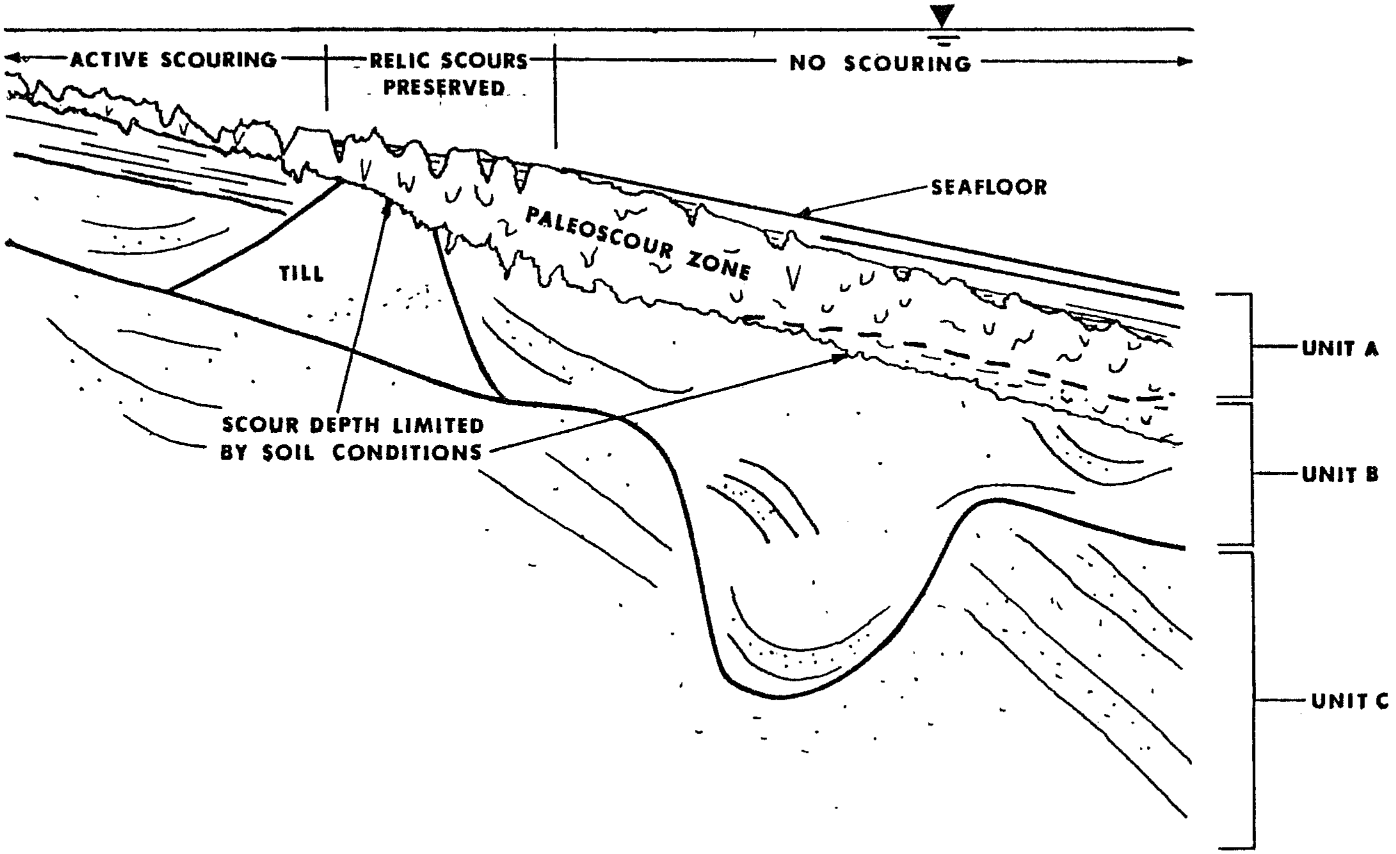
Ice scouring can have a pronounced effect on the actual sediment properties, as well as on the stratigraphy. Dense sands which occur at the seafloor in some areas may be loosened during the scouring process. Where soft cohesive sediments are scoured for the first time, however, compression by the ice may result in significant overconsolidation. The latter process may account for those rare occurrences where stiff clays of recent marine origin are encountered at the seafloor.

Drawing No. 2-3 shows a revised schematic version of the generalized geologic model which incorporates the effects of ice scouring on the sediments. It should be noted that although the stratigraphy within the paleoscour zone may often be badly disturbed, the basic lithology of each unit often remains unchanged. Thus a change in soil type or consistency which is observed above the base of the paleoscour zone in an apparently massive sequence of sediments may be the only indication of the original stratigraphic boundary separating units of the geologic model.

2.3 Sediment Dispersal and the Geologic Model

Pelletier (1975) describes an extensive study of sediment dispersal in the southern Beaufort Sea based on textural and mineralogical examination of over 1200 samples. His conclusions provide important evidence regarding the lateral distribution of geologic units proposed in the present model:

The seafloor sediments on the continental shelf consist predominantly of clay and silt in the western and central areas (Drawing Nos. 2-4 and 2-5) and somewhat coarser material in the eastern part (Drawing No. 2-6). In the offshore areas adjacent to the delta, Pelletier (1975) attributes this dispersal pattern to sediment discharge from the Mackenzie River which is carried north and east under the influence of the Coriolis force. On the eastern portion of the shelf the dispersal pattern is partly due to sedimentation of fine particles over a relic surficial sand and par



EFFECT OF ICE SCOURING ON THE GEOLOGIC MODEL	M.J. O'CONNOR & ASSOCIATES LTD.	
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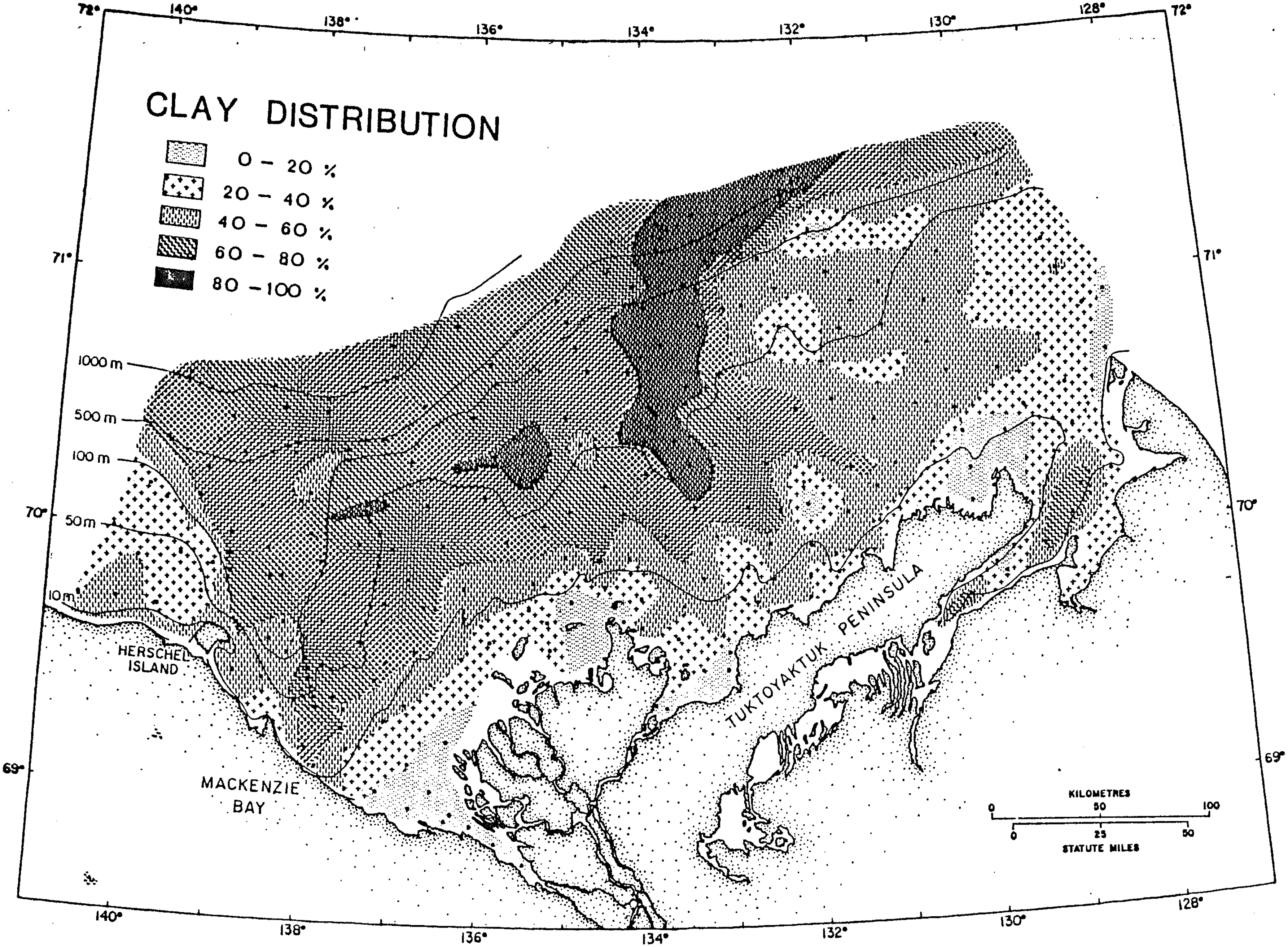

DISTRIBUTION OF CLAY
(after Pelletier, 1975)

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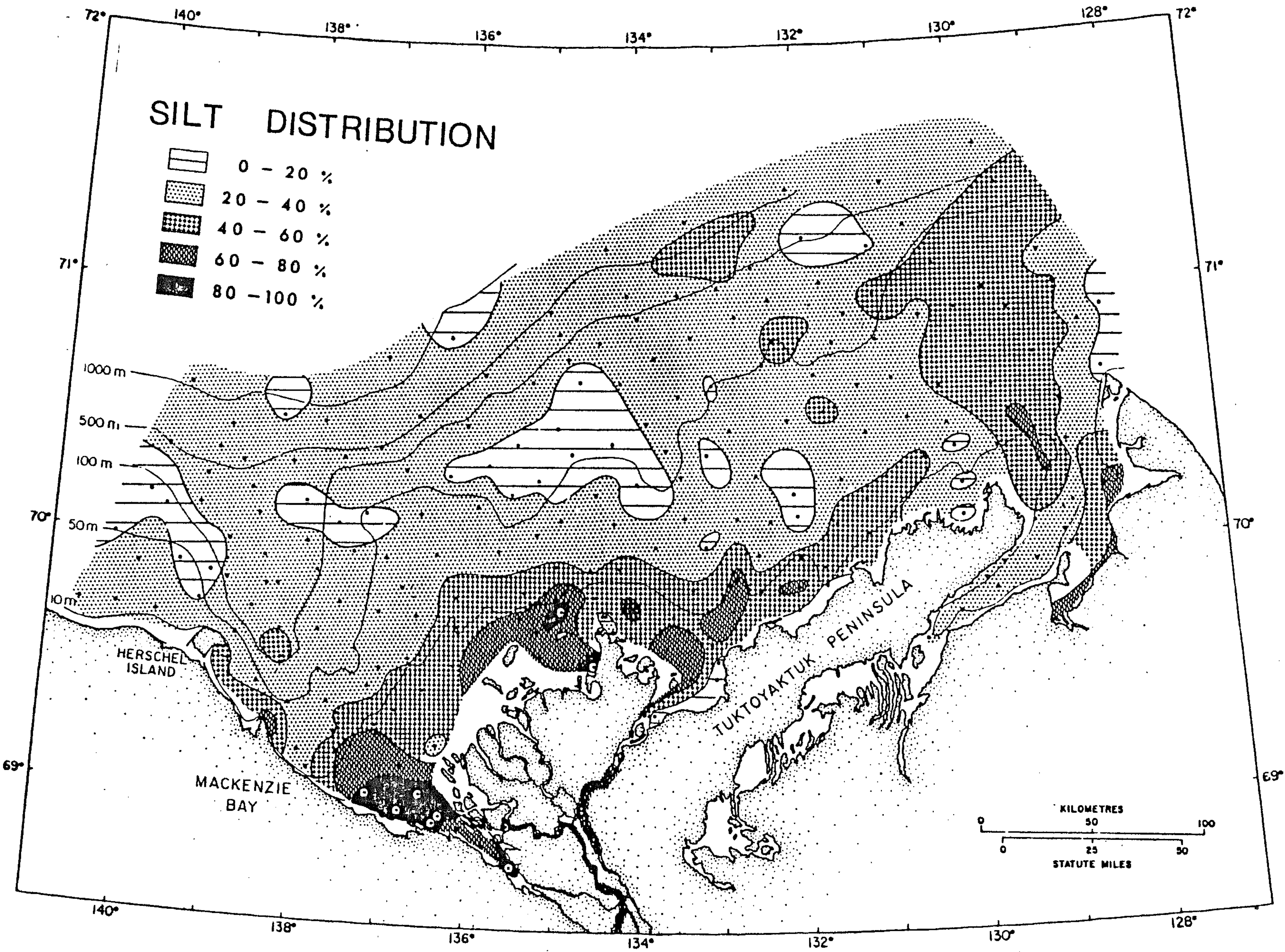

DISTRIBUTION OF SILT
(after Pelletier, 1975)

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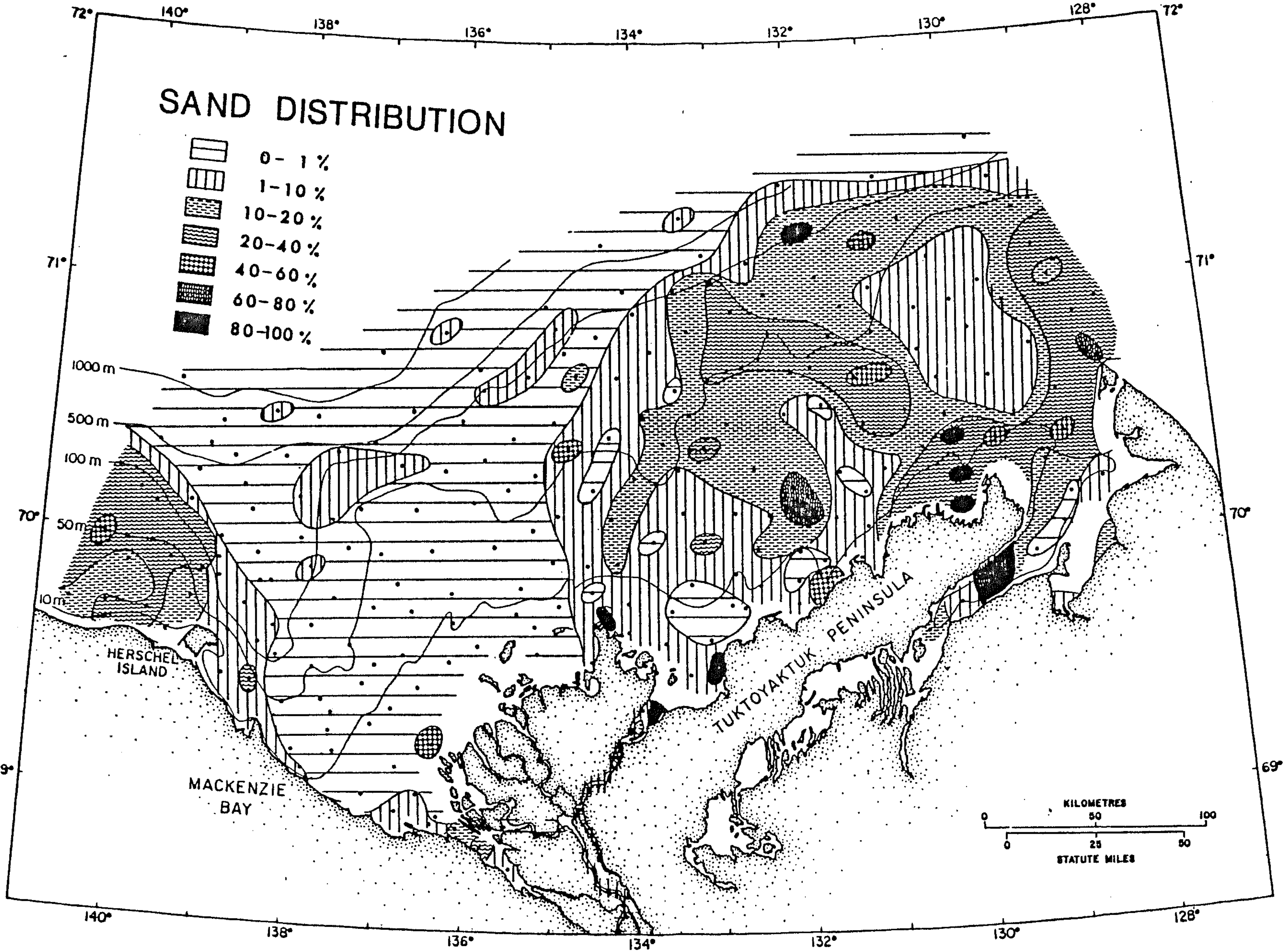

DISTRIBUTION OF SAND
(after Pelletier, 1975)

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due to possible erosion of this sand by intermittent westward-moving bottom currents. As the author points out, the eastern shelf therefore appears to serve alternately as both a depositional and erosional site.

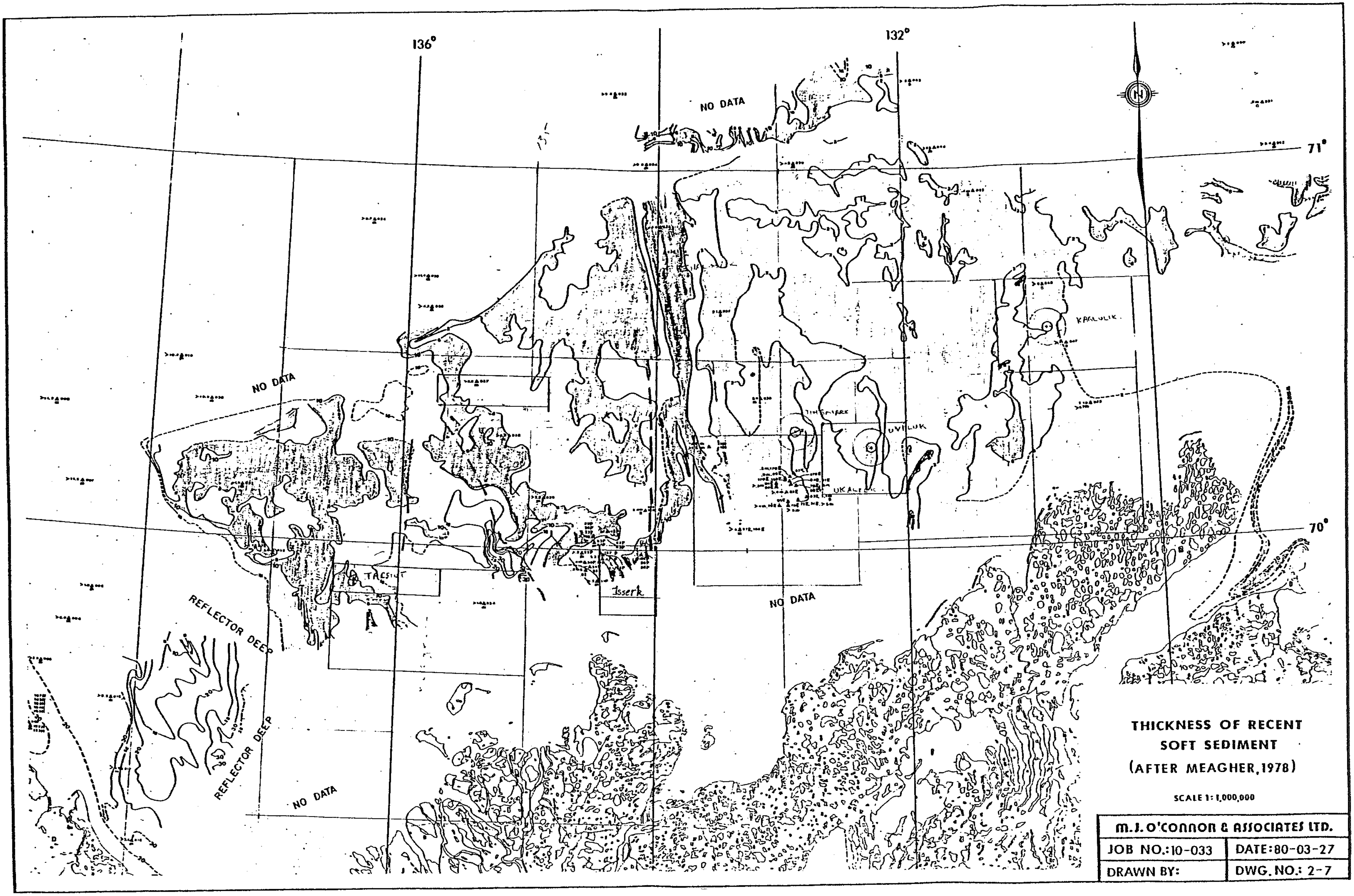
Unit A, the recent marine sequence of the generalized model, is composed principally of those fine grained sediments which Pelletier describes as being typical of the west and central shelf. Coarser grained sediments of the eastern shelf may be equivalent to either Unit B, the transgressive sequence, and/or Unit C, the pre-unconformity sequence. At the present time it is uncertain whether a thin veneer of Unit A also exists in the eastern area, or whether extensive erosion of the lower units is currently taking place.

2.4 Thickness of Recent Soft Sediments

Shearer (1972a) and Meagher (1978) used echo sounding and seismic records to map what they thought was the thickness of soft sediments on the Beaufort Shelf.

The measured unit described by these authors is generally thinner than 6 m on the shelf east of Mackenzie Bay (Drawing No. 2-7), but may thicken to 15 or 20 metres where it infills certain large north and northwest trending depressions. Values between 0 and 2 m were commonly mapped at the shelf edge, in nearshore high-energy environments composed principally of sand, and over large areas on the eastern portion of the shelf.

The question arises whether Shearer and Meagher have measured an acoustic interval which represents some unique geological unit, or have merely recorded the depth to the first high amplitude seismic event, regardless of geologic origin.



THICKNESS OF RECENT SOFT SEDIMENT (AFTER MEAGHER, 1978)

SCALE 1: 1,000,000

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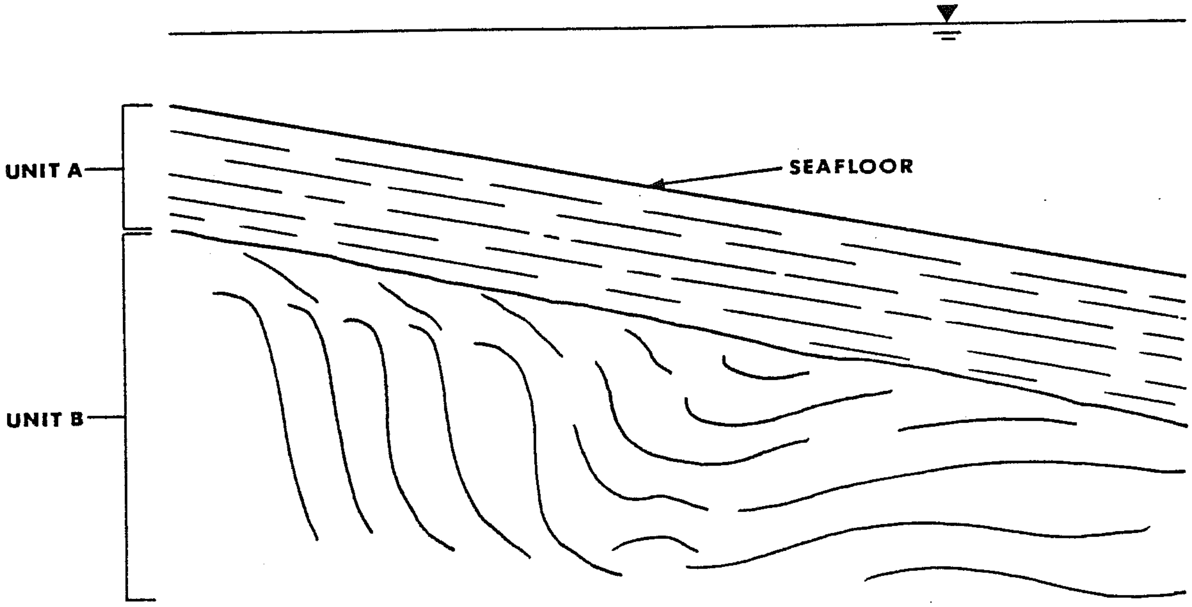
The authors make the assumption that "the thicknesses measured throughout the survey area represent the amount of post-glacial deposition of fine sediments [on the continental shelf] to date and that the lower horizon measured to is the same in every case."

The second assumption, as stated, is clearly invalid. In terms of the generalized model, the measured unit should be equivalent to Unit A, the recent marine sequence (the term post-glacial may be somewhat inaccurate here). The lower horizon measured to would not then have to be the same in every case (it could be either Unit B or Unit C), as long as it represented the base of the recent marine sequence.

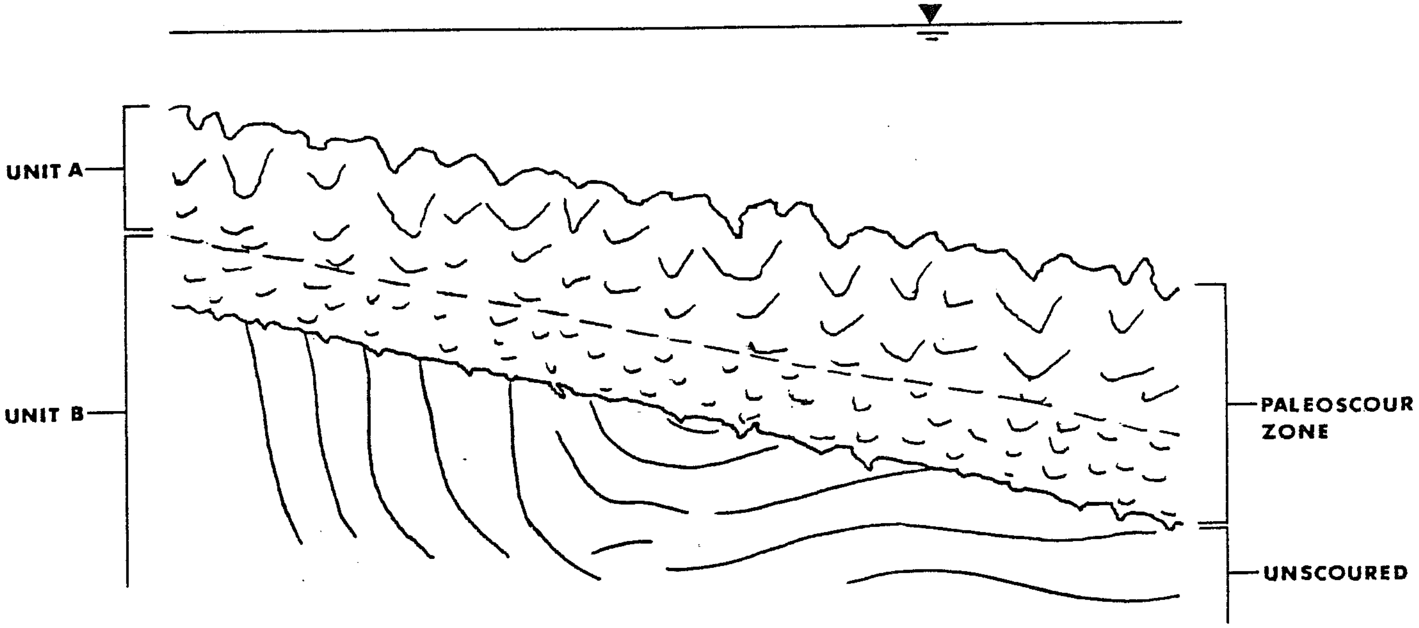
Meagher (1978) does point out that the second assumption may be in error where shallow gas or ice-bonded sediments prevent complete acoustic penetration, but makes no mention of possible errors due to paleoscouring. Drawing No. 2-8 depicts schematically the changes which can occur at an acoustic interface after scouring has taken place. In I, the soft cohesive sediments of Unit A rest directly on denser granular material of Unit B, and the acoustic interface between the two is sharp and well defined. In II, the sediments of Unit A have been compressed by repeated scouring, while the uppermost sediments of Unit B have been loosened by the same process. In addition, repeated scouring of both units has completely homogenized the soil conditions, so that the interface is now gradational.

The question must then be considered whether the acoustic response measured on the seismic record still comes from the same level as the original (prescour) interface, from the base of the paleoscour zone, or from somewhere below.

I



II



EFFECT OF SCOURING
ON STRATIGRAPHY

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In spite of these obvious points for discussion, the maps produced by Shearer (1972) and Meagher (1978) appear to be in general agreement with the geologic model as it is presently proposed. A pronounced thinning of the measured unit 25 km north of Garry Island, for instance, can be correlated to borehole evidence of a shallow till (part of Unit C) beneath the seafloor, and a shallow piston core examined by Pelletier (1975) may provide similar evidence for thinning which occurs north of Pullen Island. In addition, those western and central shelf areas mapped as having approximately 6 m of recent sediments may be correlated with Pelletier's (1975) sites of active deposition, while the thin (eastern shelf) areas correlate with his sites of non-deposition or erosion.

2.5 Permafrost

The occurrence of permafrost[1] underlying the continental shelf of the southern Beaufort Sea was first established in 1970, during an ocean floor sampling program conducted by the petroleum industry. Subsequent geothermal studies have confirmed the general presence of negative sub-bottom temperatures in those areas lying beyond the 20 m isobath and underlying much shallower areas at specific locations (Judge et al, 1976 and Macaulay et al, 1977).

Hunter et al (1974) interpreted a large velocity contrast which appeared on subsea refraction records to be the result of ice-bonding of the sediments at depth. Subsequent studies using the front ends of reflection seismic records supplied by the petroleum industry indicate that such ice-bonding is probably widely distributed under the continental shelf east of 135° longitude. According to Neave et al (1977), the depth to ice-bonding

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[1] Unless otherwise stated, the term permafrost refers to soil or rock having a temperature which is perennially below 0°C, as defined by Brown and Kupsch (1974).

may be highly variable: thin, shallow layers of ice-bonded material may be separated both laterally and vertically from deeper, thicker ice-bonded layers by patchy zones having lower seismic velocities.

O'Connor (1977) points out that the upper boundary of permafrost, as determined from the thermal condition of the soil, is not always equivalent to the upper boundary of the ice-bonded layer, as determined from the acoustic velocity, since acoustic velocity is primarily a function of ice-content, not temperature. Ice content, in turn, is related to temperature, but also to other factors, some of which include grain size, void ratio, natural moisture content and salinity. Thus, coarse grained sediments such as sands or gravels, when marginally below 0°C, may exhibit much higher acoustic velocities than silts or clays under identical thermal conditions. A permafrost-affected coarse grained sediment may therefore appear acoustically to be frozen, while an adjacent fine-grained sediment at the same temperature does not. In order to limit future confusion which occurs due to nomenclature, O'Connor (1977) proposes that the term ACOUSTIC PERMAFROST TABLE be adopted to designate the upper boundary of ice-bonding as defined by seismic reflection or refraction techniques.

Mackay (1972) considers that subsea permafrost may presently occur in two modes:

1. Where mean annual seabottom temperatures are negative, equilibrium permafrost could exist as it does on land. Ice bonding would then depend on such factors as temperature, salinity of the pore fluids, soil properties and sedimentation rates.

2. Where permafrost beneath the seafloor is not in thermal equilibrium with bottom temperatures, then most of it is probably degrading relic permafrost originating from subsidence, marine transgression and/or coastal retreat.

MacKay (1972) estimates that permafrost formed in the first mode is unlikely to exceed 150 m in thickness. Using the generalized sea-level curve for the past 100,000 years and some assumed temperature and soil properties, he estimates that relic permafrost up to 600 m in thickness could be present under some areas of the shelf.

No large, massive ice samples have been recovered from beneath the seafloor to date, although MacAulay (1980, pers. comm.) reports evidence which suggests that massive ice may have been encountered during 1977 jet drilling operations conducted by Energy Mines and Resources Canada north of Pullen Island.

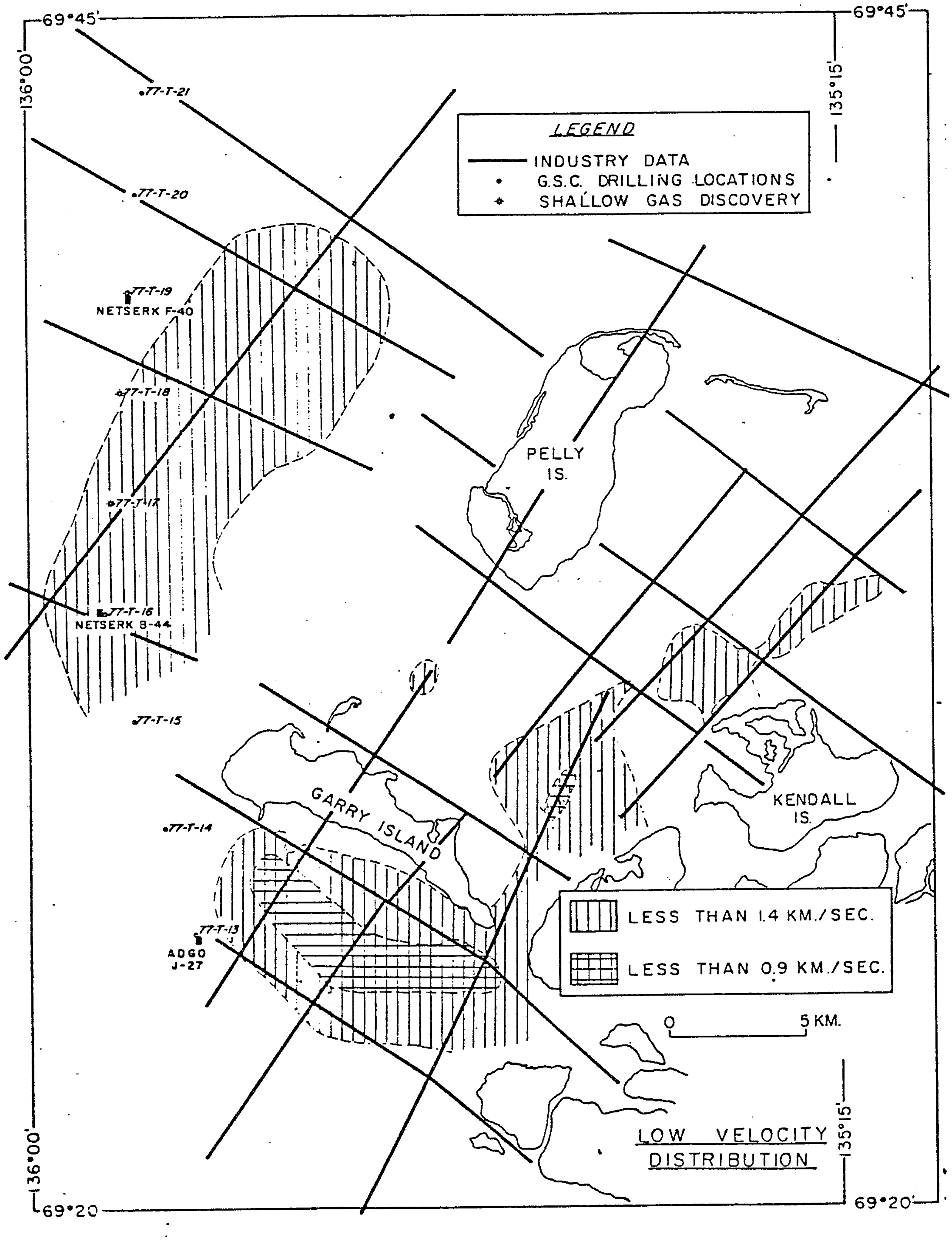
Small ice lenses had already been recovered earlier from boreholes drilled north of Garry Island and north of Pullen Island. In the latter case, Mackay (1972) concluded from laboratory analyses that the ice (water) probably came from rain and snow, indicative of a cold climate, and therefore may represent relic permafrost. If such is the case, then the surficial clayey silt in which the ice lenses were found is probably not equivalent to Unit A, the recent marine sequence, but may be a fine grained equivalent of either Unit B or C. This points to the danger of relying on a single piece of information, eg. soil type, to determine completely the nature of the stratigraphic units in such a complex geologic environment as currently exists under the southern Beaufort Sea.

2.6 Shallow Gas

Shallow gas has been encountered during several recent studies of soil conditions underlying the continental shelf. Neave et al (1977) state that anomolously low acoustic velocities in the subbottom sediments near Garry Island can be correlated with the occurrence of gas in many of the jet-drilled boreholes shown in Drawing No. 2-9. MacAulay (1980, pers. comm.) confirms that shallow gas was also encountered during drilling operations approximately 14 km north of Pullen Island. At one location a 20 cm diameter stovepipe was reportedly used to flare gas which collected under the sea ice following drilling. In spite of the fact that most of the gas was probably carried away from the drilling location by currents, the gas collected in the stovepipe flared continuously for more than 3 days.

Natural gas seeps north of Kugmallit Bay were described by O'Connor (1977); the author reported using side scan sonar and high resolution seismic techniques to show that gas bubbles which appeared in the water column were seeping from several small vents on the sea floor. It could not be determined, however, whether the gas originated from decomposition of organics (swamp gas), from degradation of gas hydrates as Neave et al (1977) suggest for the area near Garry Island, or from leaky stratigraphic traps in the deeper geologic section.

Shallow gas may be encountered within any of the units of the proposed geologic model, as shown schematically in Drawing No. 2-10. At I, gas has been trapped by fine grained, relatively impermeable sediments deposited over a topographic high formed from coarse grained, high porosity sediments. At II, the overlying sediments are not sufficiently impermeable to prevent continued upward migration of the gas, with the



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DISTRIBUTION OF LOW VELOCITY LAYER
(after Neave et al, 1977)

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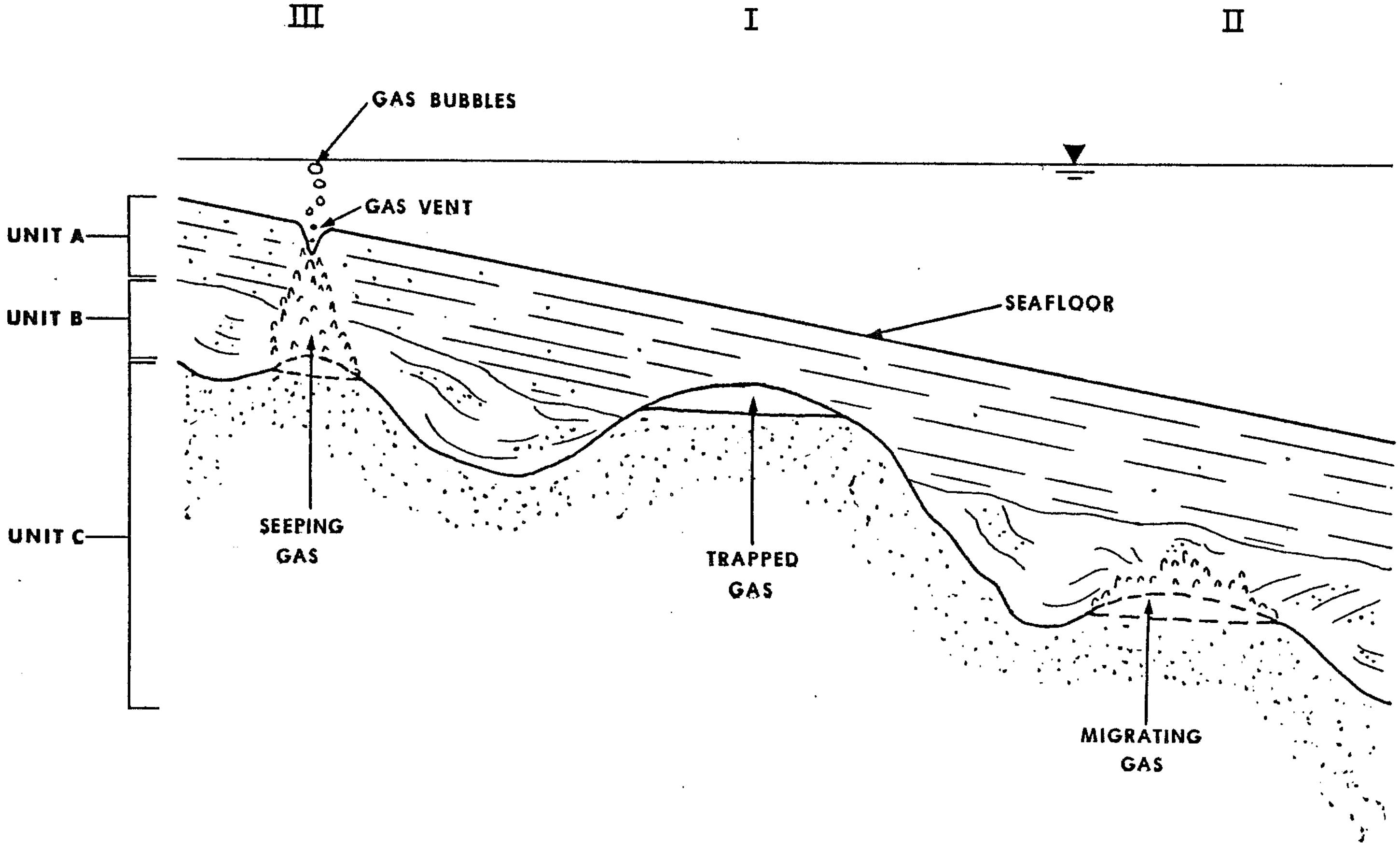

SCHEMATIC DIAGRAM
OF
SHALLOW GAS OCCURRENCE

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result that the lower beds of the surficial unit have become gas-charged. At III the trapping mechanism is clearly ineffective and subsurface gas migrates upwards through the subbottom sediments until it bubbles out at the seafloor. Continuous upward gradients in the area of the seep have removed some of the shallow sediments, creating a small crater.

3.0 ACOUSTIC EVIDENCE AND ITS RELATIONSHIP TO THE MODEL

The Geological Survey of Canada has been gathering seismic reflection data in the southern Beaufort Sea since 1970, using a variety of vessels and equipment (see Table 3-1). While no formal compilation of all these data has yet been undertaken, the scope of the present contract did provide an opportunity to briefly review and interpret some of the seismic profiles as they relate to the development of a geologic model for the continental shelf.

In the section which follows, photographs of reflection seismic profiles are used to illustrate many aspects of the geologic model presently being proposed; some acoustic examples of special features which occur on the shelf are also presented and discussed.

A numbering system has been adopted on the photographs to facilitate description of the acoustic stratigraphy in the text. The geographic location of each seismic section is shown on Drawing No. 3-1, according to plate number. Each arrowhead on the map designates the direction in which the seismic profile was shot; the direction of shooting on all photographs is left to right. The locations given on Drawing No. 3-1 are approximate, since all locations had to be transferred from other maps having different scales and projections.

3.1 Acoustic Stratigraphy

Of all the seismic profiles reviewed during this study, Plate 1, shot about 14 km north of Hooper Island, undoubtedly provides the best definition of the acoustic stratigraphy characterizing Units B and C of the geologic model. The unconformity (1) occurs at about 20 milliseconds (ms)

CRUISE		SEISMIC EQUIPMENT				
SHIP	YEAR	ENERGY SOURCE	OUTPUT	HYDROPHONE	RECORDER	RECORD
CSS HUDSON	1970	Huntec 2A Sparker	165 joules	G.I. MP 35	Huntec 2A	8" wes paper 250 ms/sp
		10 cu in Bolt Par Air Gun Model 600B	120 db	Custom Cable 25' array	Alden 419	19"wes paper 500 ms/sp
CSS RICHARDSON	1970	Huntec 2A Sparker	165 joules	G.I. MP 35	Huntec 2A	8" wes paper 250 ms/sp
NORTH STAR	1971	Huntec 2A Sparker	165 joules	G.I. MP 35	Huntec 2A	8" wes paper 250 ms/sp
		1 cu in & 5 cu in Bolt Par Air Gun Model 600B	1-108 db 5-118 db			
NORTH STAR	1972	1 cu in & 5 cu in Bolt Par Air Gun Model 600B	1-108 db 5-118 db	G.I. MP 35	Huntec 2A	8" wes paper 250 ms/sp
CSS PARIZEAU	1972	1 cu in & 5 cu in Bolt Par Air Gun model 600B	1-108 db 5-118 db	G.I. MP 35	Huntec 2A	8" wes paper 250 ms/sp
PRESSURE RIDGE	1974	BBN Acoustipulse Boomer	500 joules	BBN-Aquatronics 30' array	EPC 4100	19"des paper 250 ms/sp
NAHIDIK	1977	EG&G Model 234 Energy Source & Uniboom	300 joules	EG&G Model 265 8 element eel	RATHEON UGR-196A	49 cm dry paper 500 ms/sp
NAHIDIK	1978	EG&G Model 234 Energy Source & Uniboom	300 joules	EG&G Model 265 8 element eel	EPC 4100	19" des paper 250&500 ms/sp

Table 3-1

High Resolution Reflection Data Collected

by

the Geological Survey of Canada

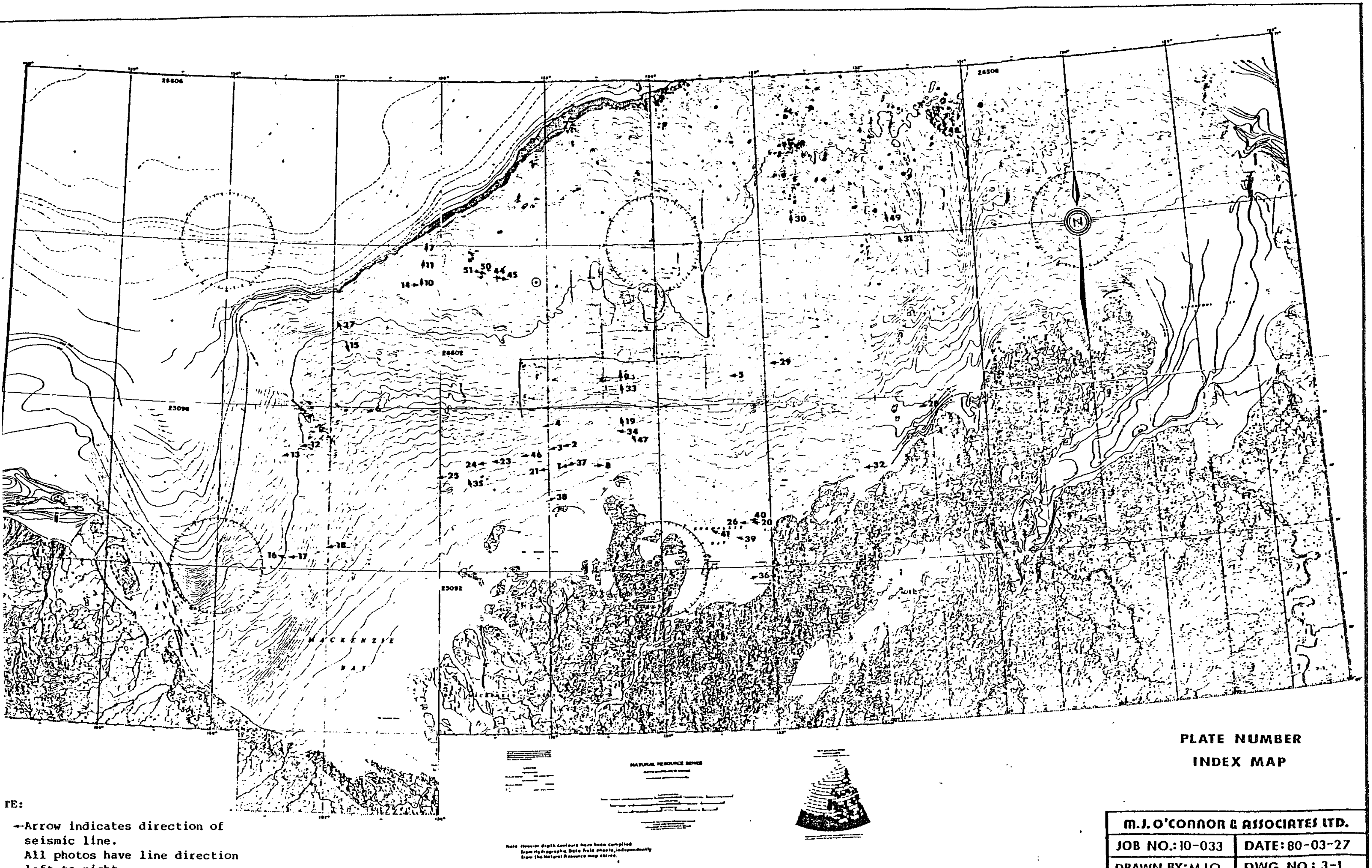

PLATE NUMBER
INDEX MAP

TE:

←Arrow indicates direction of seismic line.
All photos have line direction left to right.

M.J. O'CONNOR & ASSOCIATES LTD.	
JOB NO.: 10-033	DATE: 80-03-27
DRAWN BY: MJO.	DWG. NO.: 3-1

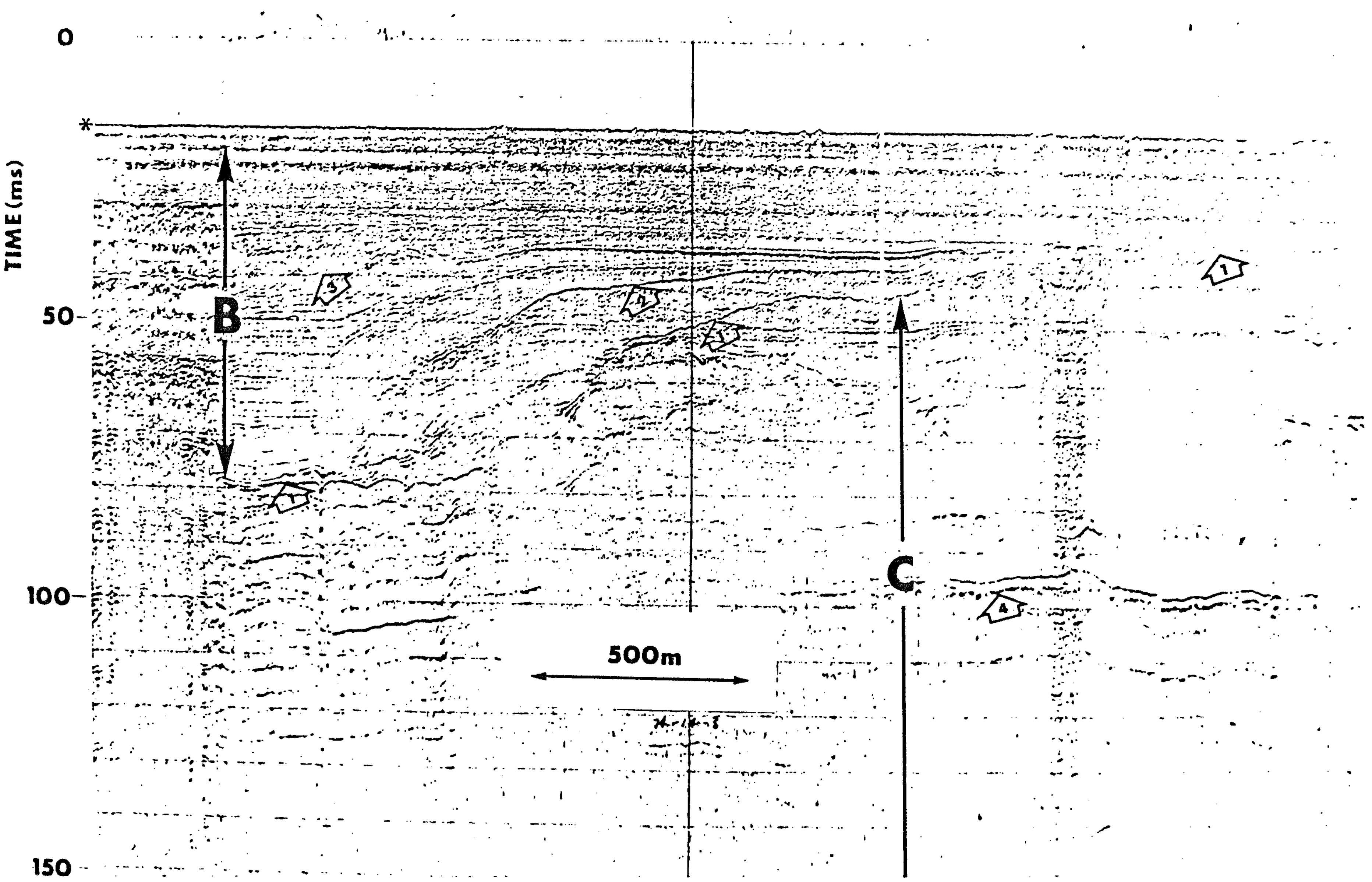

Plate 1.

below the seabed[1] on the right side of the photograph. This represents a depth[2] of about 15 m subseabottom. The left side of the section shows a 33 m deep channel cut into the pre-unconformity sediments (Unit C). This channel has been progressively infilled by subsequent deposition of a transgressive sequence (Unit B), which includes a series of beach terraces (2) and some cross-bedding (3). Lithologies in such a complex environment probably include clays, silts, sands and gravels. A deep reflector (4) may represent the acoustic permafrost table, ie. the top of acoustic ice-bonding in the sediments. Negative temperatures likely occur above this level, but the soil is either too fine-grained or the pore waters too saline to generate substantial interstitial ice. The boundary between Unit B and Unit A is not evident, but the latter sequence is expected to be thin at this location, perhaps less than 3 m thick.

The principal criterion normally used to identify the top of Unit C is its unconformable relationship to the overlying sediments. The nature of the interface (good reflection coefficients) and the nature of the survey instrumentation (analog recording, no time-varying gain control) often preclude significant acoustic penetration below the unconformity. This often makes positive identification of the unconformity more difficult, since it may be easily confused with another irregular impenetrable

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[1] Where it can be identified, the seabed has been marked with an asterisk along the left hand side of each photograph.

[2] The formula 7.5 m = 10 ms has been used in this report to calculate approximate depths from two-way seismic travel times through non-ice-bonded sediments.

reflector representing the acoustic permafrost table.

Both sides of the channel shown on Plate 1 are also evident on data recorded on board the Nahidik in 1977. Plates 2 and 3 were shot approximately 7 km northwest of the section shown in Plate 1. They indicate that the channel is approximately 4 km wide, flat bottomed and only 22 m deep at this location. While the unconformity surface (1) and acoustic permafrost table (2) are weak but still recognizable reflectors, interpretation of individual strata in the overlying transgressive sequence is all but impossible. The origin of the dark area (3) shown on Plate 3 is not presently known, but either shallow gas or discontinuous acoustic permafrost (local ice-bonding) is suspected.

As mentioned above, the nature of the unconformity is such that a good acoustic signal is usually returned from this interface even when definition of the other units is impossible. Plate 4 shows low frequency air gun data obtained in 1972 along a northwest section across the same channel. The record indicates that the bottom of the unconformity channel (1) may not be as horizontal as observed elsewhere. Acoustic permafrost (2), which is apparently quite shallow under the banks, seems to dip off under the channel.

Plate 5, recorded approximately 75 km north of Tuktoyatuk, confirms Meagher's (1978) conclusion that the post-unconformity sediments in the eastern and control shelf areas are relatively thin, except where they infill old channels. Indeed the record suggests that the unconformity (1) may be coincident with the seafloor on the left side of the photograph, supporting Pelletier's (1975) hypothesis regarding possible active erosion in this area.

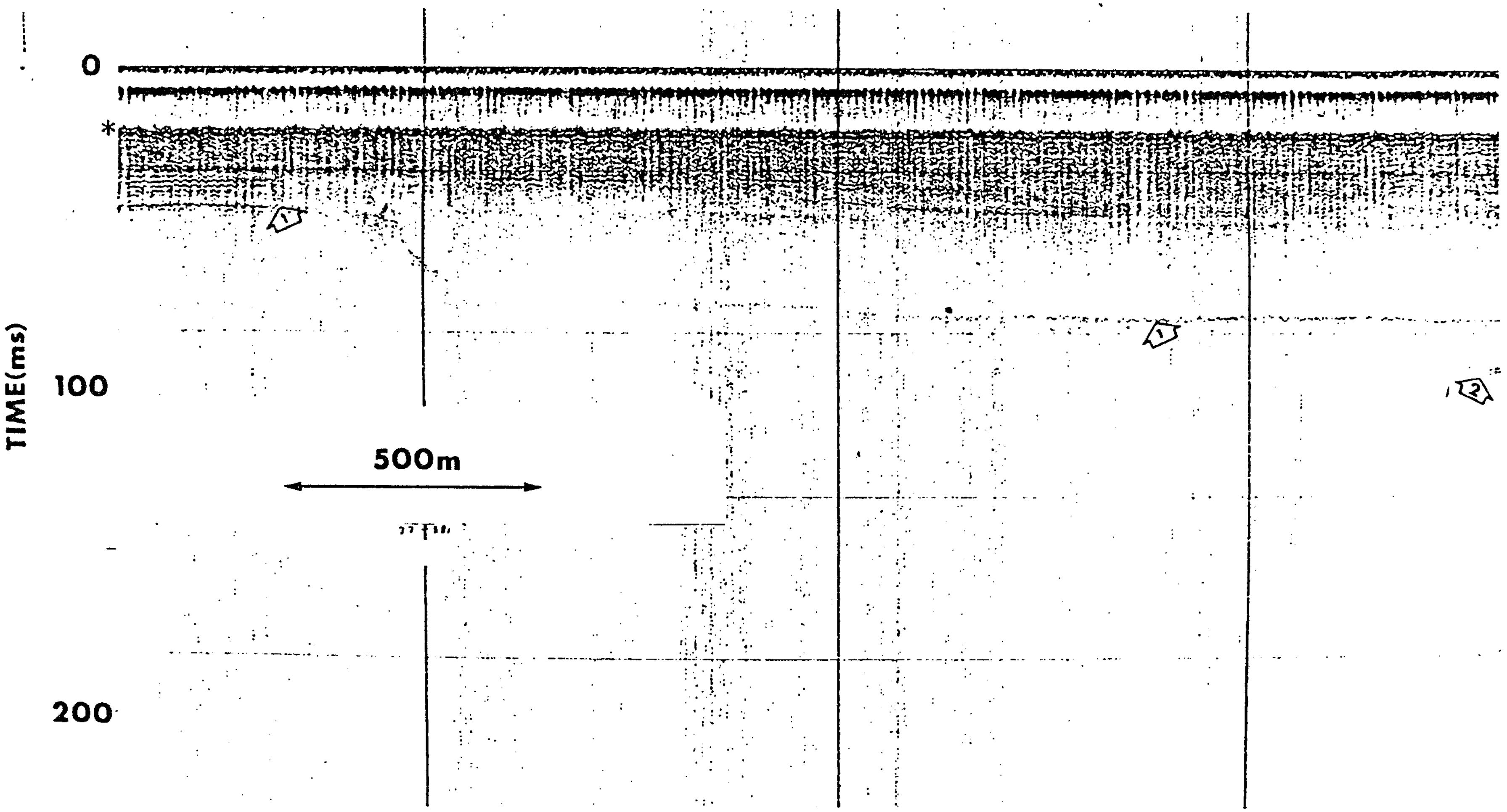

Plate 2.

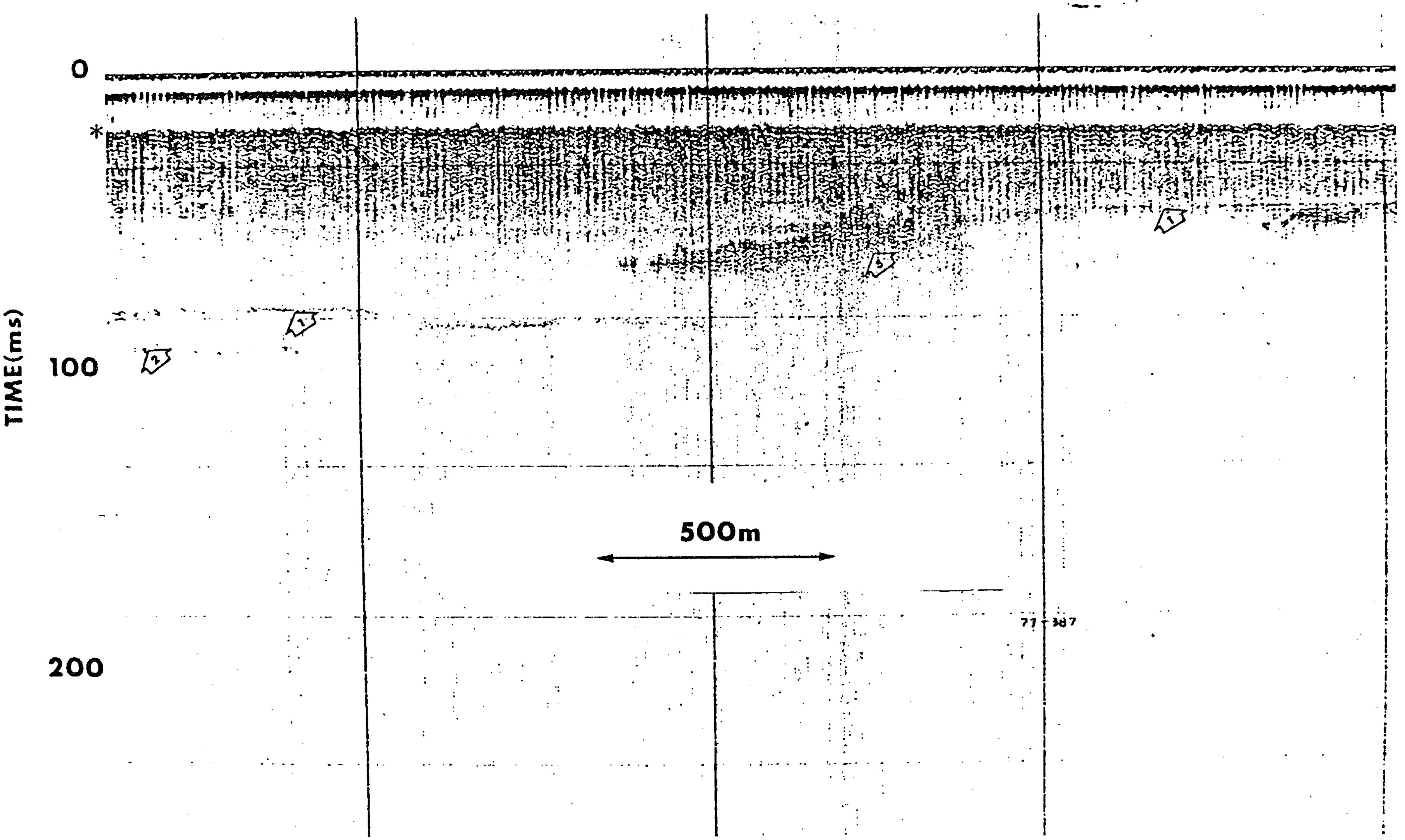

Plate 3.

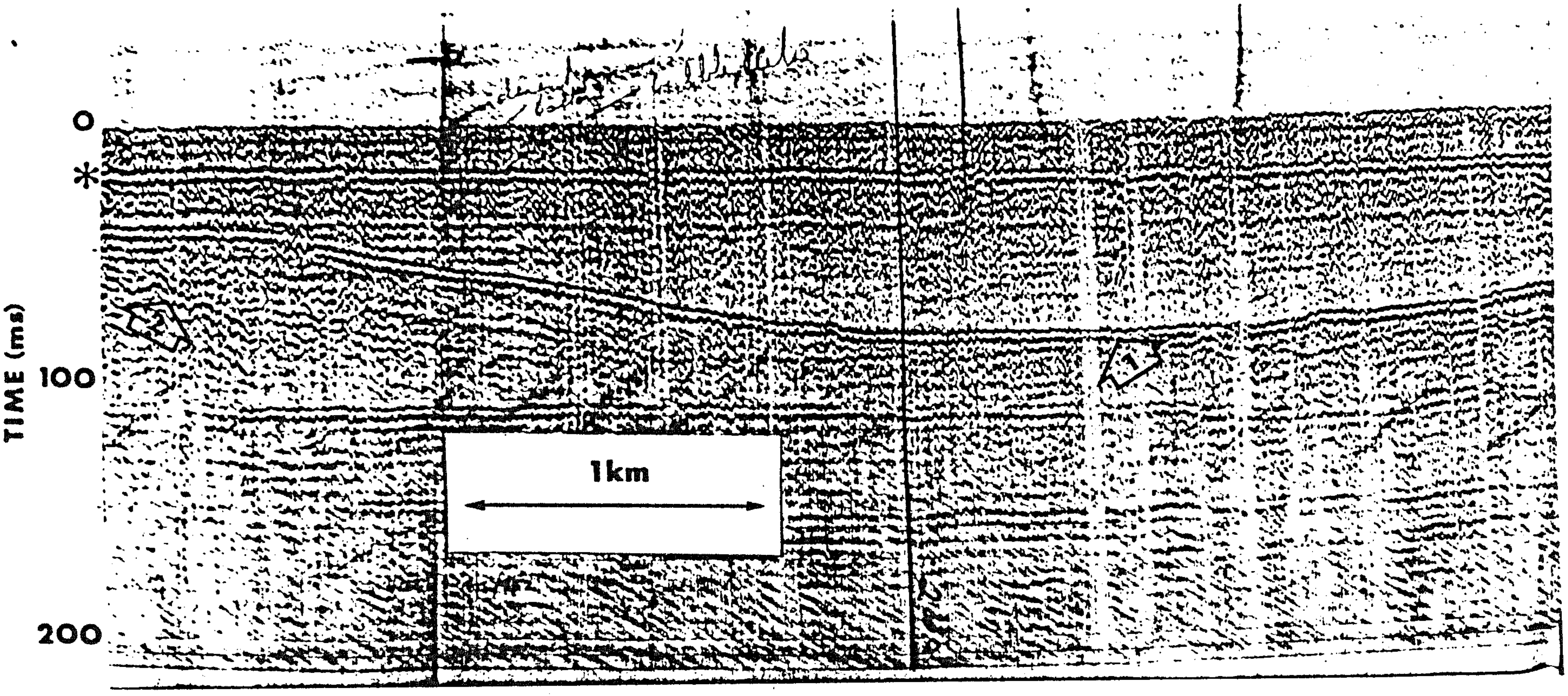

Plate 4.

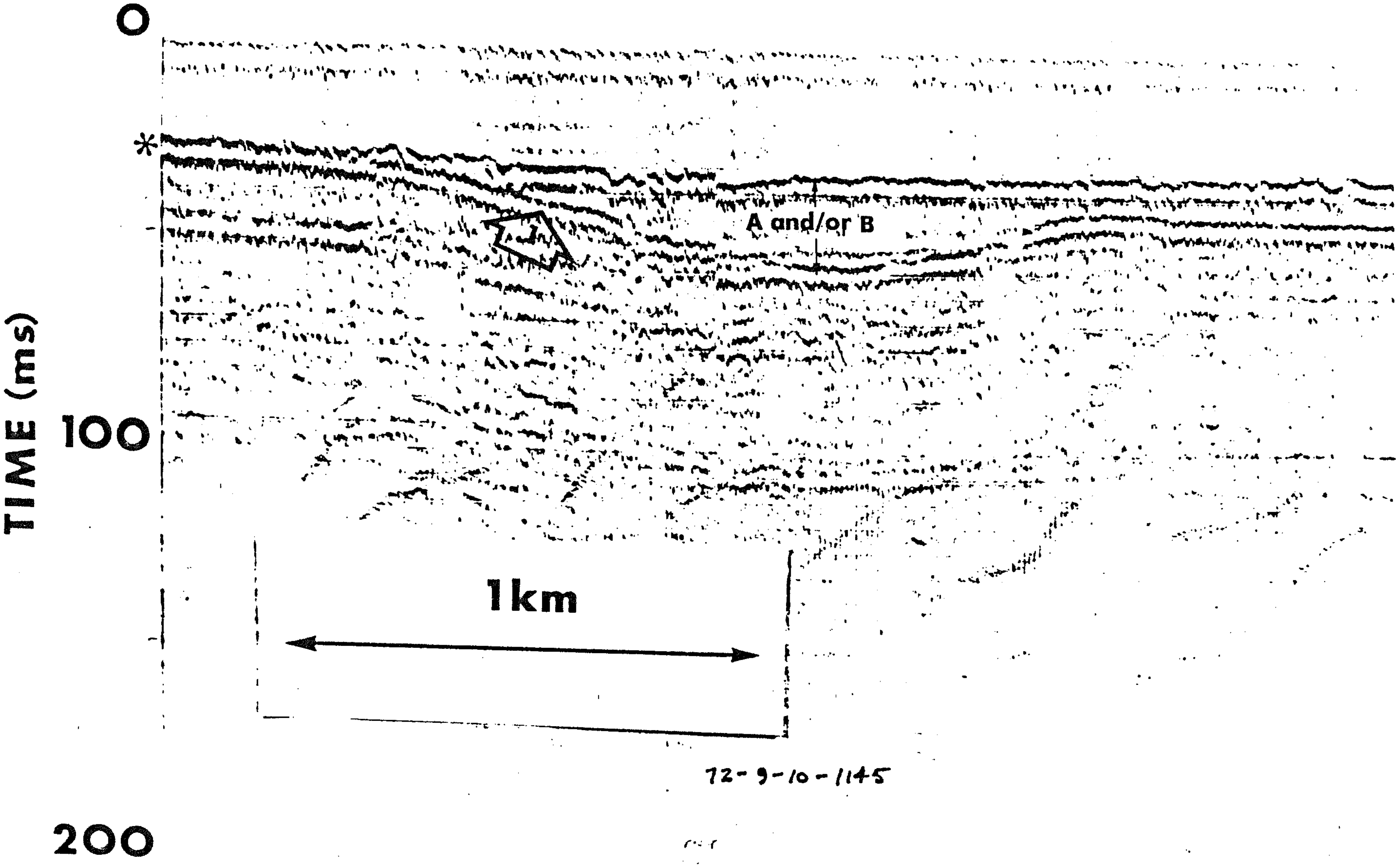

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Plate 5.

A strong shallow reflector (1) occurring above the unconformity (2) on Plate 6 may represent the top of the transgressive sequence (Unit B). This has been buried, in turn, by recent marine sediments (Unit A) shown on the right side of the photograph to be approximately 7 m thick. Apparent dips of approximately 0.5° are evident on strata (3) below the unconformity.

Dips of 1° to 3° are apparent on similar beds (1) which underly the unconformity (2) on Plate 7. Blasco (1980, pers. comm.) considers these to be possible foreset beds of a former deltaic sequence. The top of the transgressive sequence on this section is well marked by an acoustic character change (3) which can be traced for many kilometres. A subtle monocline (4) which occurs at the seafloor is nearly coincident with similar features on other horizons (5 and 6). This fact, along with a slight thickening of the overlying marine sequence, suggests a common and recently active origin for the similar structures observed at all three levels.

The complex depositional environment which is believed to characterize Unit B is evident on many of the seismic sections north of Pullen Island. As Plate 8 demonstrates, the unconformity (1) in this region of the shelf is very shallow and the recent marine sequence is either thin or absent. Cross-bedding (2) within Unit B is evident near the centre of the section, but detailed interpretation of the record is hampered by the presence of strong multiples (3 and 4) arising from the seafloor and the subbottom stratigraphy.

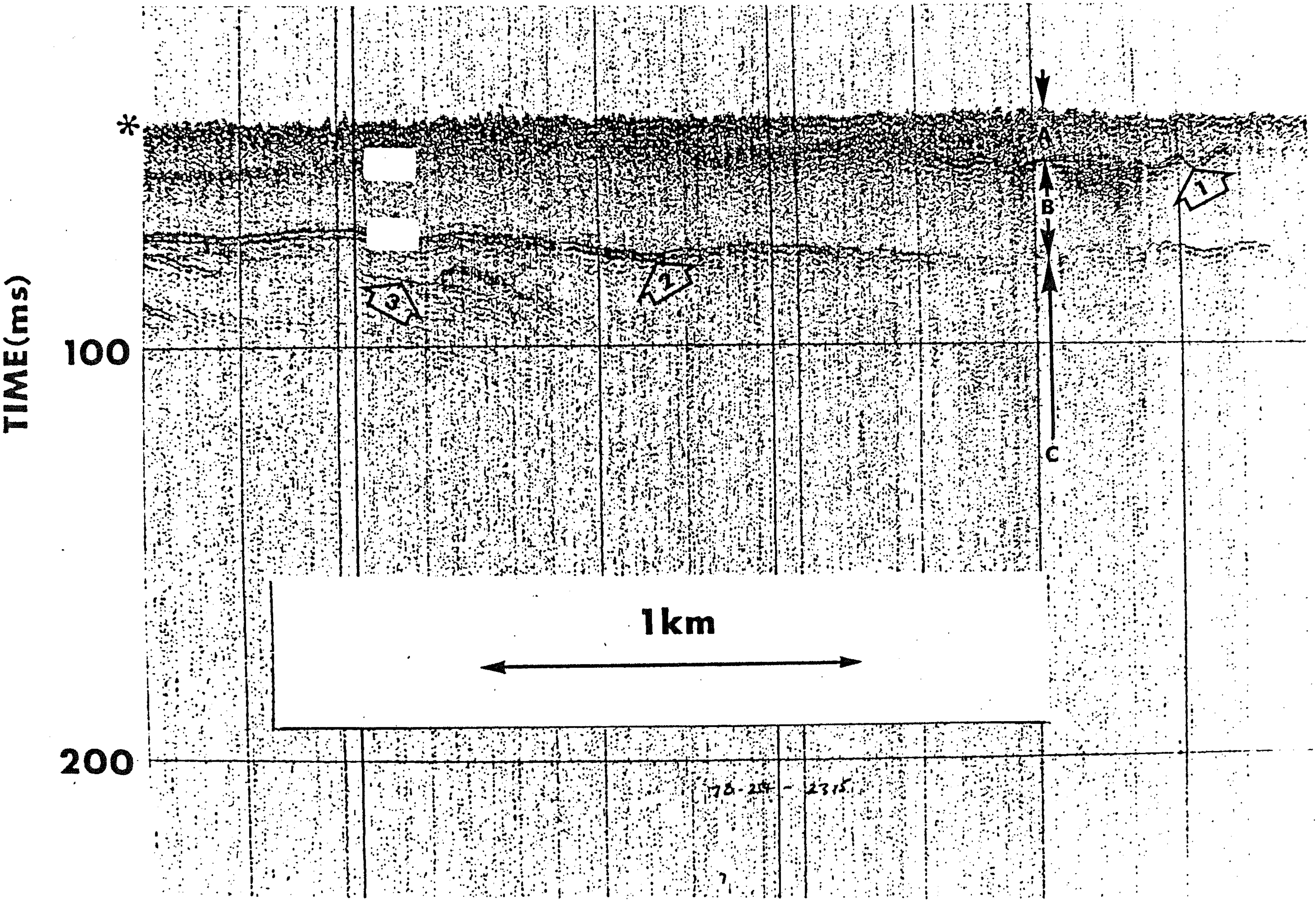

Plate 6.

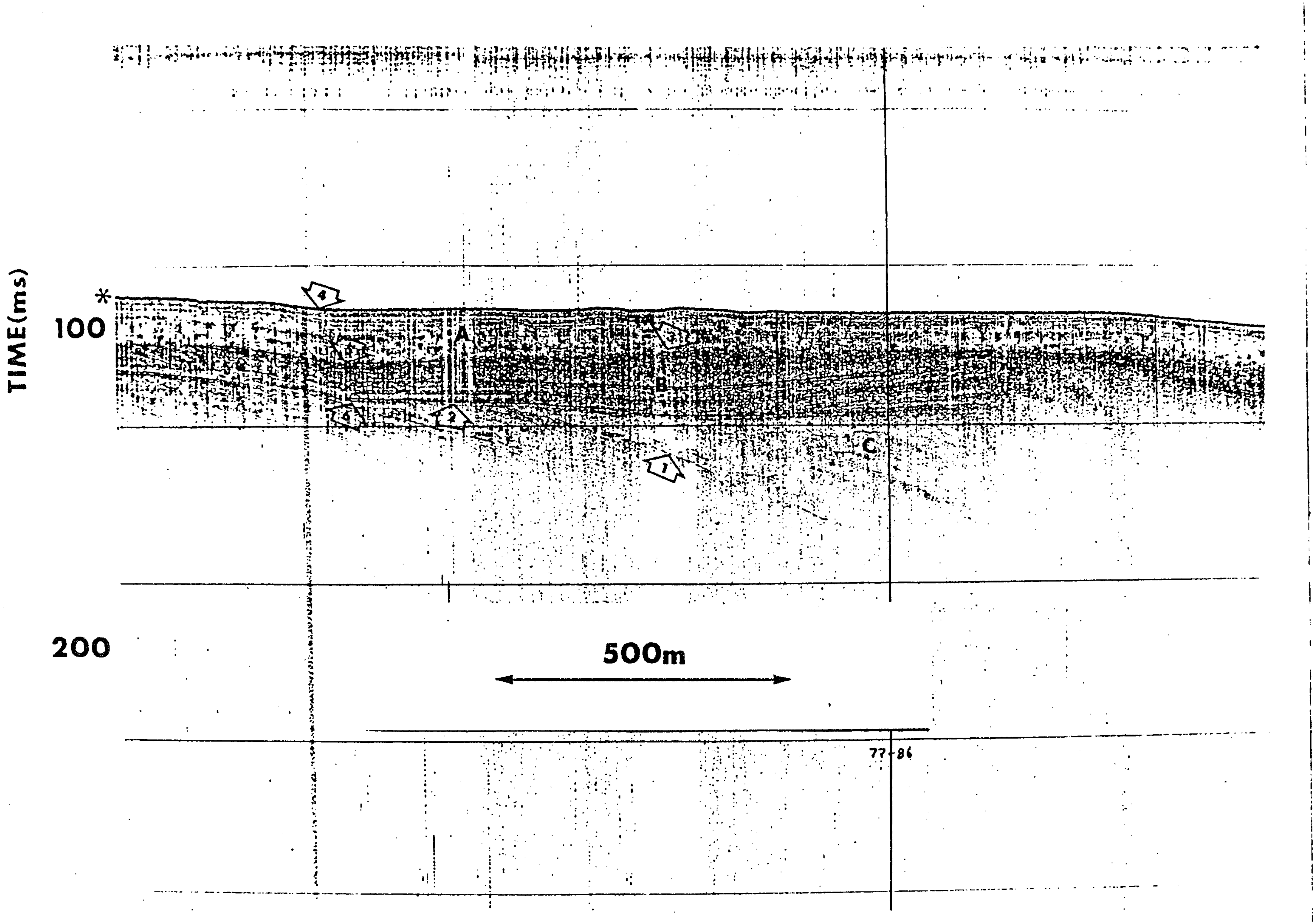

Plate 7.

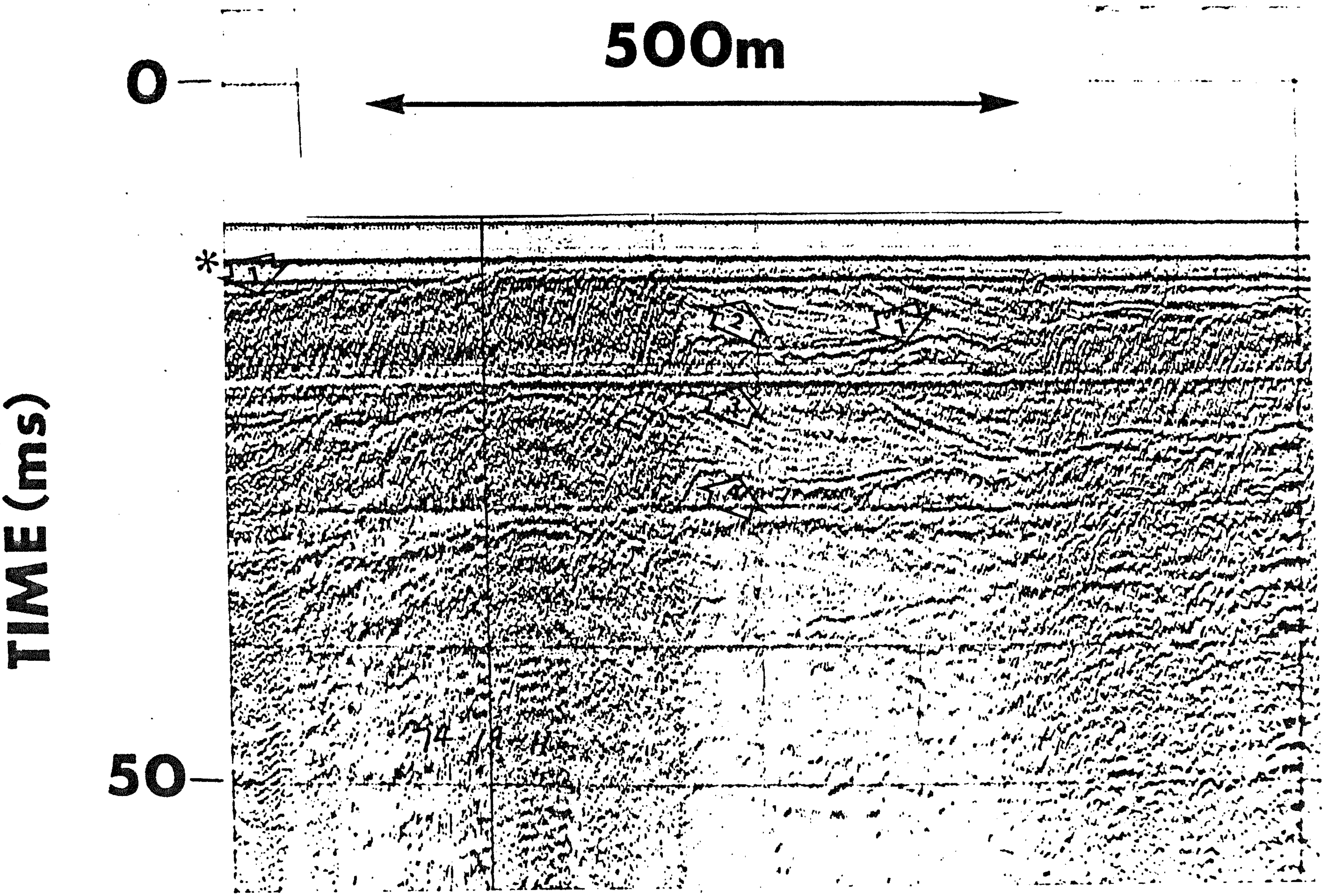

Plate 8.

3.2 Ice Scouring

As Section 2.2 describes, ice scouring is one of the dominant factors affecting the acoustic stratigraphy of the continental shelf. Plate 9 shows a seismic profile about 35 km north of Pullen Island where both the seafloor and subbottom sediments have been repeatedly scoured to the extent that the original bedding is now completely destroyed to a depth of about 4 or 5 m. This interval, termed the saturated paleoscour zone (SPZ), is a common feature on nearly all the high resolution seismic records collected in the west and central areas of the shelf. As Plate 9 demonstrates, the acoustic character which indicates original (in this case horizontal) bedding of the underlying geologic units (B and C) is usually evident below the base of the SPZ. In deeper water, near the shelf edge, the seafloor is normally only lightly scoured and the unconformity (1) may occur within the SPZ (Plate 10). The transgressive sequence, Unit B, appears to be either thin or totally absent at this one location.

Further north along the same profile (Plate 11) the unconformity (1) dips below the SPZ and the overlying transgressive sequence (B) becomes heavily scoured. A horizontal sequence (2) of recent marine sediments (A) is apparent beneath the seafloor, suggesting that the SPZ does not outcrop at the seafloor in these water depths, although some relic seafloor scours are apparent.

Plate 12 shows the marked decrease in the frequency of seabed scours observed at the 50 m isobath (1) north of Mackenzie Bay. Shoreward of this location the top of the SPZ is coincident with the seafloor. Beyond the 60 m isobath (1) on Plate 13 the number of seabed scours is negligible and the top of the SPZ is again at some depth.

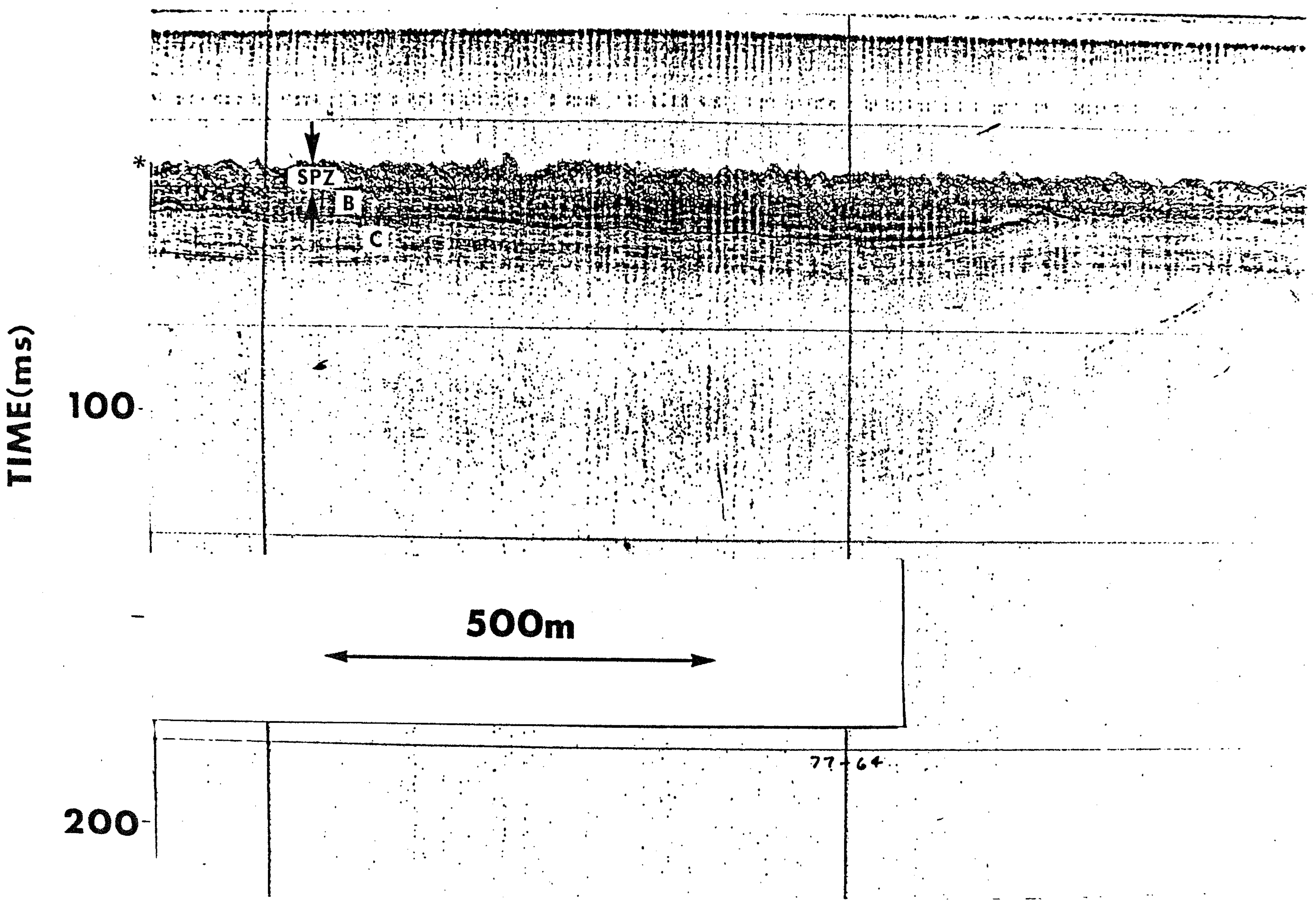

Plate 9.

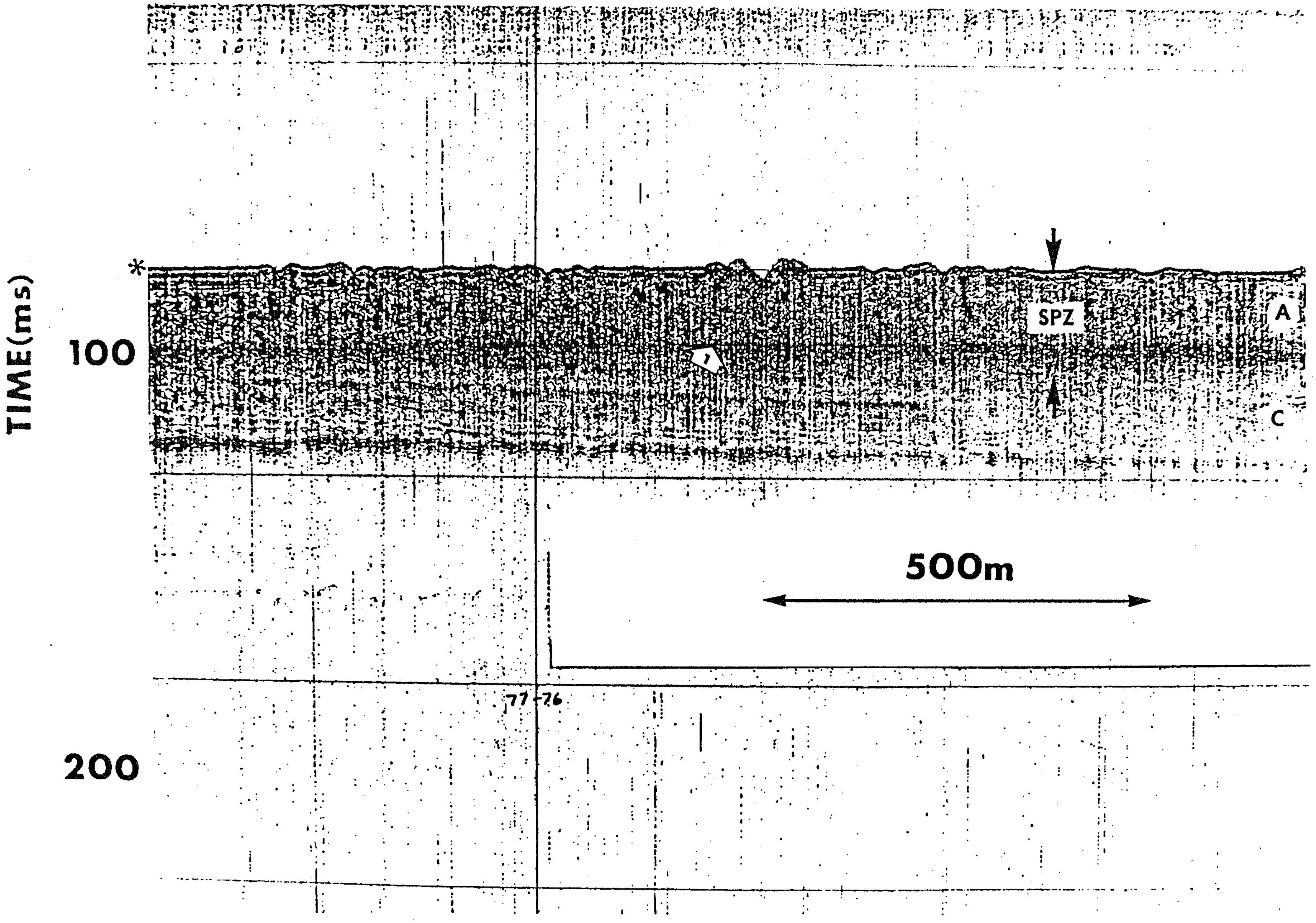

Plate 10.

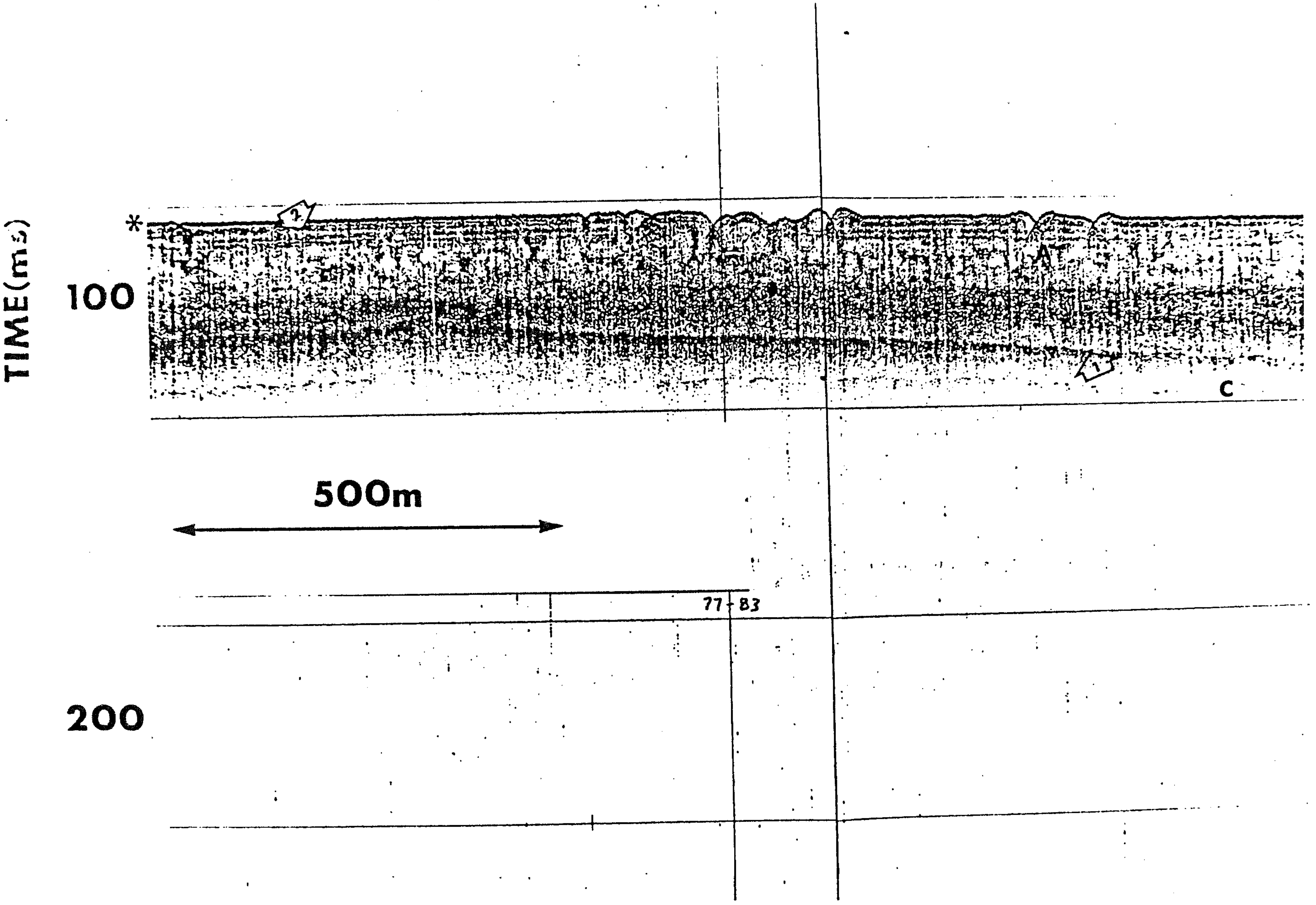

Plate 11.

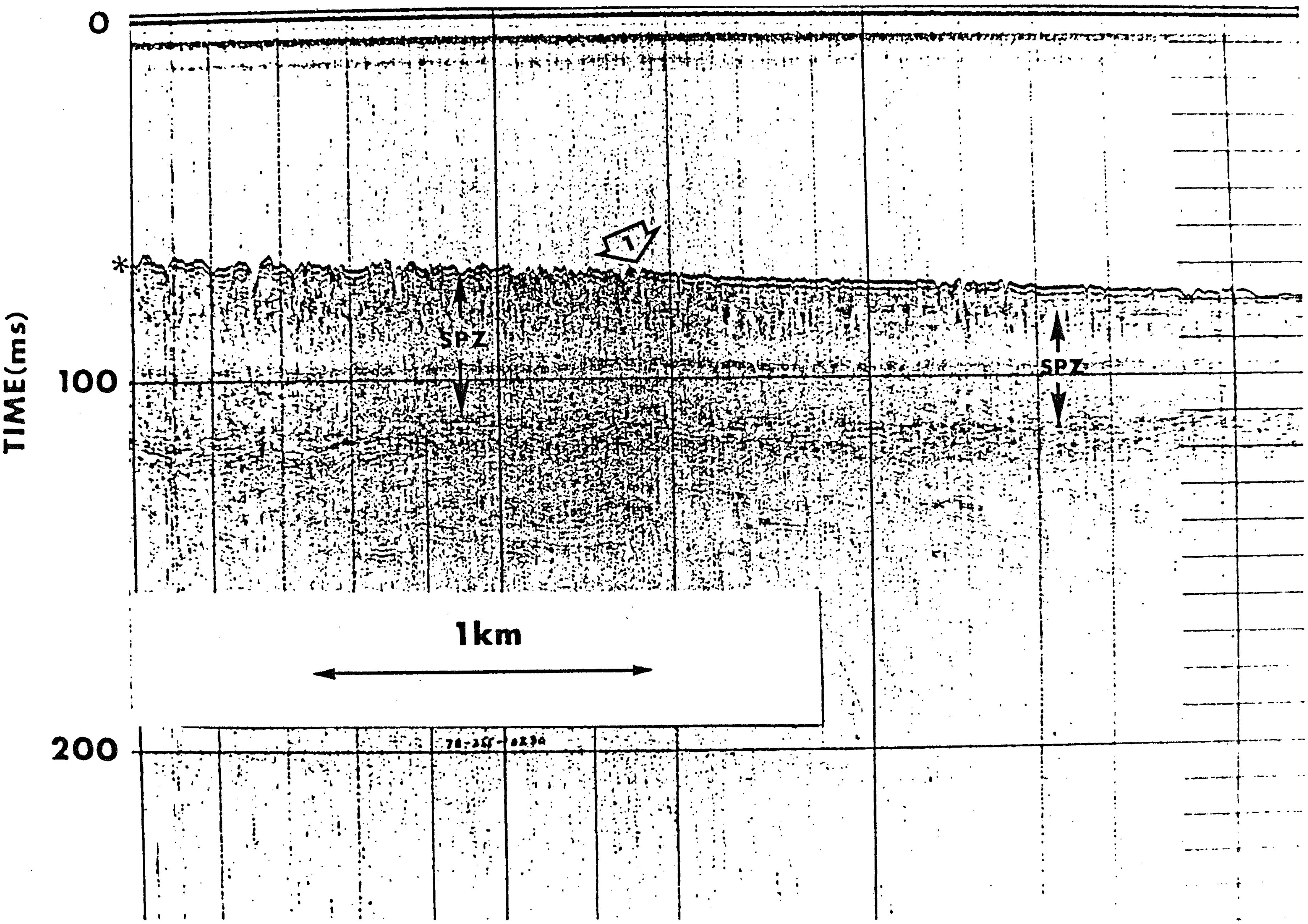

Plate 12.

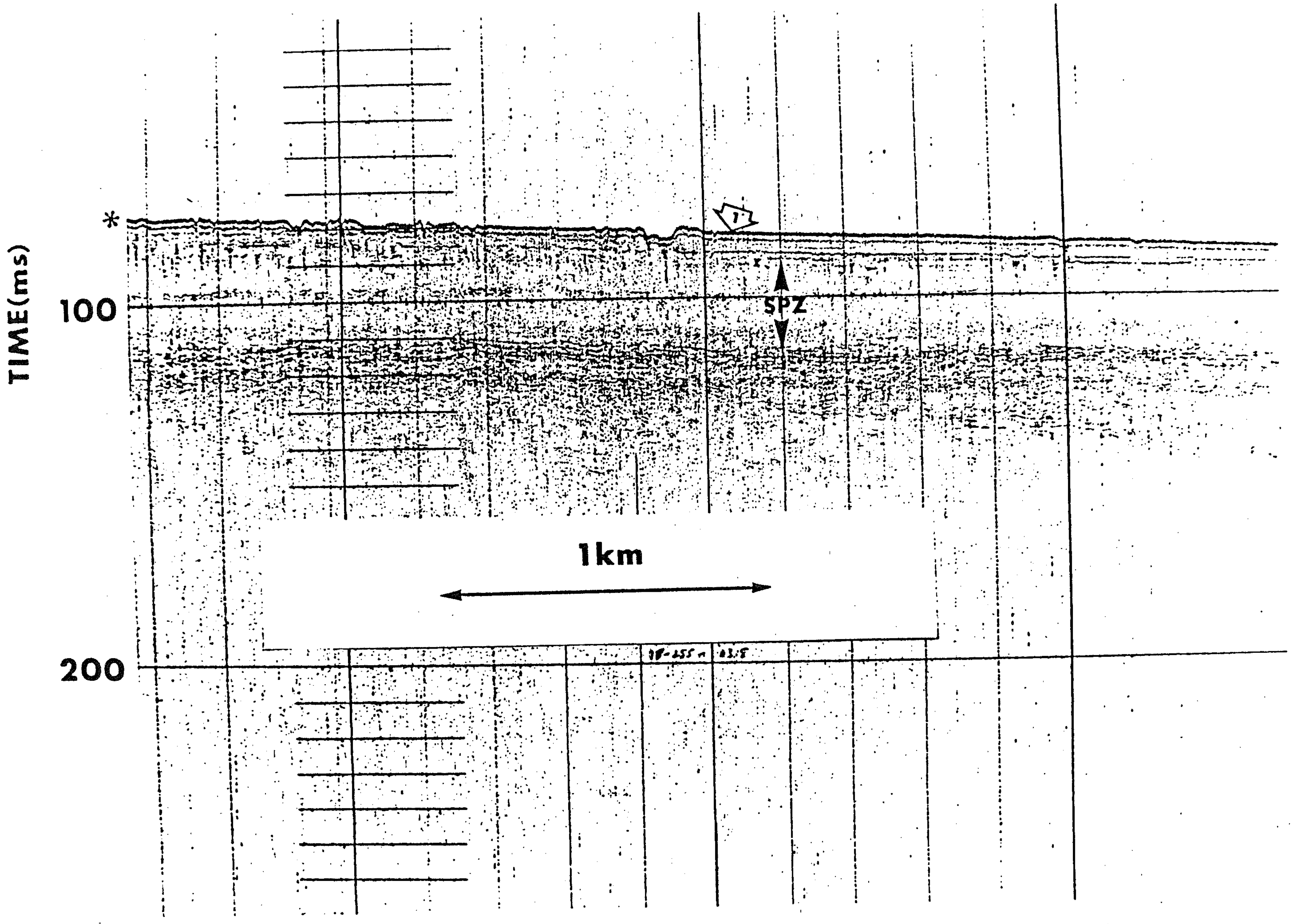

Plate 13.

Plate 14 shows good evidence that relic scours occurring beyond the 50 m isobath may be progressively infilled by subsequent sedimentation. The 4.5 m deep scour at (1) is so old that it has been completely infilled, while the much younger, shallower scour at (2) shows little evidence of any such process. Shallow relic scours (3) evident near the base of the saturated paleoscour zone are believed to be coincident with the unconformity surface. Deeper scouring of Unit C was probably prevented by the dense, granular nature of the pre-unconformity sediments. Note that the top of the transgressive sequence (4) is represented by a change in the optical density of the section, even though it occurs well within the SPZ.

Relic scouring at the unconformity has also been observed elsewhere on the shelf, as demonstrated by the 6 m deep angular feature (1) which occurs on Plate 15, located about 30 km southwest of Plate 14. If the poorly defined relic features which appear on foreset (2) beds below the unconformity are also due to ice scouring, then these would represent the earliest preserved scours encountered to date.

Some of the best examples of infilled and/or relic scours are found on data collected along the east side of Mackenzie Bay in 1974. Plate 16 shows the morphology of two scours which occur in about 50 m of water. The present depth (D) of the left scour, as measured from the undisturbed seafloor, is about 2.3 m, but it appears that up to 2 m of infilling (1) may have already taken place. While the total depth of the original furrow may therefore have been only about 4 m, it is evident from the acoustic character change (2) that the sediments in a broad zone outside the scour are also badly disturbed, perhaps to a depth of 10 m. A similarly disturbed zone (3) appears on the smaller scour to the right of the section.

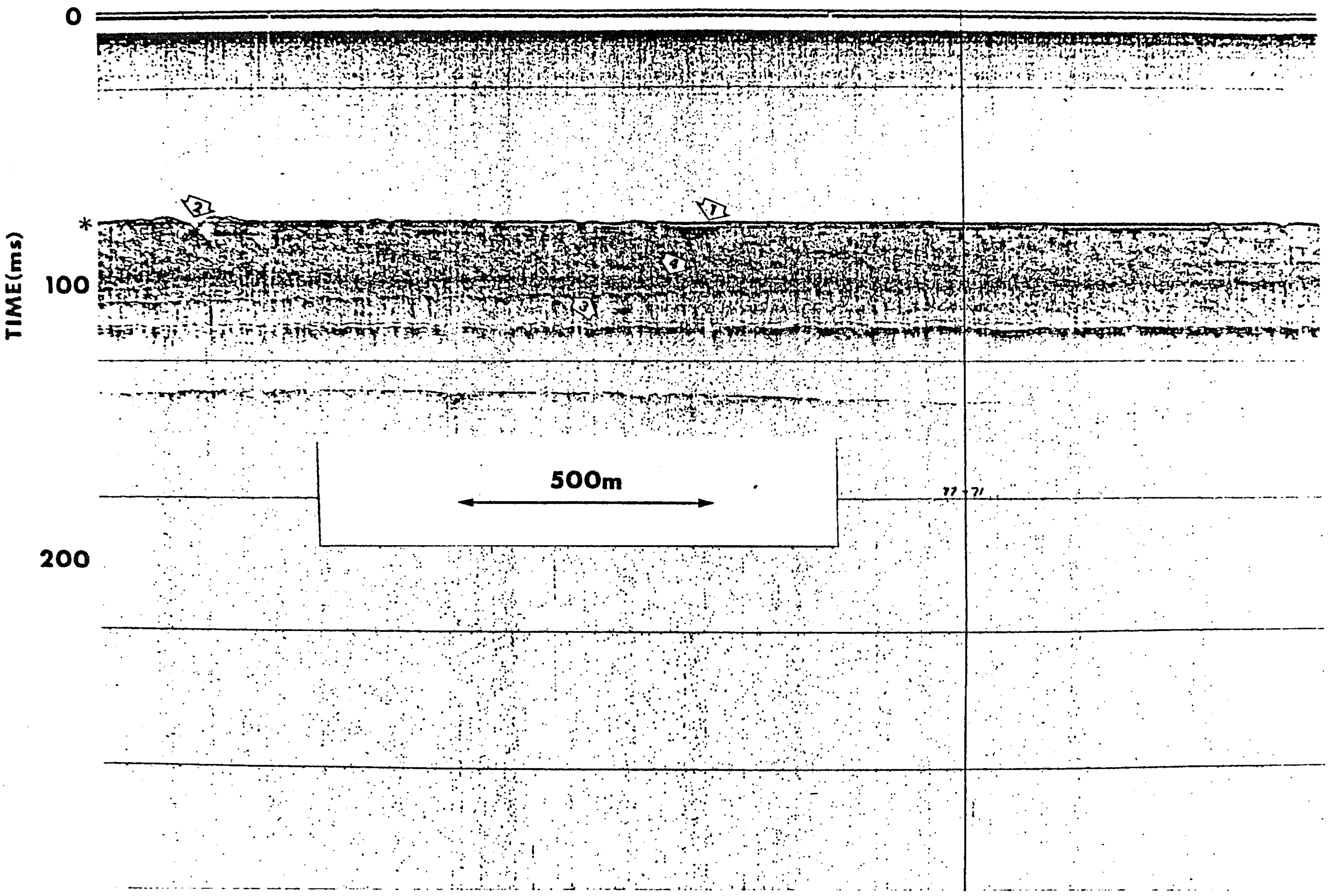

Plate 14.

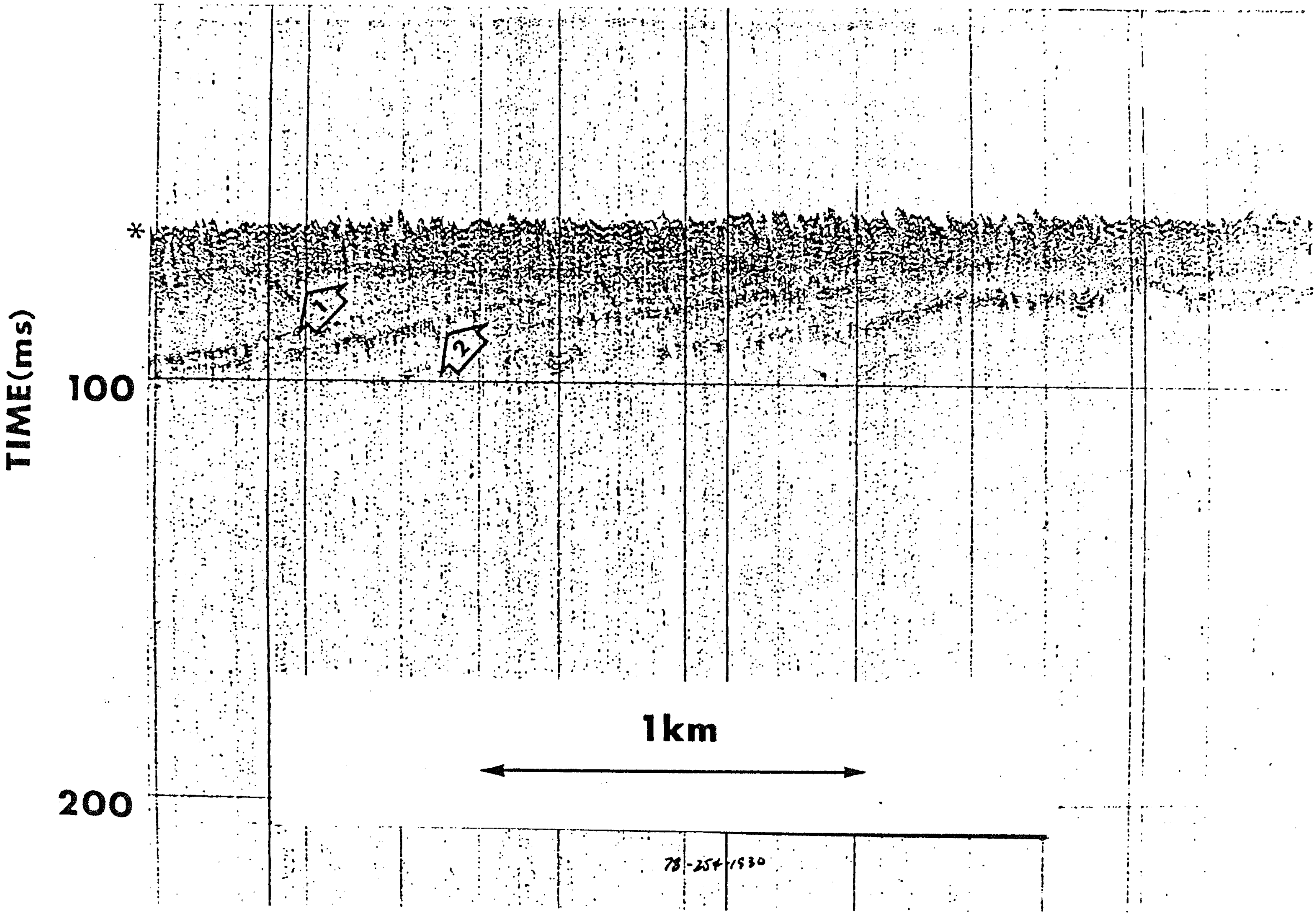

Plate 15.

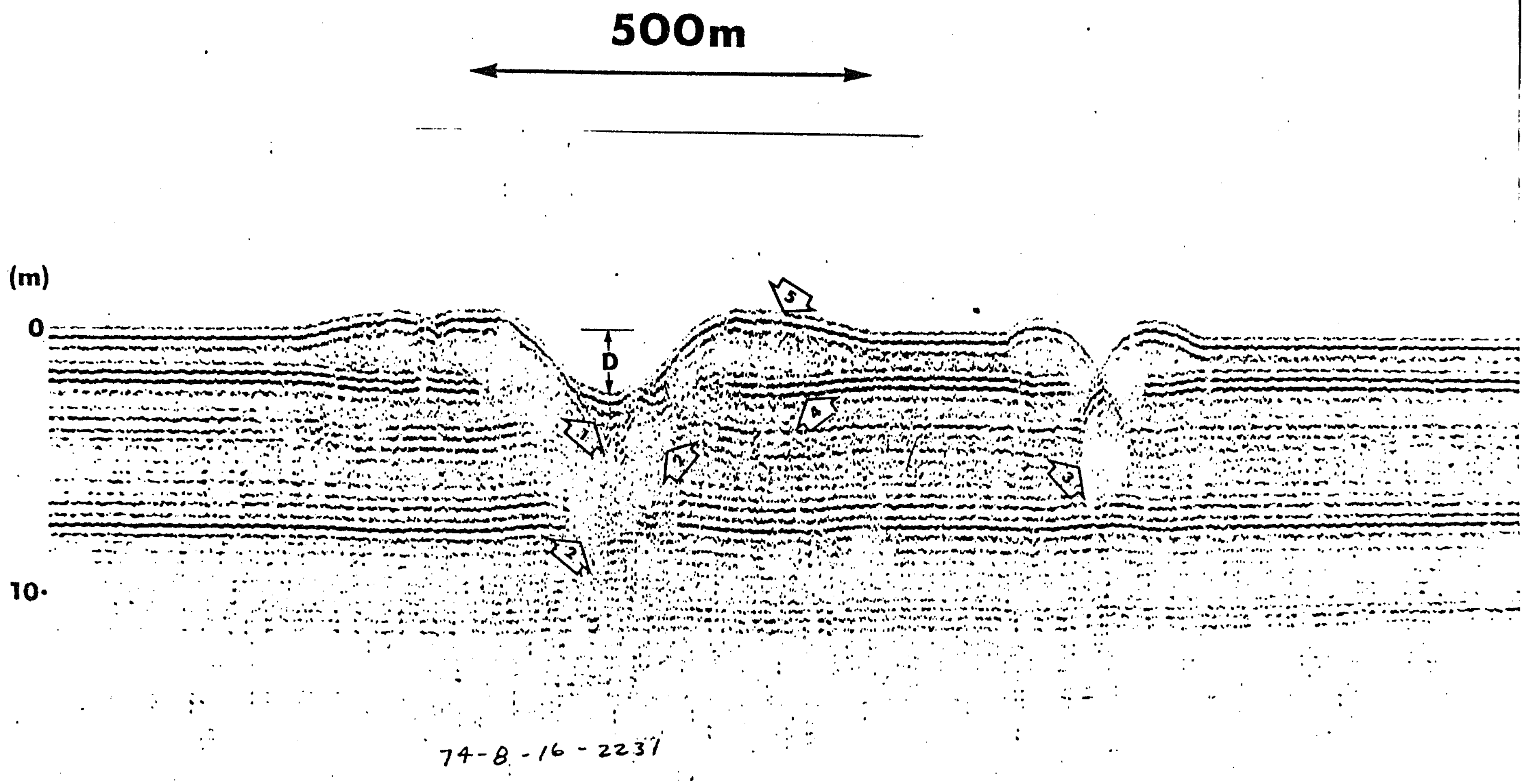

Plate 16.

The zone of disturbed bedding on the left appears to be highly irregular and somewhat asymmetric, unlike the present seabed morphology. One possible interpretation is that the original scour occurred as shown by the perimeter of the disturbed zone, but was then partially infilled by subsequent slumping of the adjacent silty sediments. Later marine sedimentation infilled the scour from 4 to 2 m. Another interpretation favoured by the present author is that the disturbed zone (2) represents the true extent of the ice keel's influence on the subsurface. Sediments within this zone of influence may be compressed, tilted, remoulded and/or loosened, depending on the soil type, the shape of the keel and the nature of the ice forces. During formation of the scour it would appear that some seabed material may have actually been injected between surficial beds, depressing the shallow layers (4) and building the lateral embankments (5).

Similar acoustic features can be observed along most of this seismic line, although slight variations due to depositional environment also may be noted. On Plate 17, for example, the horizontal stratigraphy serves as a useful acoustic contrast to the disturbed zones evident around many of the relic scours. In shallower waters or within the SPZ, no such useful acoustic contrast exists (Plate 18) and individual relic scours can only be identified by infilling at the seafloor (1).

3.3 Shallow Gas

Next to ice scouring, shallow gas occurrences are probably the most significant factors effecting the acoustic stratigraphy observed on reflection seismic profiles. Where soil conditions are suitable, the gas is often trapped in small topographic highs (1) on the unconformity (2) as shown in Plate 19, north of Pullen Island. Structural closure

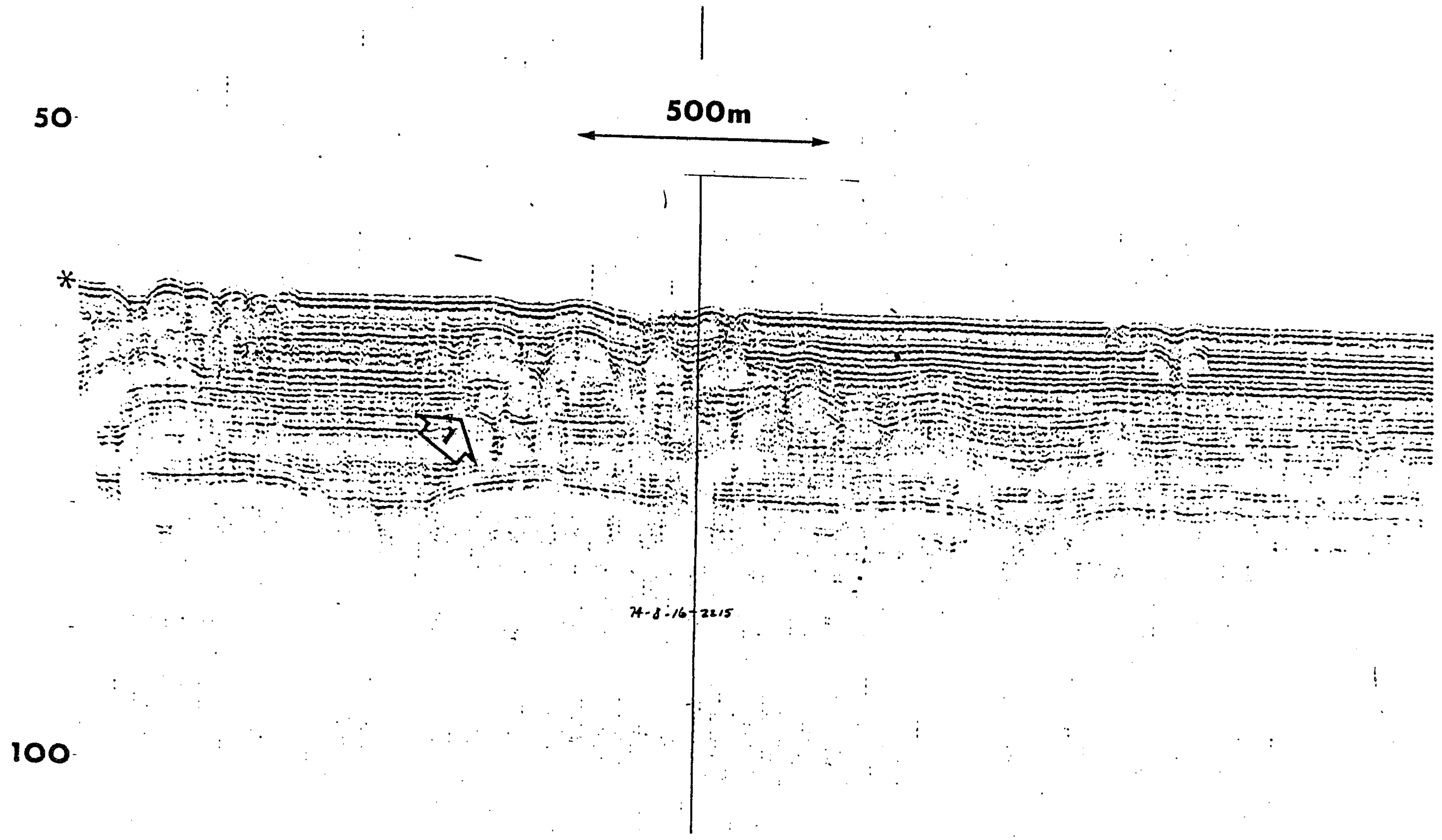

Plate 17.

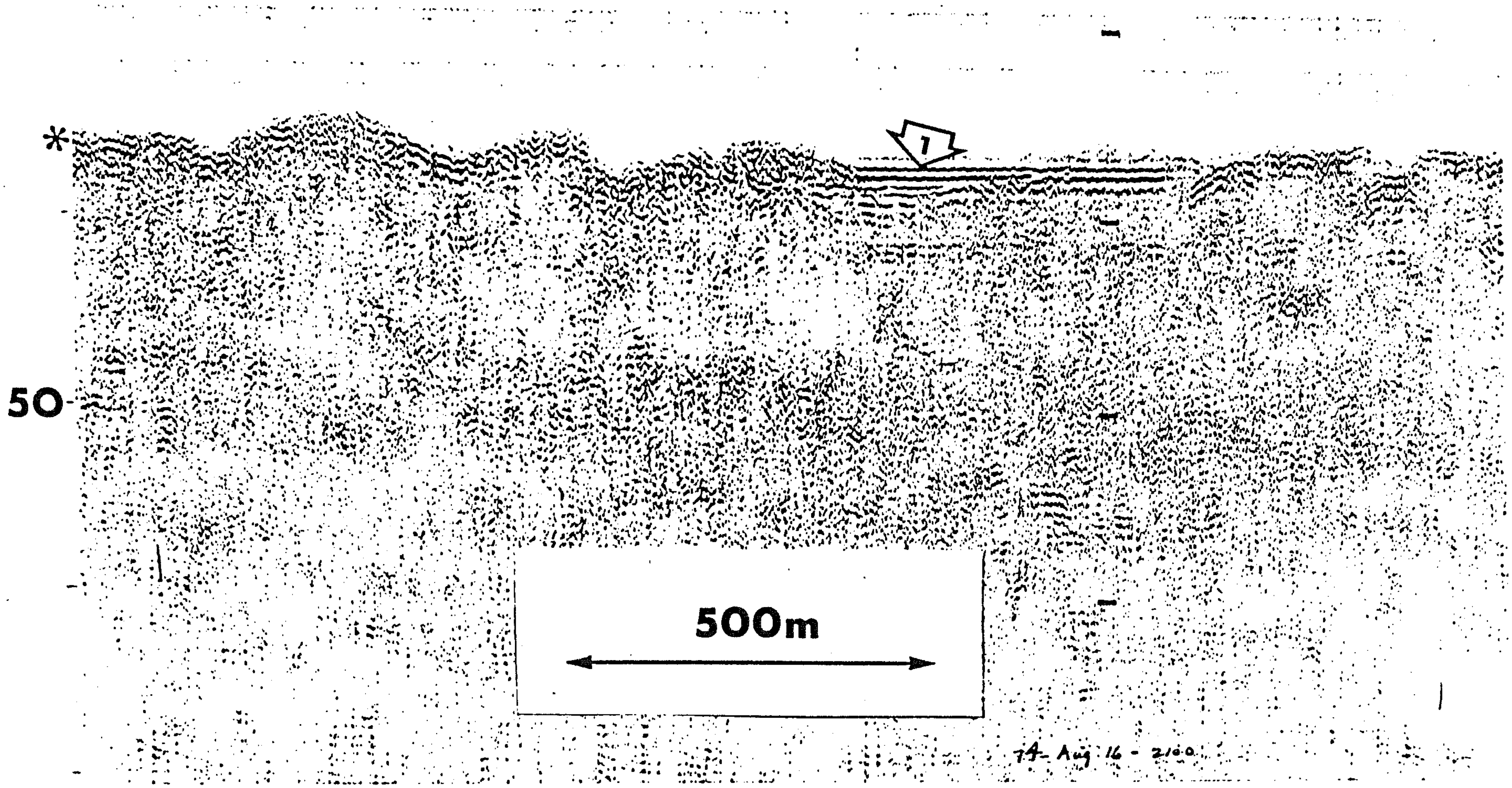

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Plate 18.

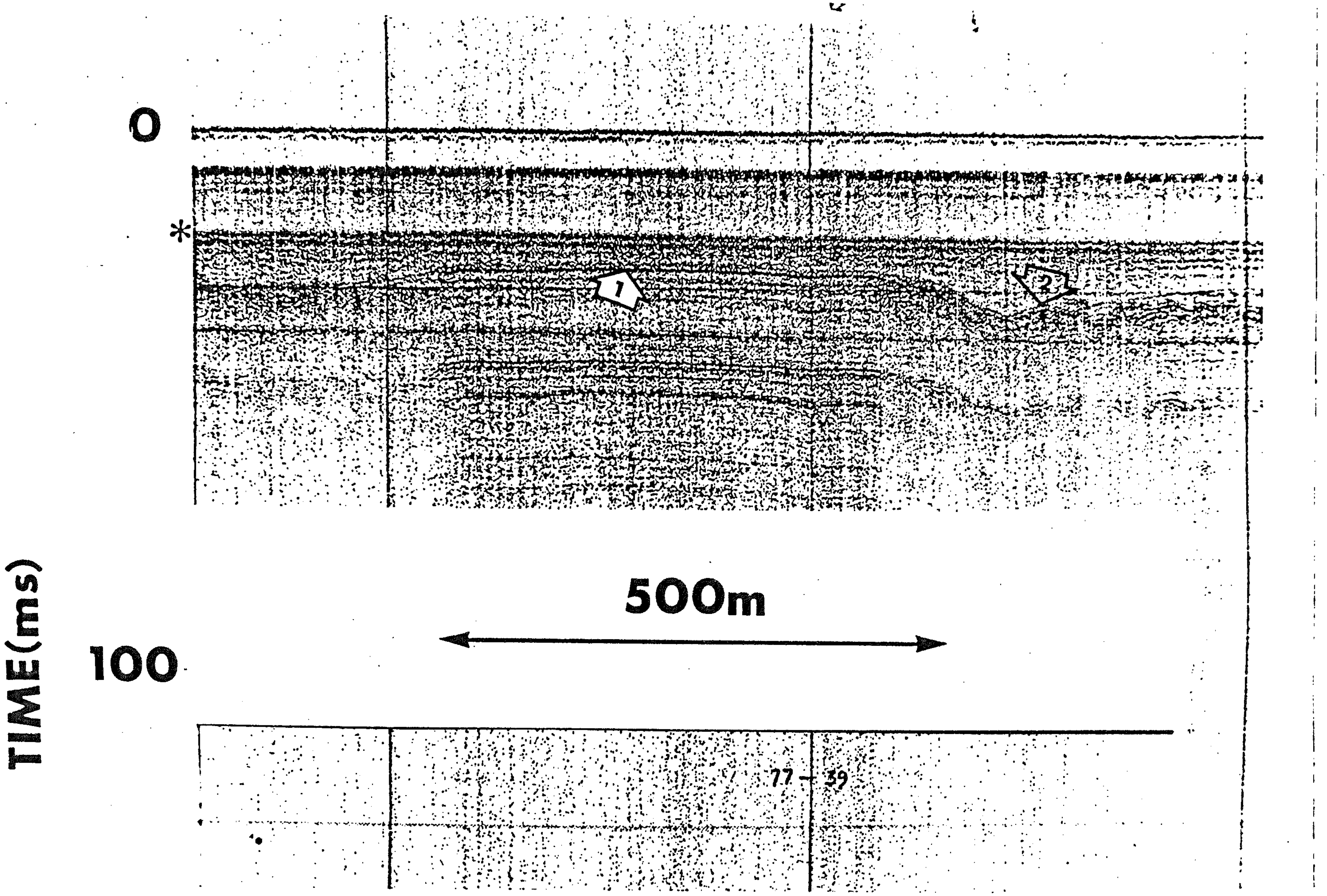

Plate 19.

of the trap along the plane of the section may often be very small. Such is the case in Kugmallit Bay (Plate 20) where a gas pocket (1) almost 1 km wide occurs at the unconformity (2). It is apparent that sufficient gas is available here to significantly reduce the seismic velocity of the lower sediments resulting in very large negative reflection coefficients at the interface. These conditions generate a sharp polarity reversal (3) at the edges of the gas pocket and numerous multiple reflections (4) below. Plate 21, northwest of Hooper Island, shows several gas pockets (1) at the unconformity occurring in close proximity. A closeup of the same section (Plate 22) reveals that individual polarity reversals (2) are associated with the edge of the pockets (1) and that slight relief is present on the (normal polarity) unconformity (3) in the spaces between gas pockets.

Where the sediments overlying the unconformity are not sufficiently impermeable to totally trap the gas accumulating below, the gas may migrate upwards along selective routes toward the seafloor, producing a discontinuous and highly irregular zone of gas-charged sediments. A series of seismic sections shot approximately 20 km north of Pelly Island demonstrates this transition very effectively.

On Plate 23, the gas front (1) has migrated above the unconformity surface (2) but remains within the lower beds of the transgressive sequence. On Plate 24, the rising gas front has become highly irregular (1), probably due to differential vertical permeabilities arising from intensive scouring of Unit B. On Plate 25, the gas front has risen to the seafloor (1), completely masking the acoustic stratigraphy of the sediments below.

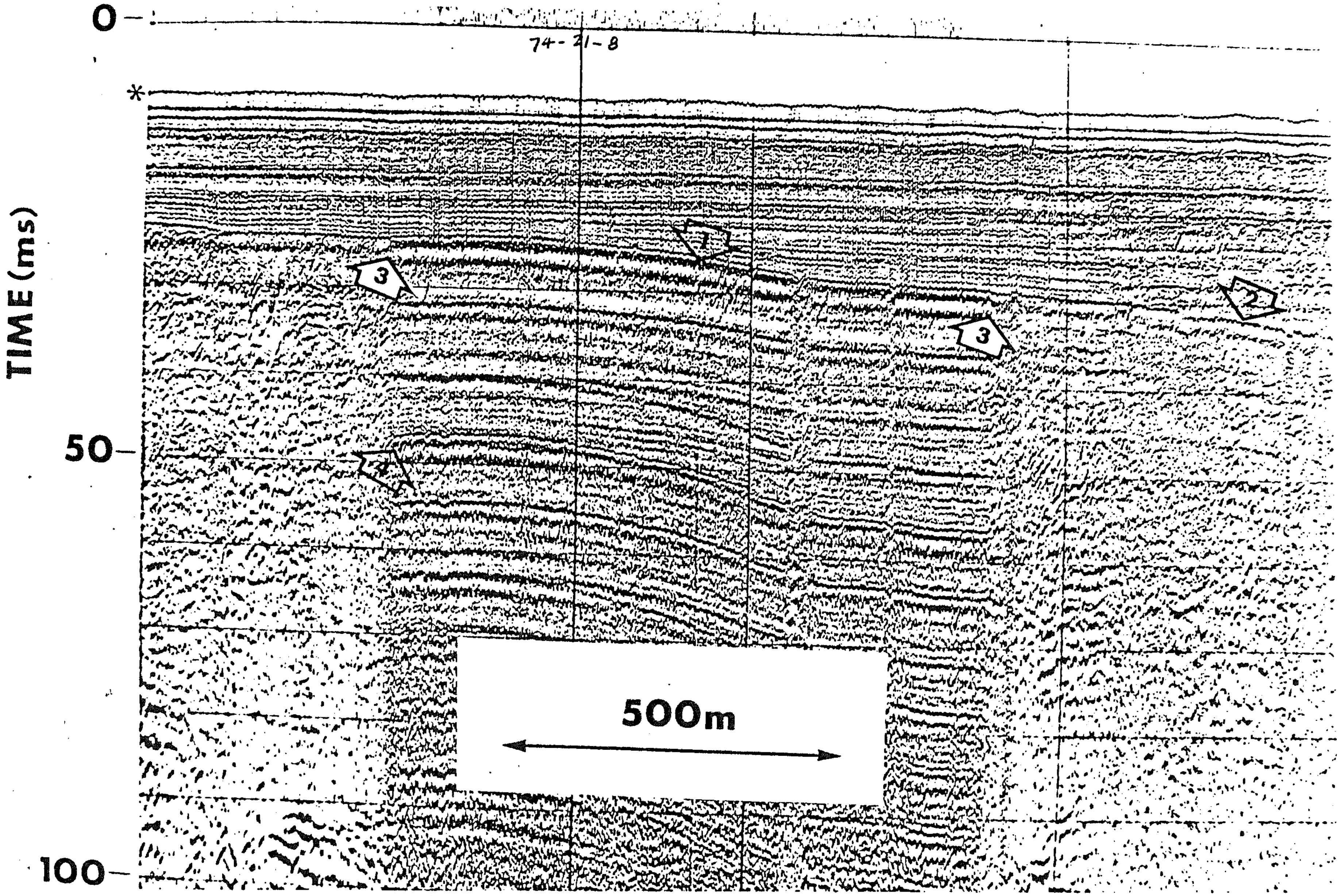

Plate 20.

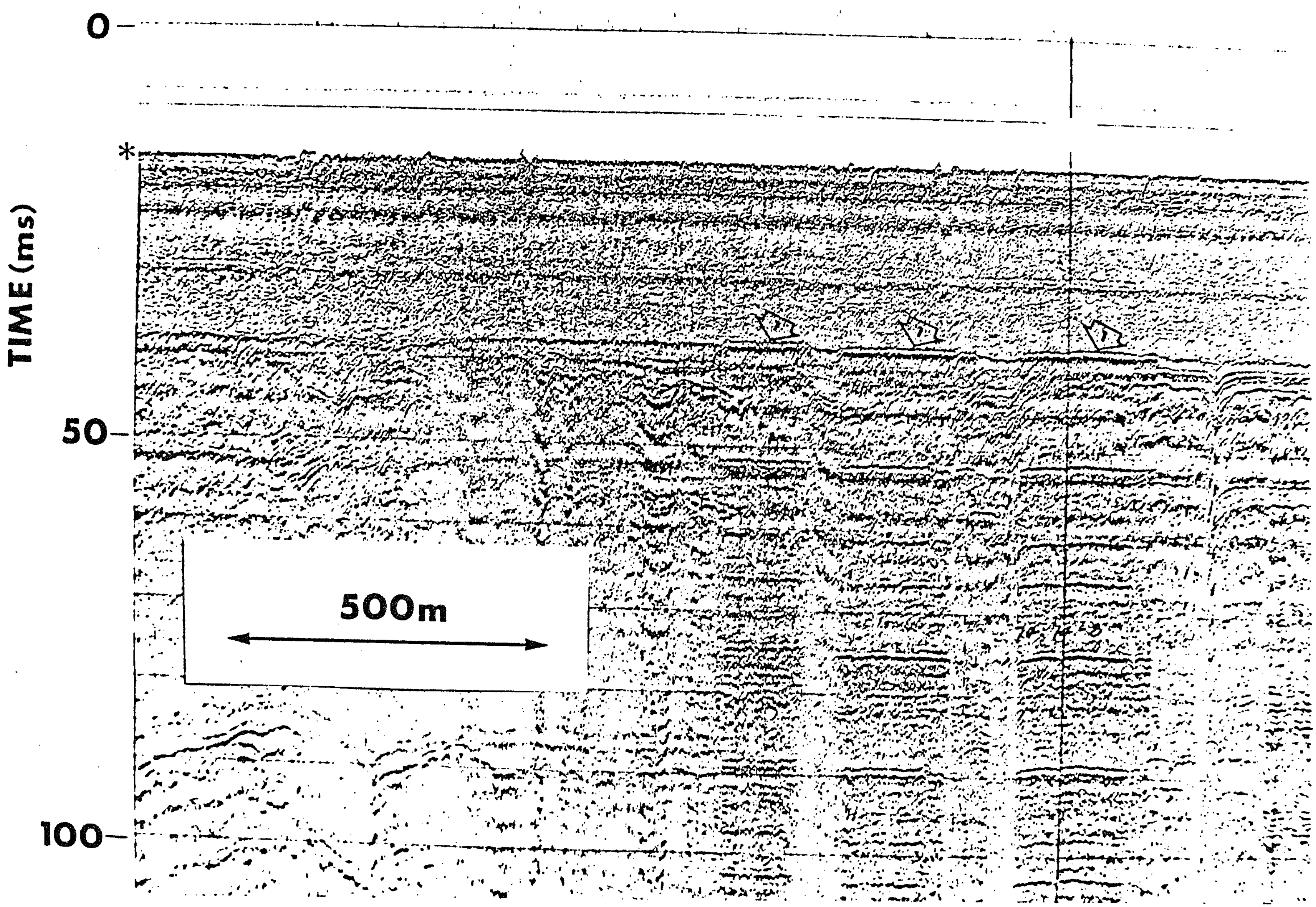

Plate 21.

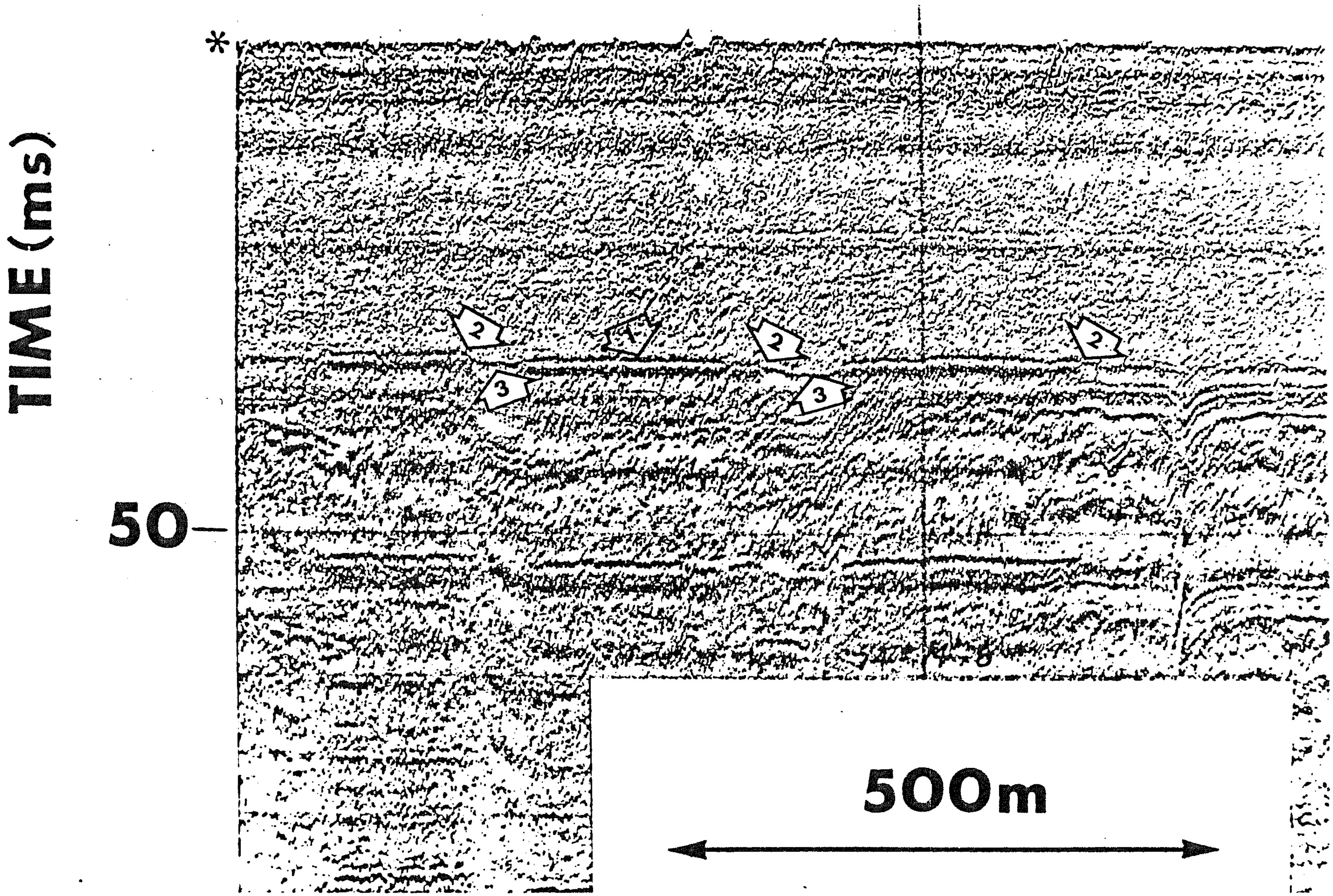

Plate 22.

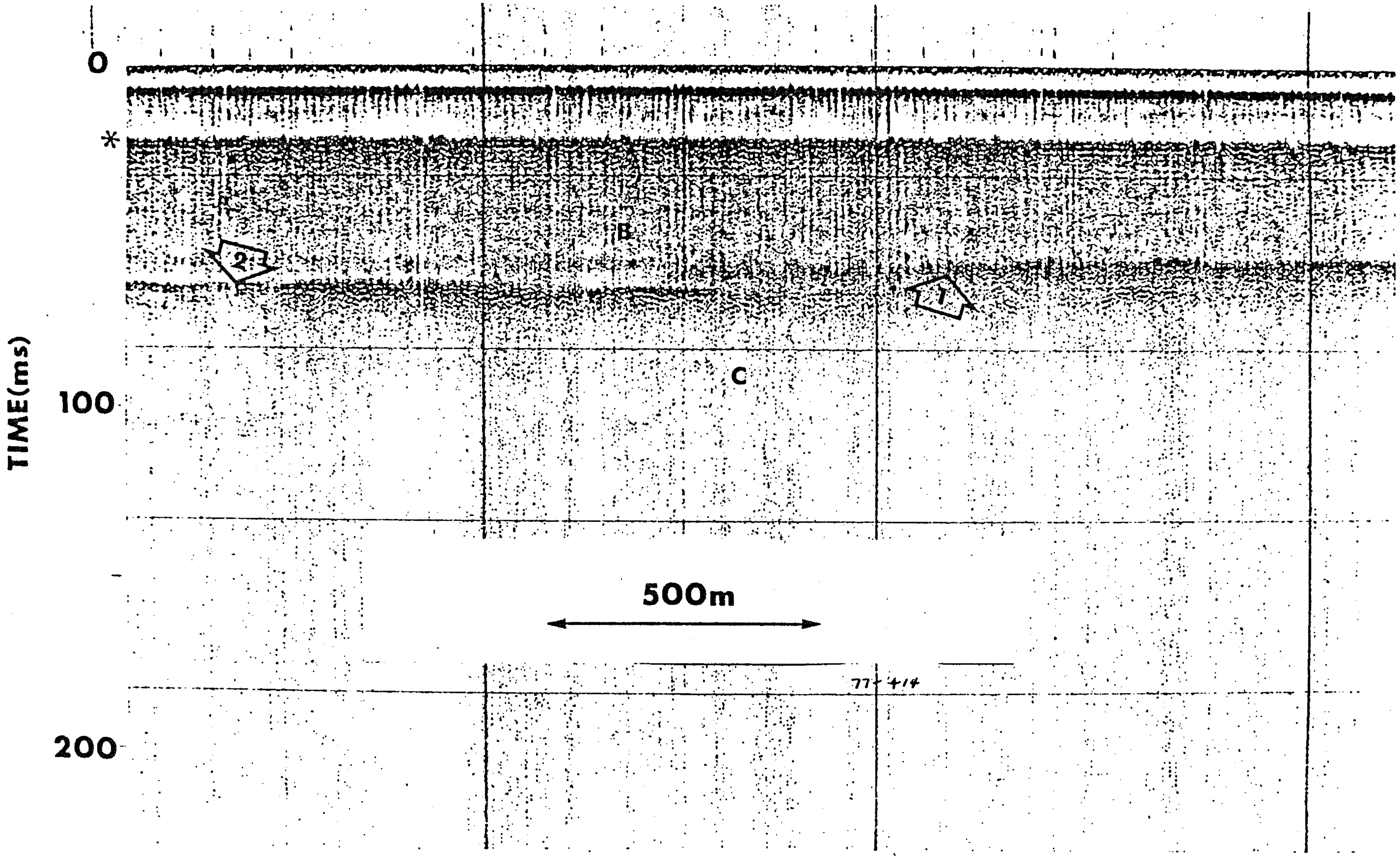

Plate 23.

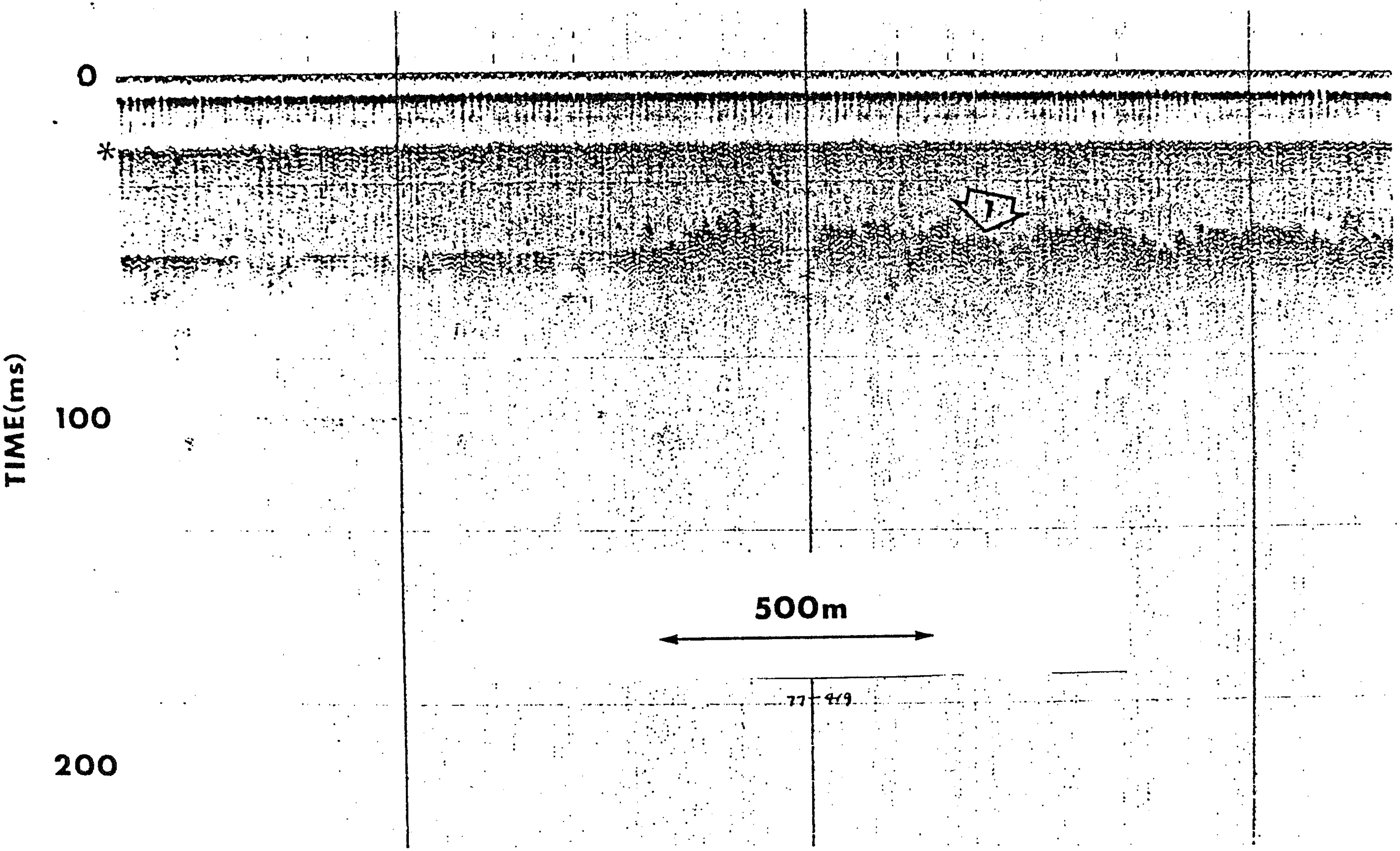

Plate 24.

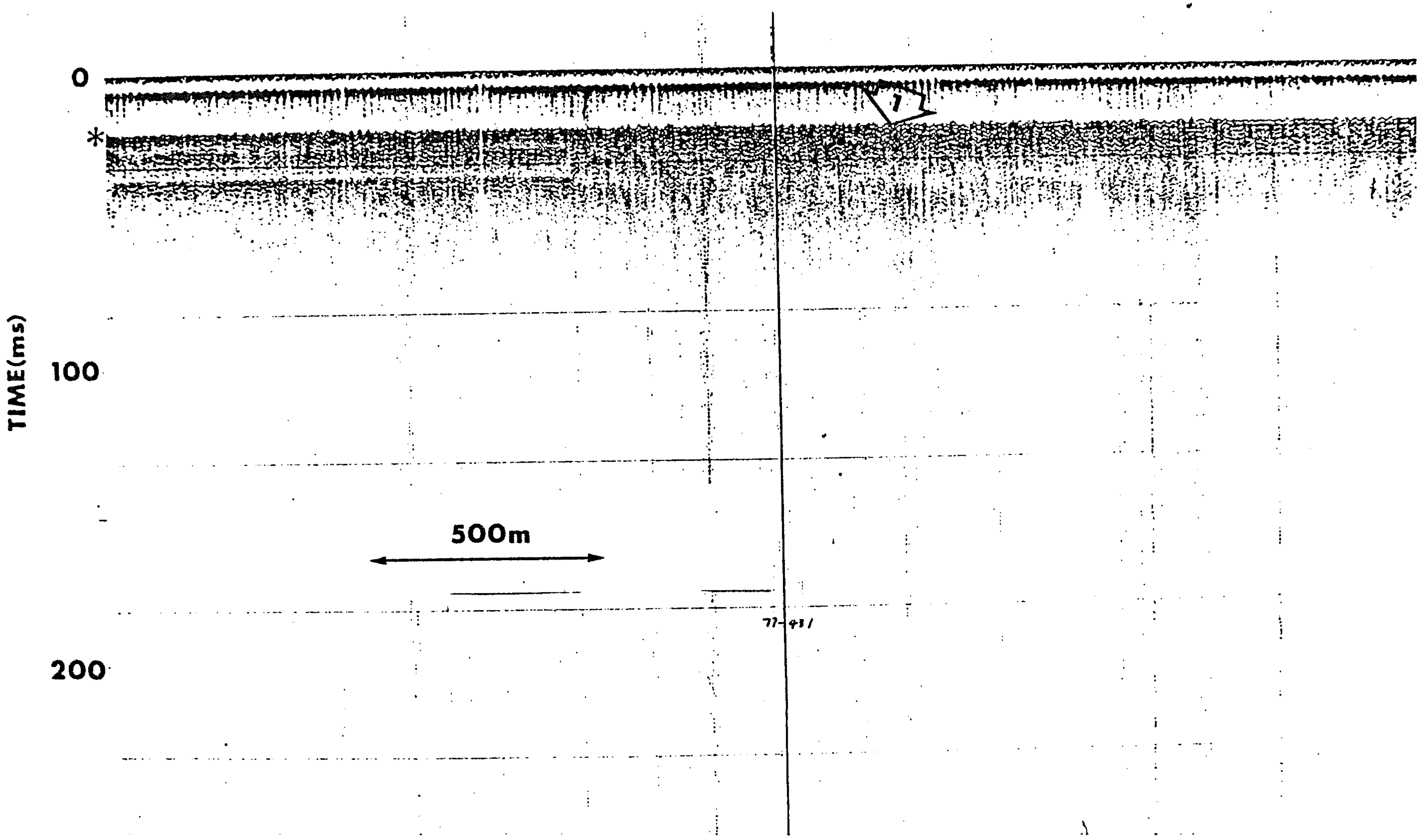

Plate 25.

Similar acoustic conditions arising from shallow gas-charged sediments are also present beneath the seafloor in Kugmallit Bay (Plate 26), effectively precluding the mapping of any subbottom stratigraphy (1) in this area.

Shallow gas occurrences are also common features near the northwest edge of the continental shelf. As Plate 27 demonstrates, a discontinuous shallow gas front (1) in this area may be observed beneath the unconformity (2), within the sequence comprising foreset bedding (3). No relationship between the gas front and the bedding is apparent on the seismic sections examined during this study.

3.4 Permafrost

Acoustic permafrost usually occurs on the reflection seismic records as a strong, nonconformable and often discontinuous event below the unconformity. Plates 28, 29 and 30 show typical profiles from the central and eastern continental shelf, where the unconformity is believed to be at, or close to, the seafloor. In each photograph the acoustic permafrost table (1) appears to be laterally discontinuous. It is not yet clear whether this is a function of the particular soil/temperature conditions which characterize the surficial sediments or whether it is a function of the data acquisition system's limited penetration. On Plates 31 and 32 the acoustic permafrost table (1) is interpreted as being continuous across the entire section, but it appears as a very weak reflector (2) beyond 100 milliseconds (75 m).

On Plate 33, north of Pullen Island, the acoustic permafrost table (1) is visible as a weak but consistent reflector approximately 20 m beneath

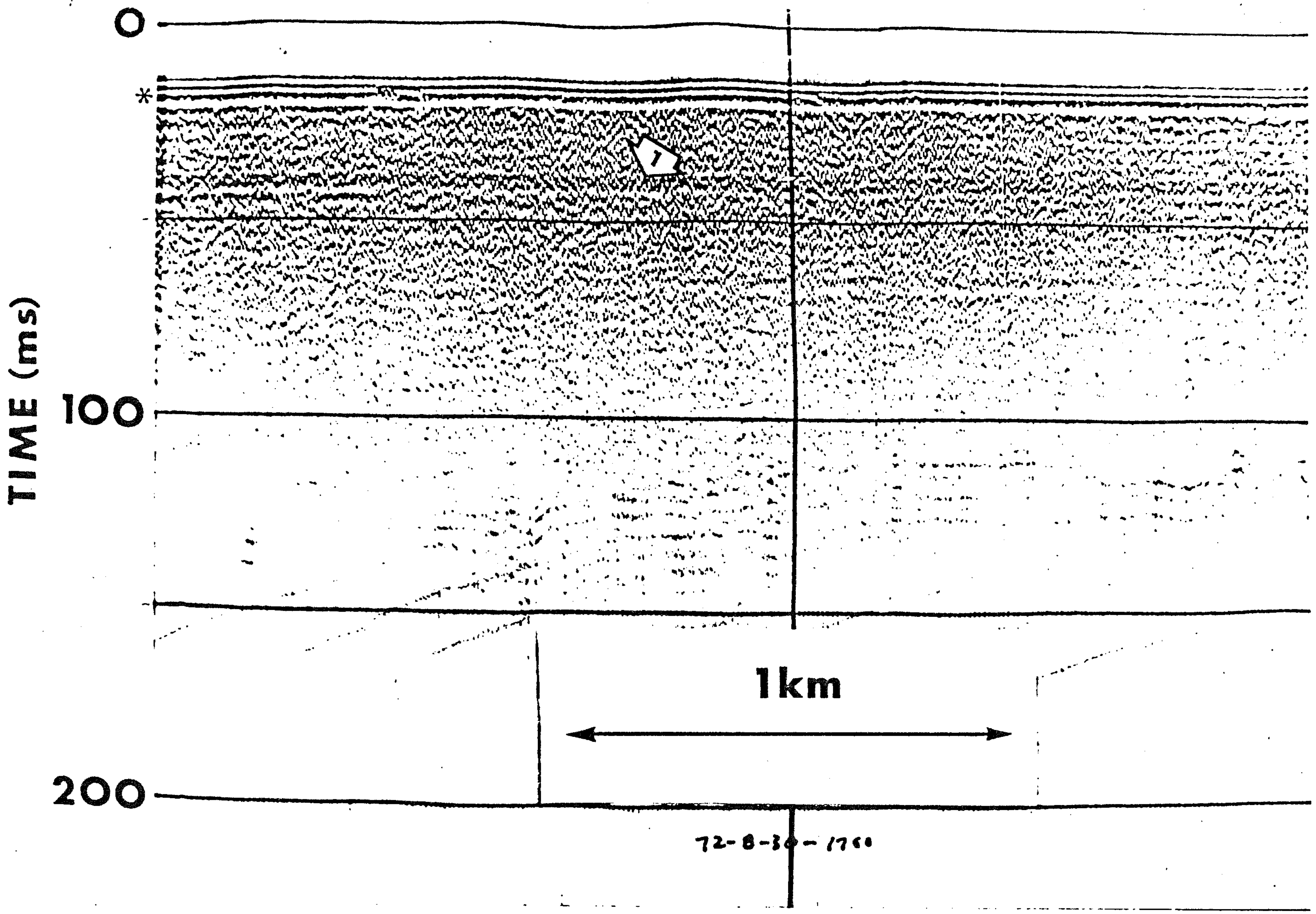

Plate 26.

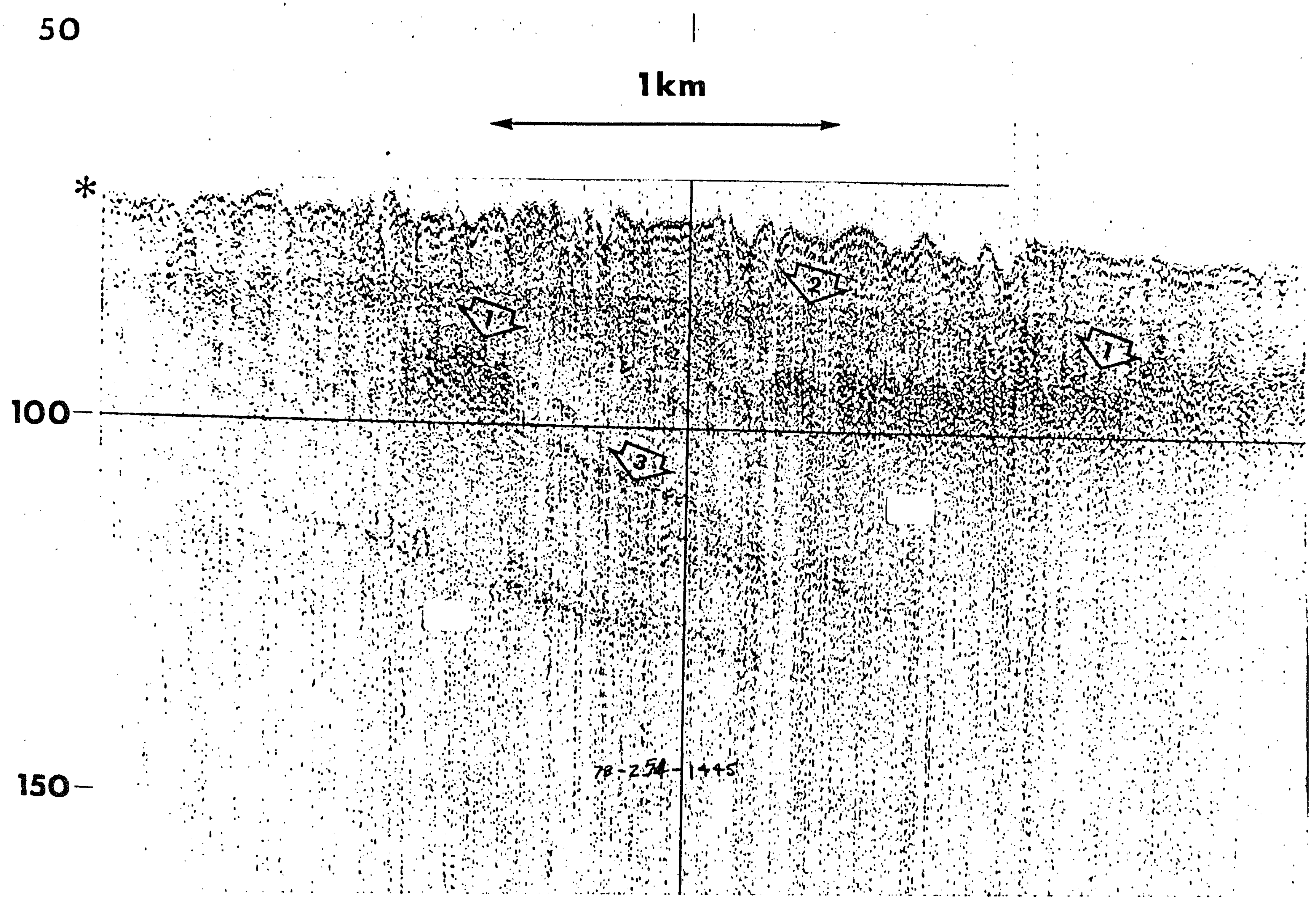

Plate 27.

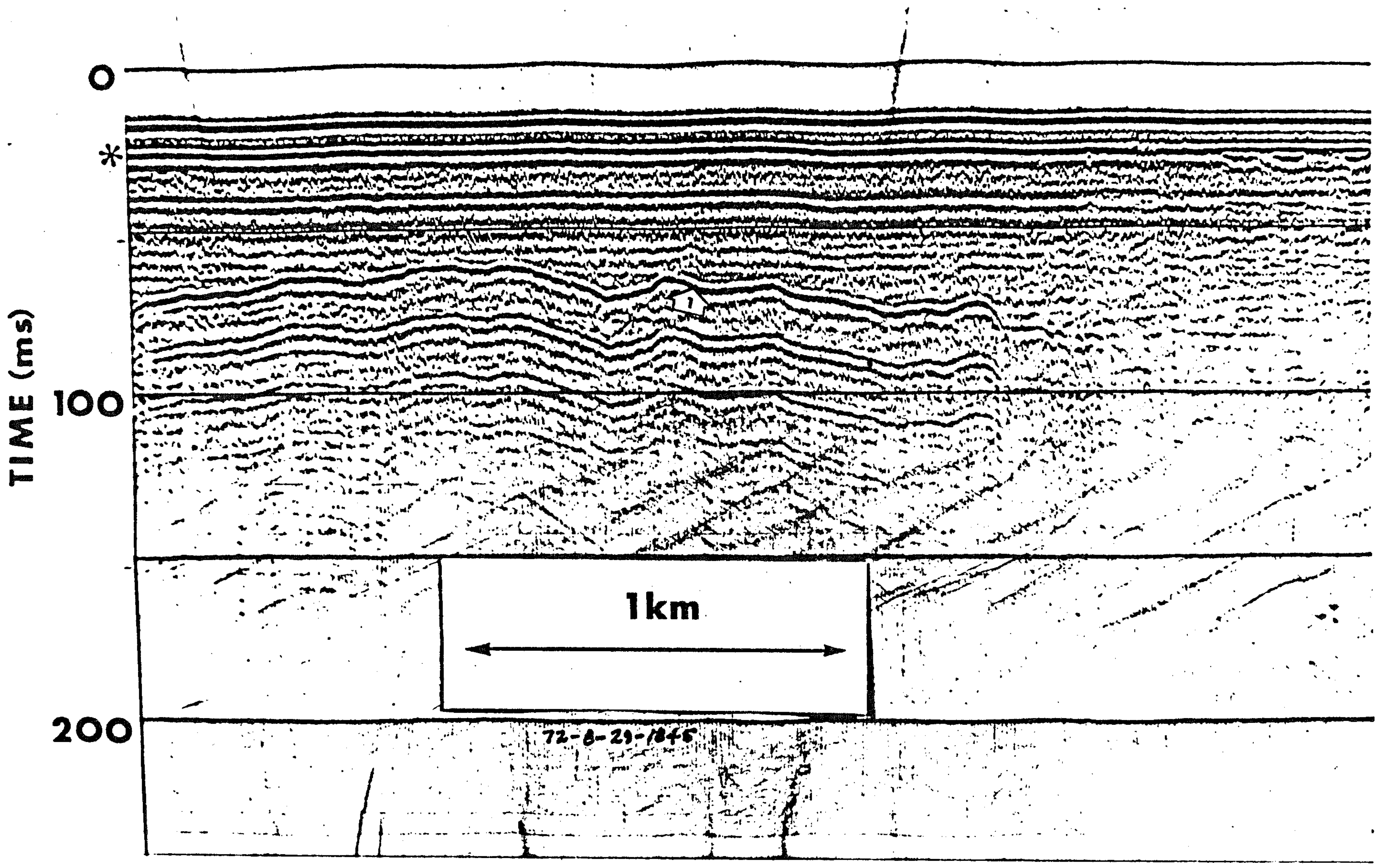

Plate 28.

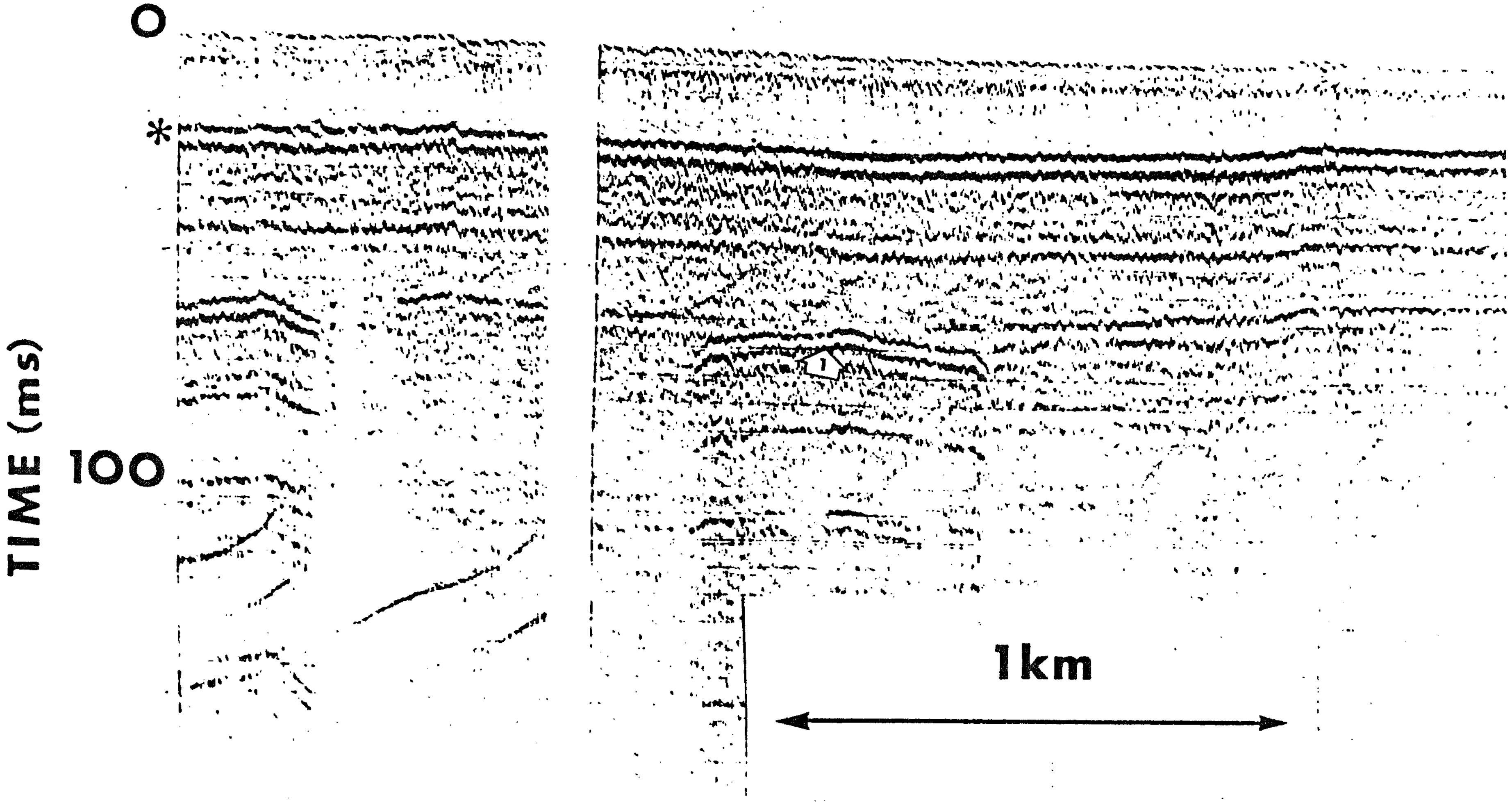

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Plate 29.

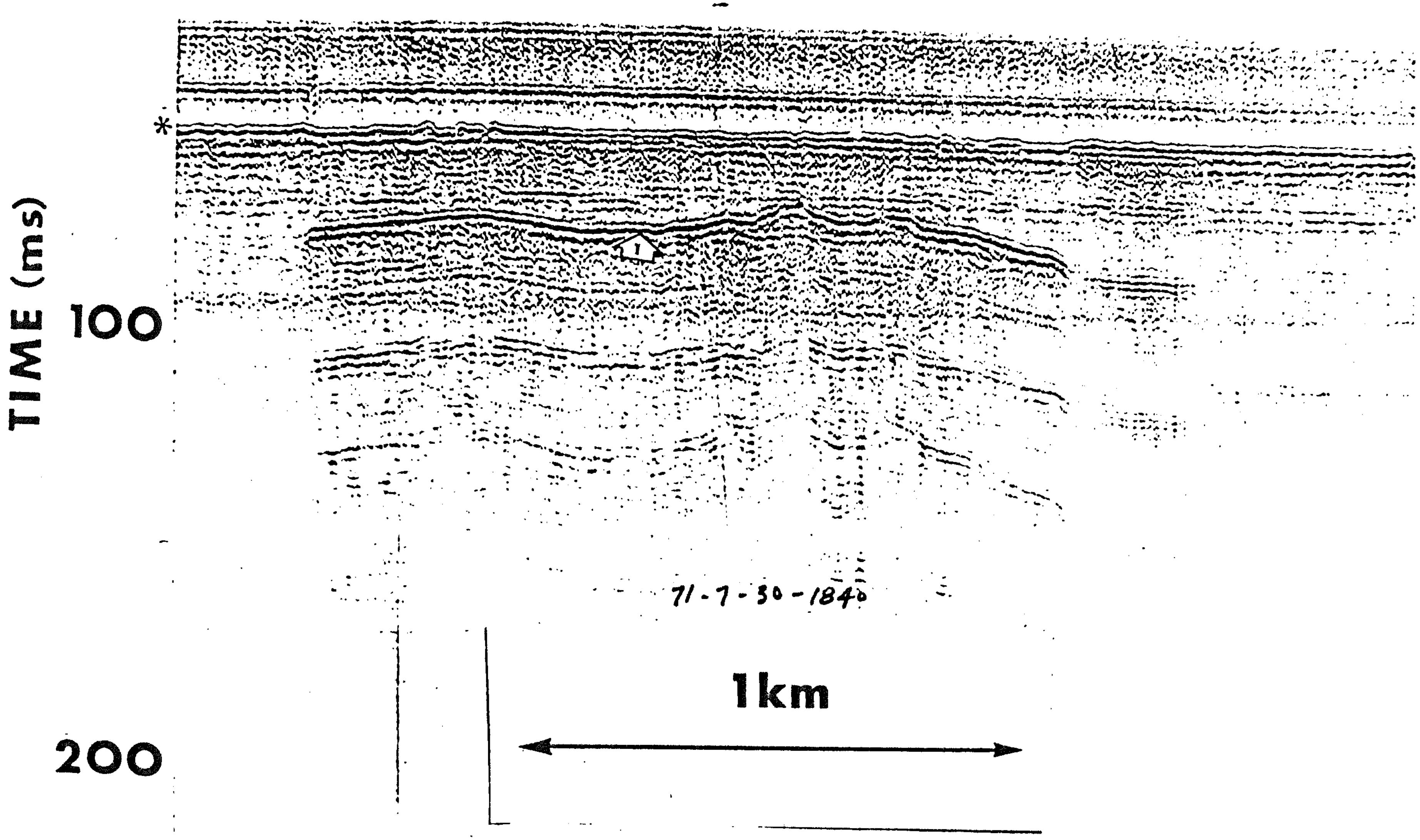

Plate 30.

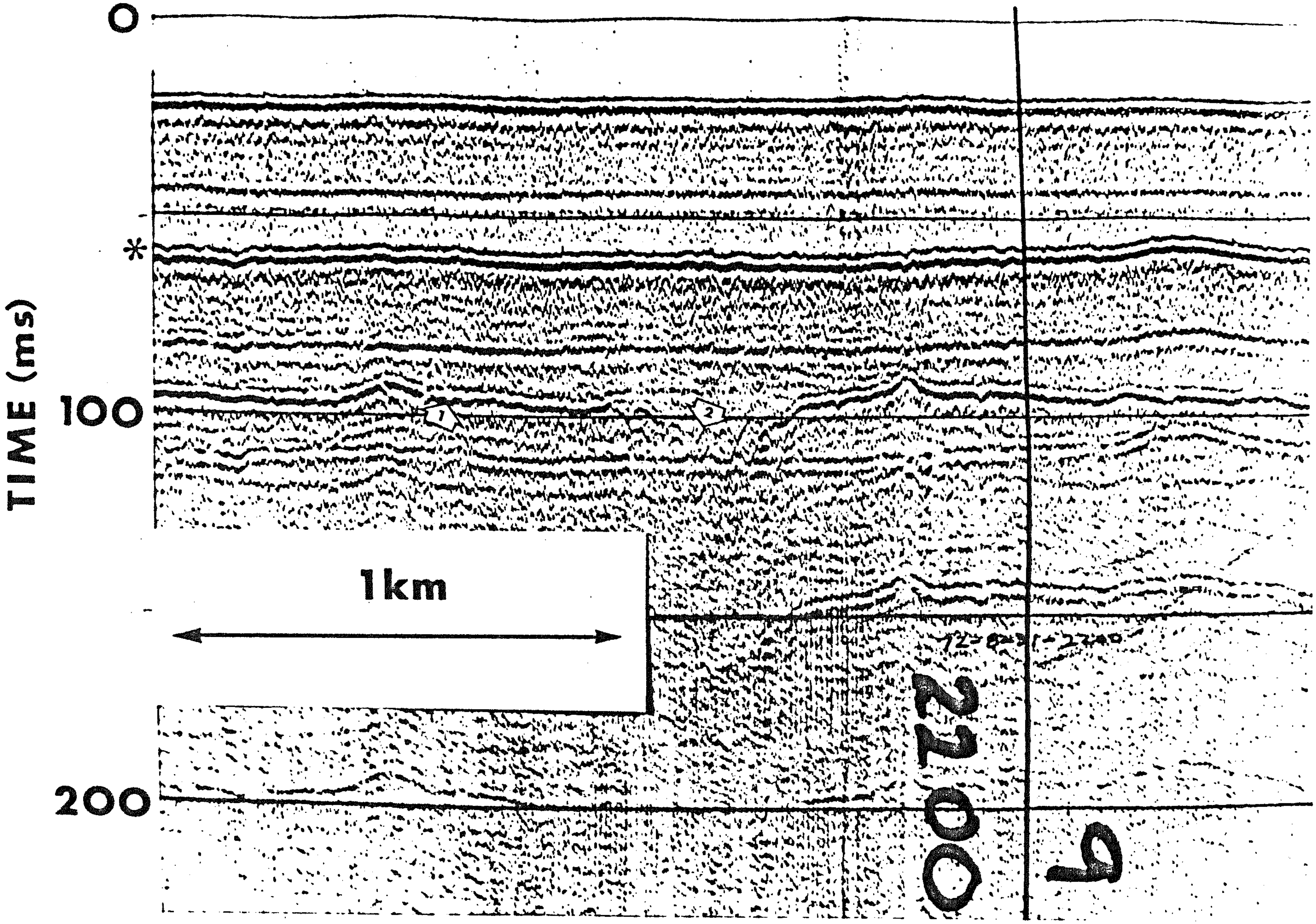

Plate 31.

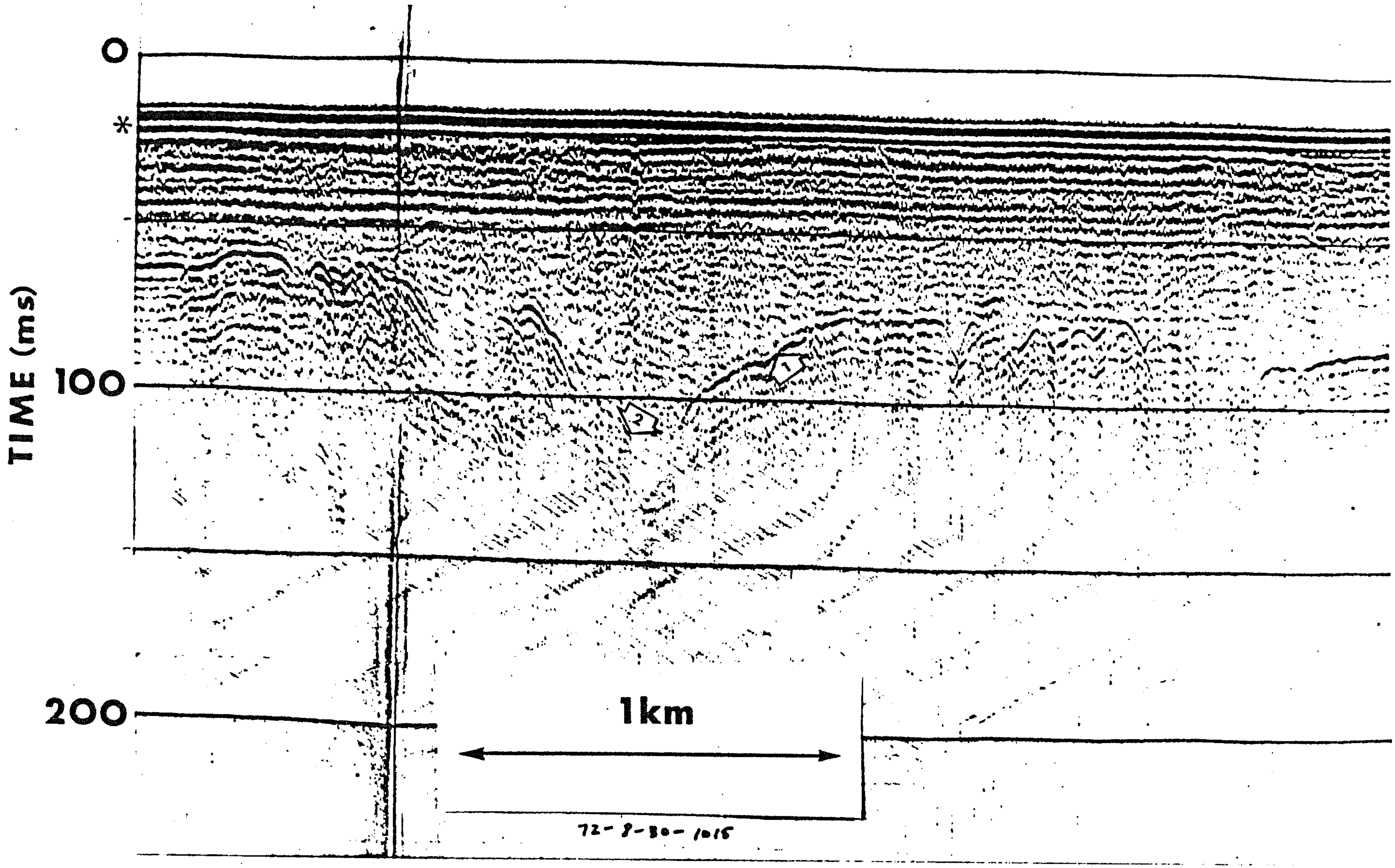

Plate 32.

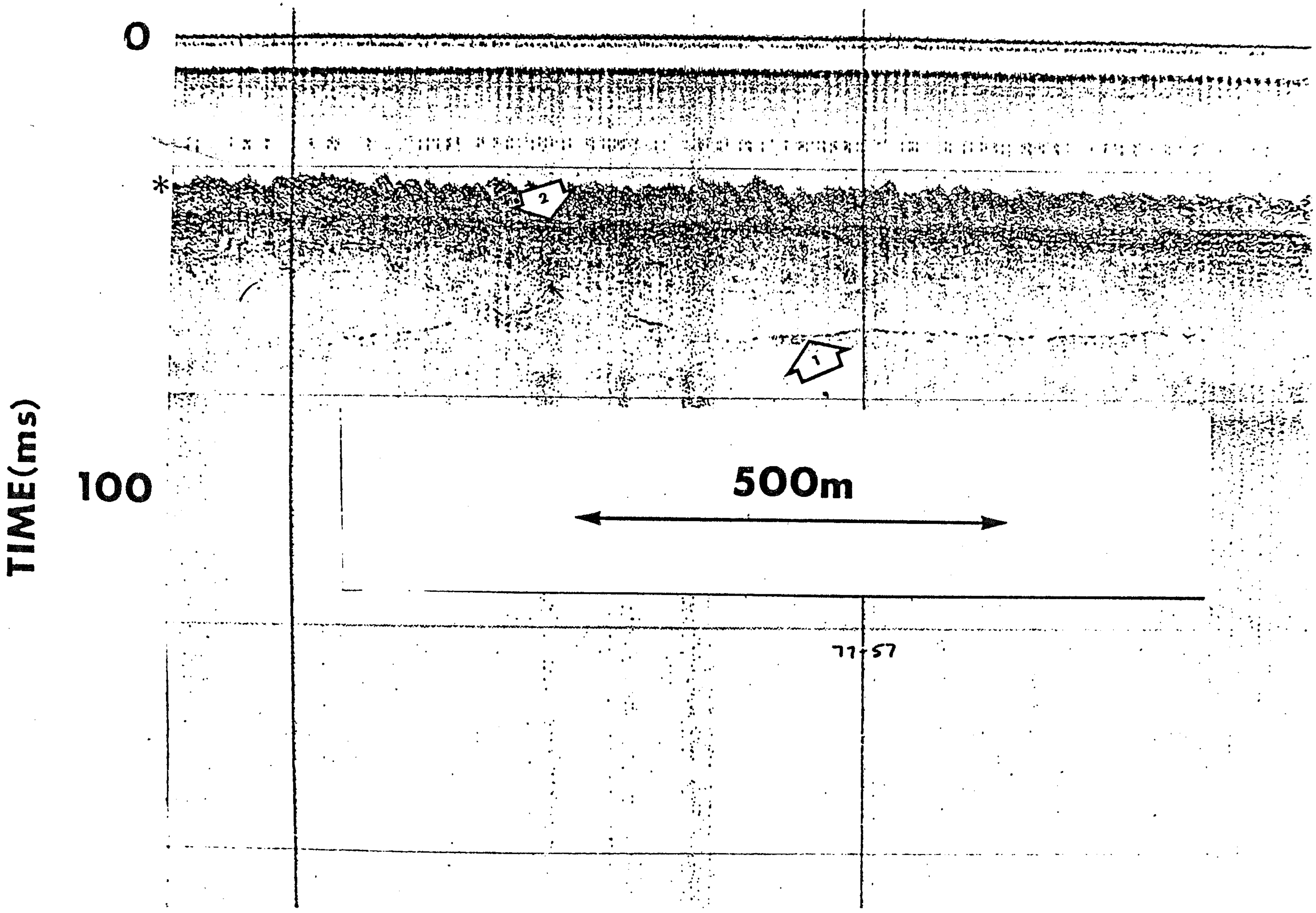

Plate 33.

the seafloor. Blasco (1979, pers. comm.) reported that this reflector was often confused with a similar event caused by a stiff, overconsolidated clay which occurs at about the same level. Where the acoustic permafrost table appears to be somewhat shallower, local ice lenses may be present near the unconformity (2). O'Connor (1977) interpreted horizontal, discontinuous reflectors above the unconformity south of this location to be lenses of acoustic permafrost, but no good examples of such reflectors were encountered on data reviewed during this study.

Nearer shore, where both Unit A and Unit B are known to be thinner, acoustic permafrost may occur at or near the seafloor itself, as shown by the strong, irregular reflector (1) on Plate 34. Westward, where the transgressive unit is believed to be thicker, the acoustic permafrost table (1) occurs much deeper in the section (Plate 35). It is similarly depressed (1) under Kugmallit Bay (Plate 36) due to thermal degradation resulting from the warming influence of the Mackenzie River.

3.5 Relationship Between Acoustic Permafrost and Shallow Gas

In some areas of the shelf there appears to be little relationship between the occurrence of shallow gas and acoustic permafrost. Northwest of Hooper Island, for instance, a small shallow gas pocket (1) occurs at the unconformity while ice-bonded sediments (2) are clearly evident in the section below (see Plate 37). Near the island, however, Plate 38 demonstrates that shallow gas-charged sediments (1) almost completely obscure the acoustic stratigraphy, except in local "windows" where deeper ice-bonded sediments (2) are apparent.

In Kugmallit Bay (Plate 39) shallow gas (1) migrating through a thick sequence of recent marine (?) strata occurs at exactly the same location

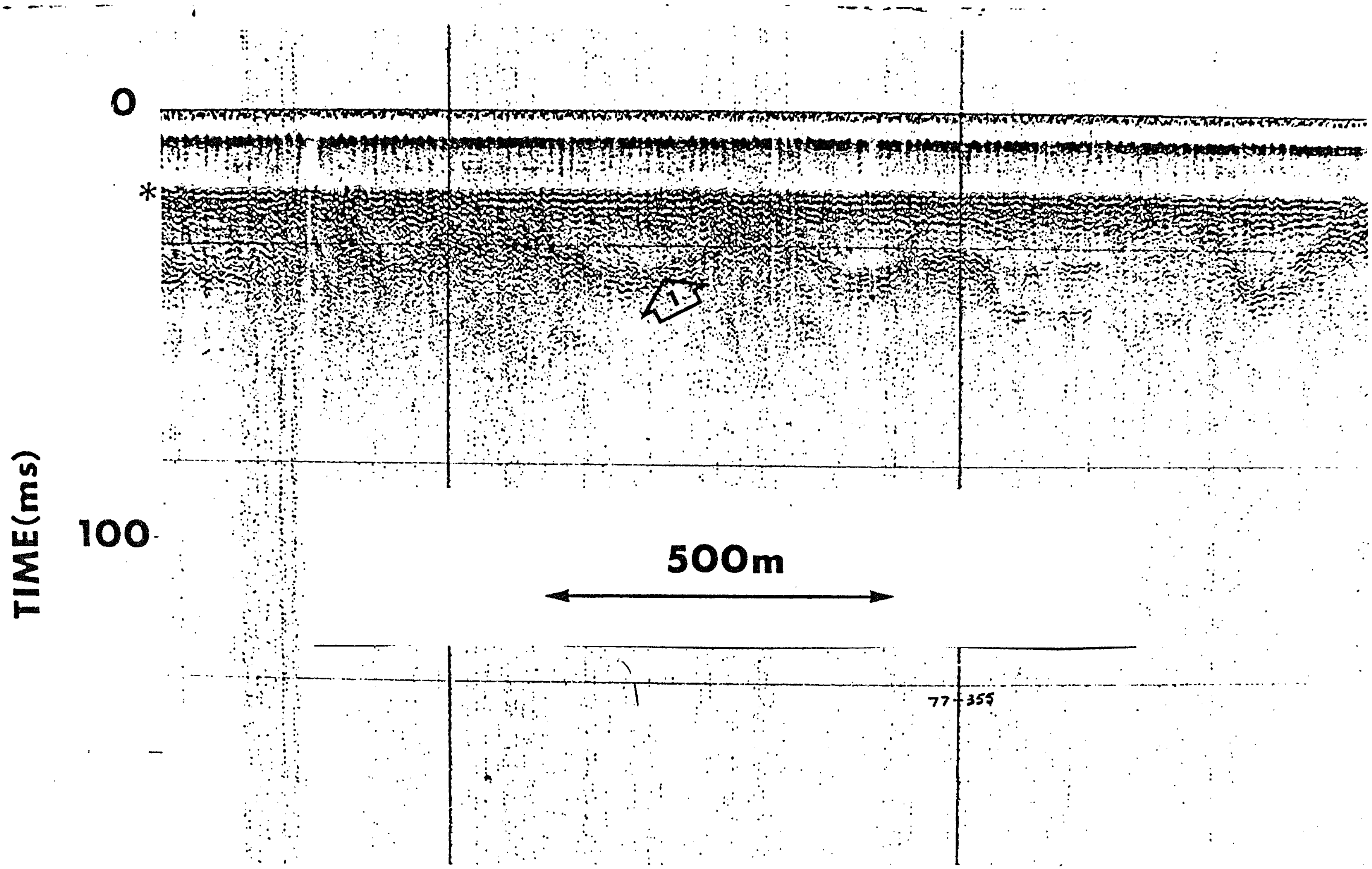

Plate 34.

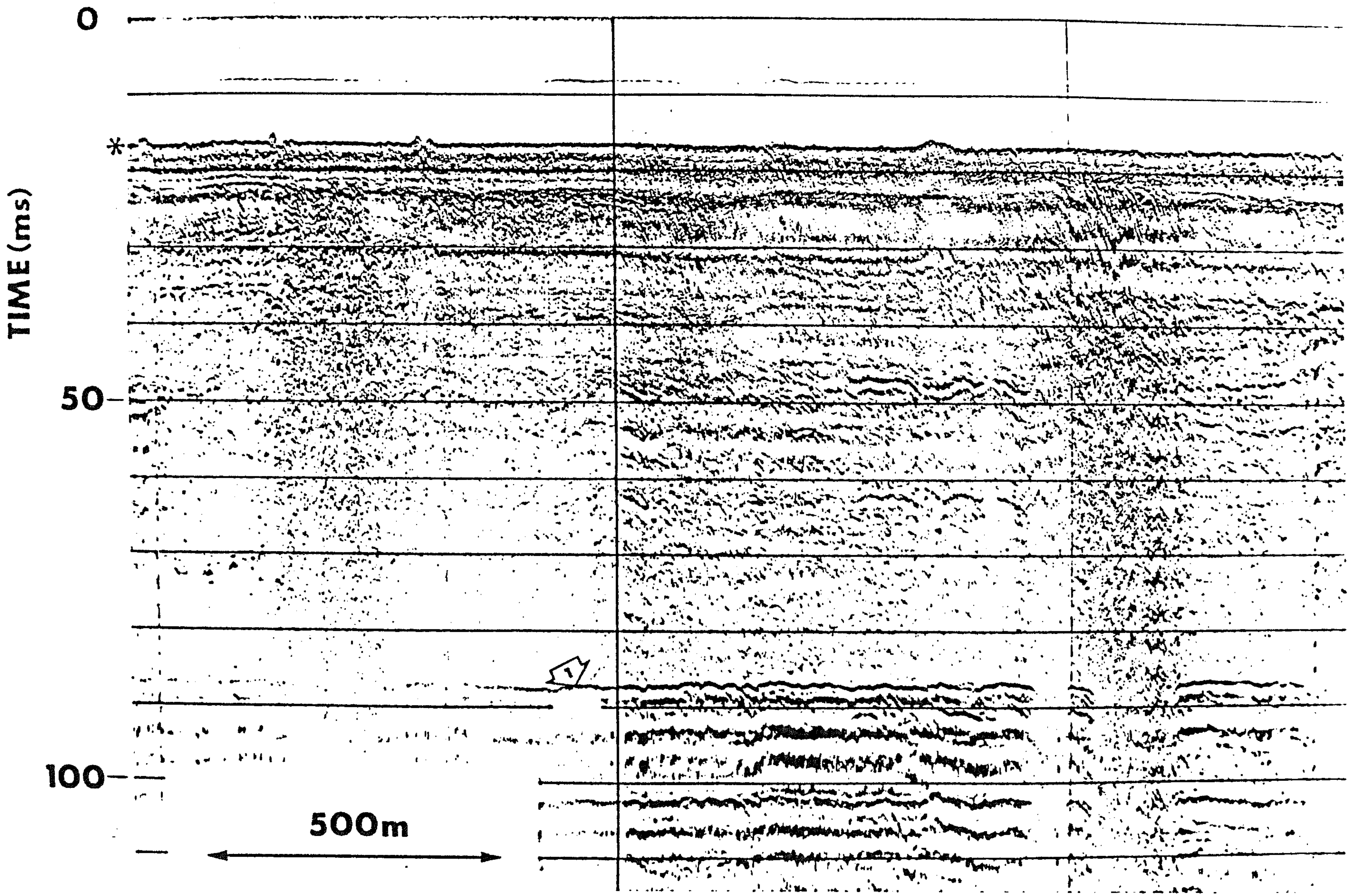

Plate 35.

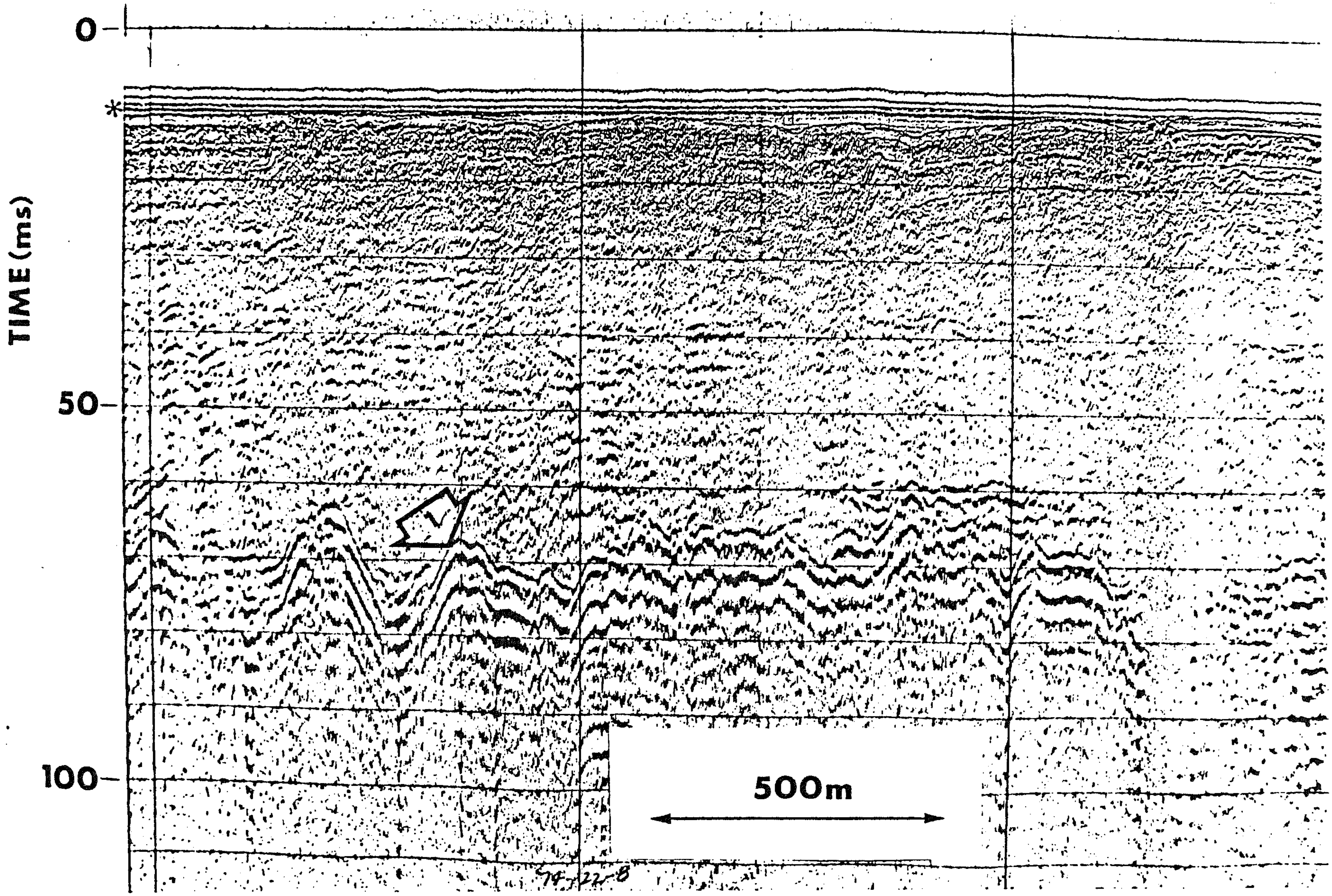

Plate 36.

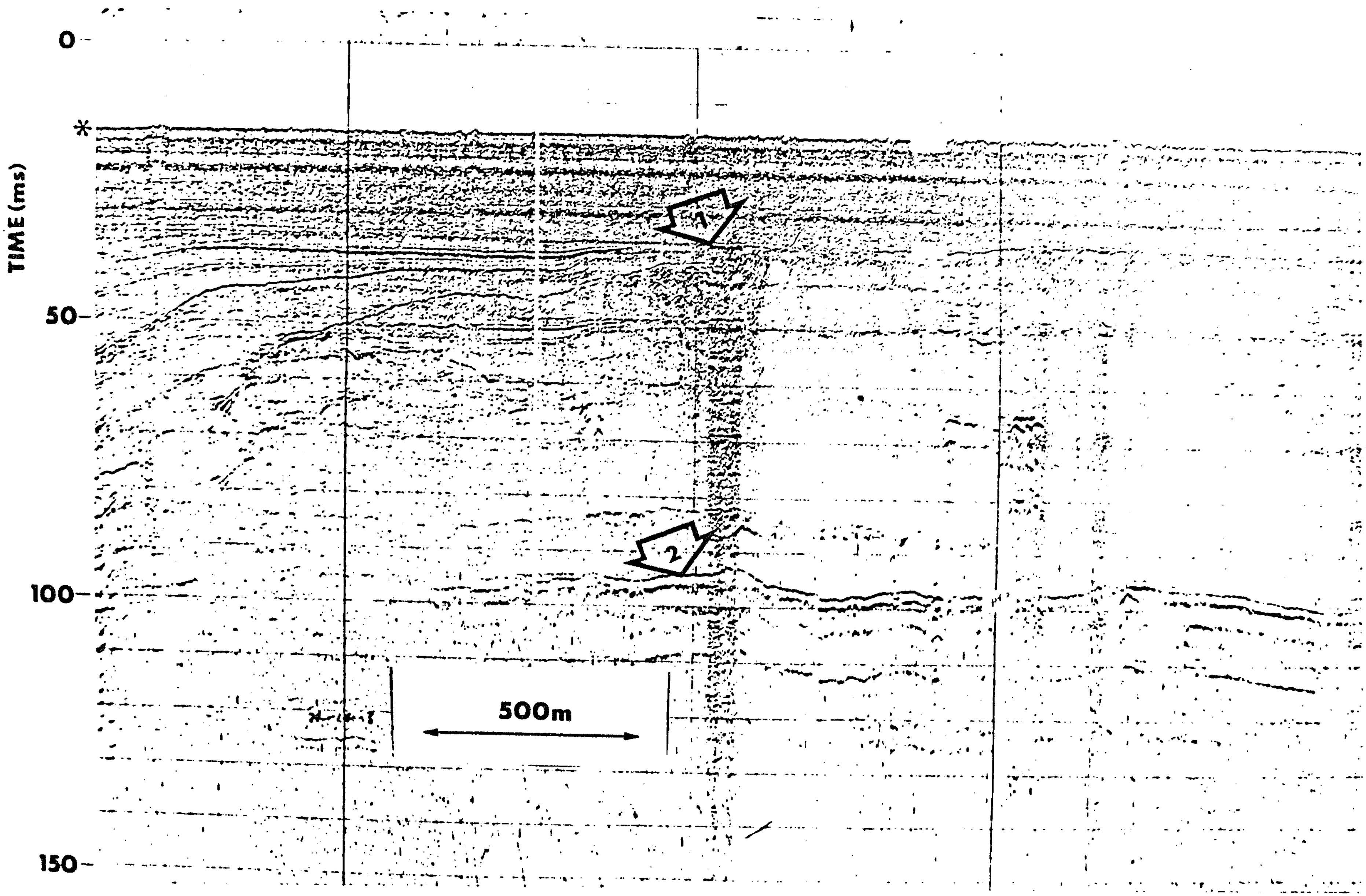

Plate 37.

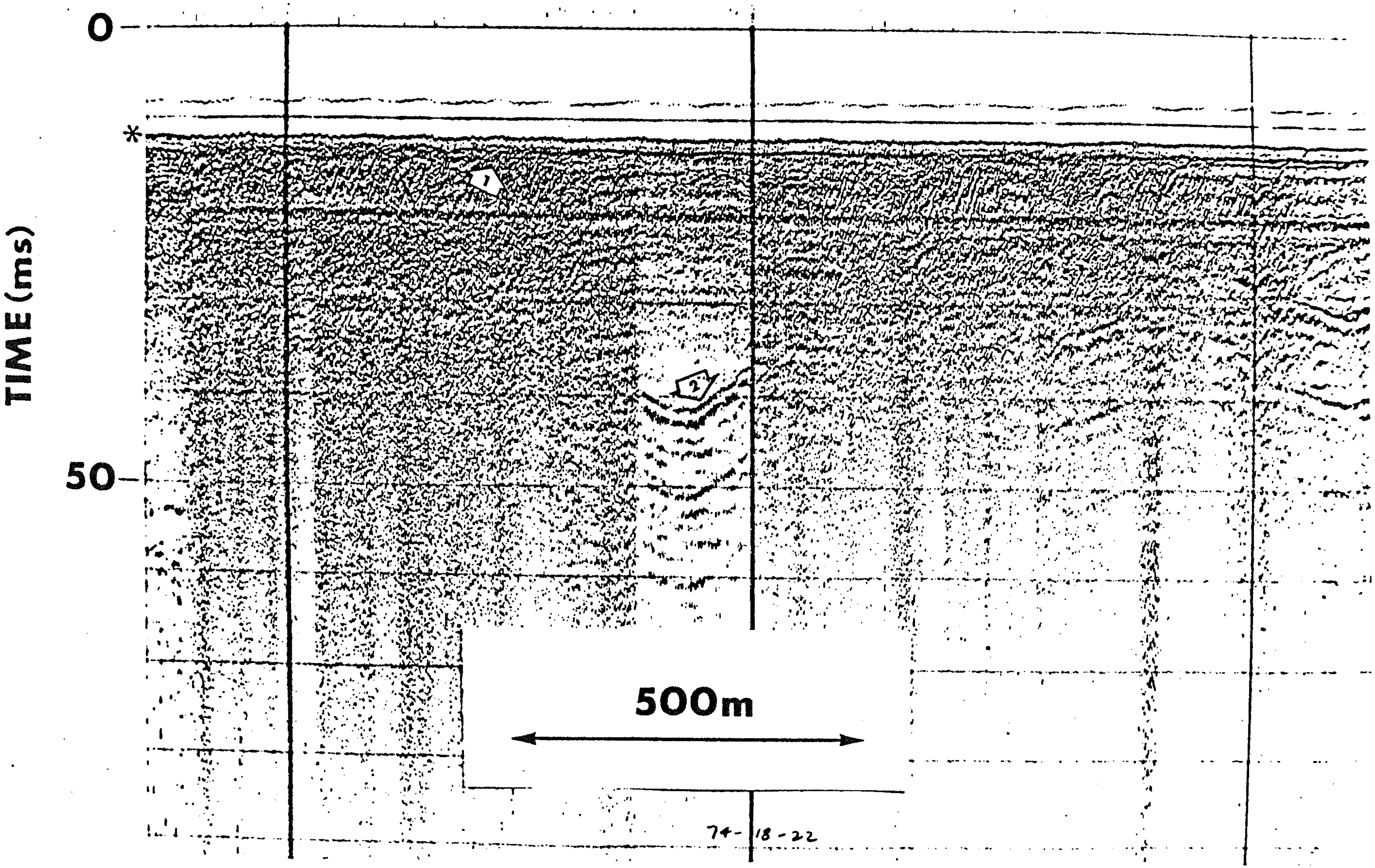

Plate 38.

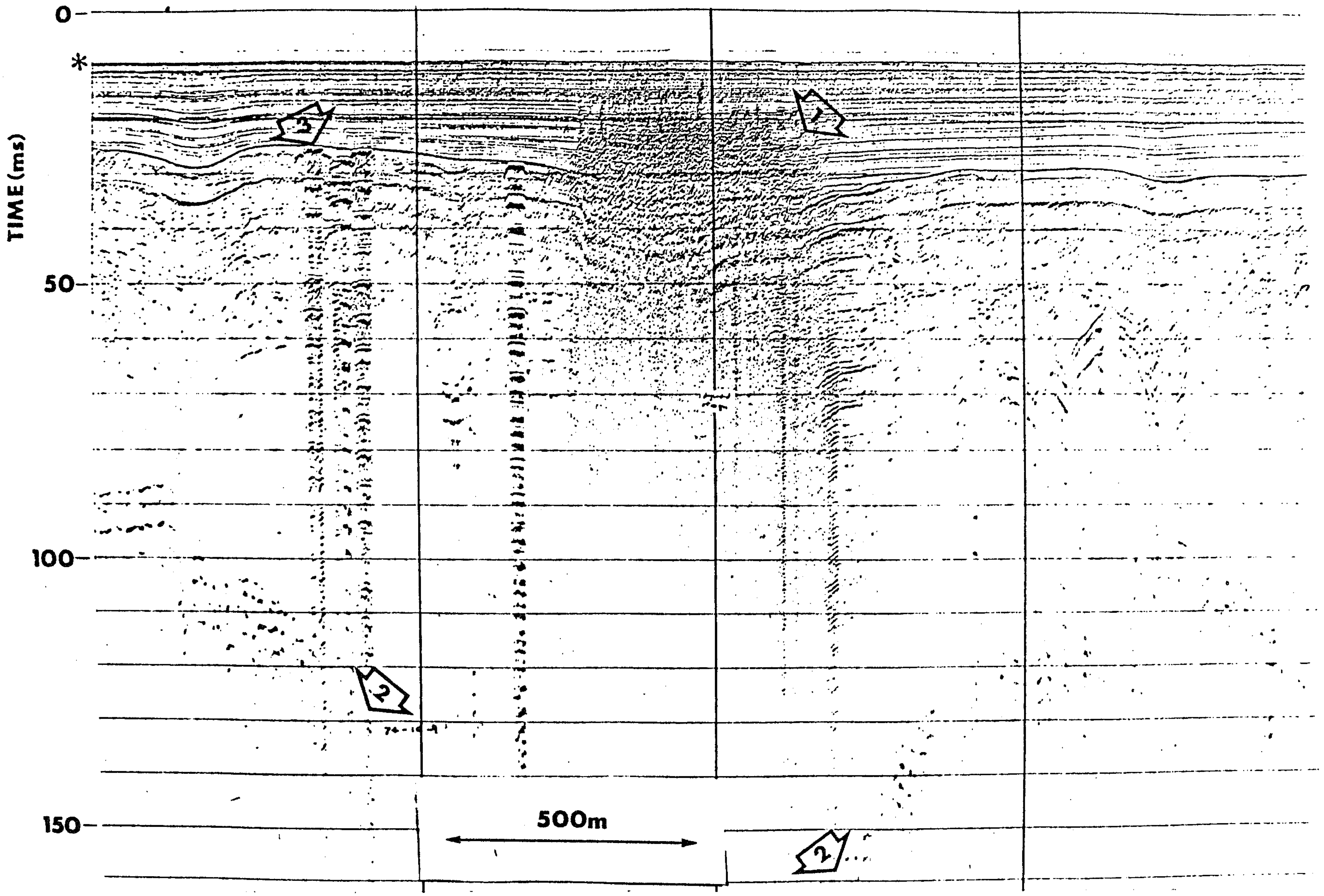

Plate 39.

as a pronounced depression on the acoustic permafrost table (2). Small gas traps (3) at the unconformity apparently bear little relationship to either of the foregoing at this location, but Plate 40 demonstrates that a marked depression of the acoustic permafrost table (1) can be associated with the edge of some much larger gas traps (2).

It has been suggested that these apparent depressions of the acoustic permafrost table are entirely the result of velocity pushdown caused by the presence of gas in the overlying sediments. Such appears not to be the case in Plate 41, since the edge of the shallow gas (1) is not coincident with the boundary of the permafrost depression (2). Neave et al (1977) suggest that shallow gas occurrences should be very common in the vicinity of major permafrost boundaries where the decomposition of degrading hydrates will be most rapid and a permeable path to the surface exists through the unfrozen sediments.

Since the largest known shallow gas occurrences are located near actively degrading permafrost areas such as Mackenzie and Kugmallit Bay, Neave's explanation would appear to have considerable merit.

3.6 Special Features

The seismic profiles often reveal special seabed or subbottom features which would be difficult to locate using other techniques, but which provide invaluable evidence regarding the geologic processes which are active in this complex environment.

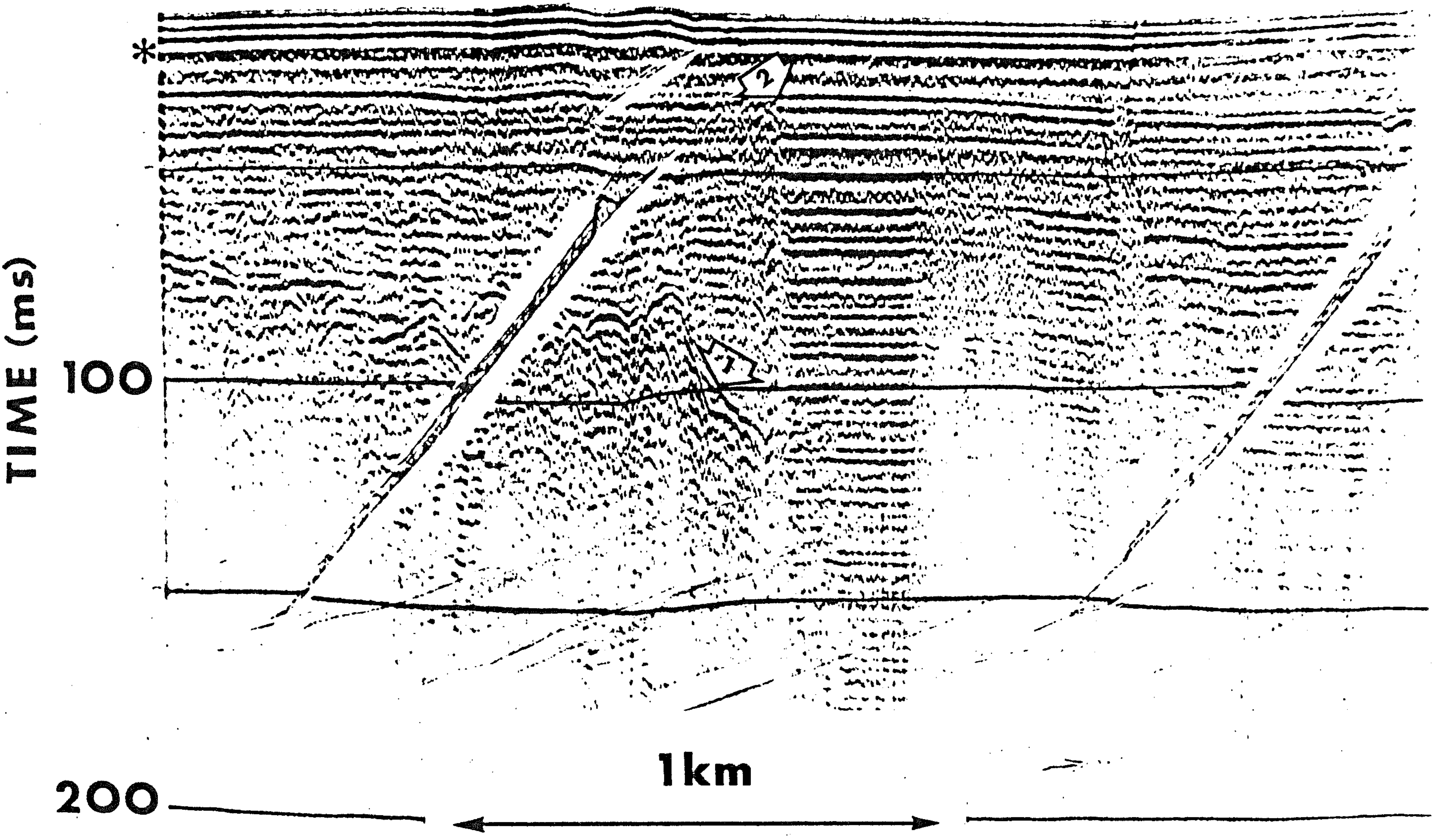

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Plate 40.

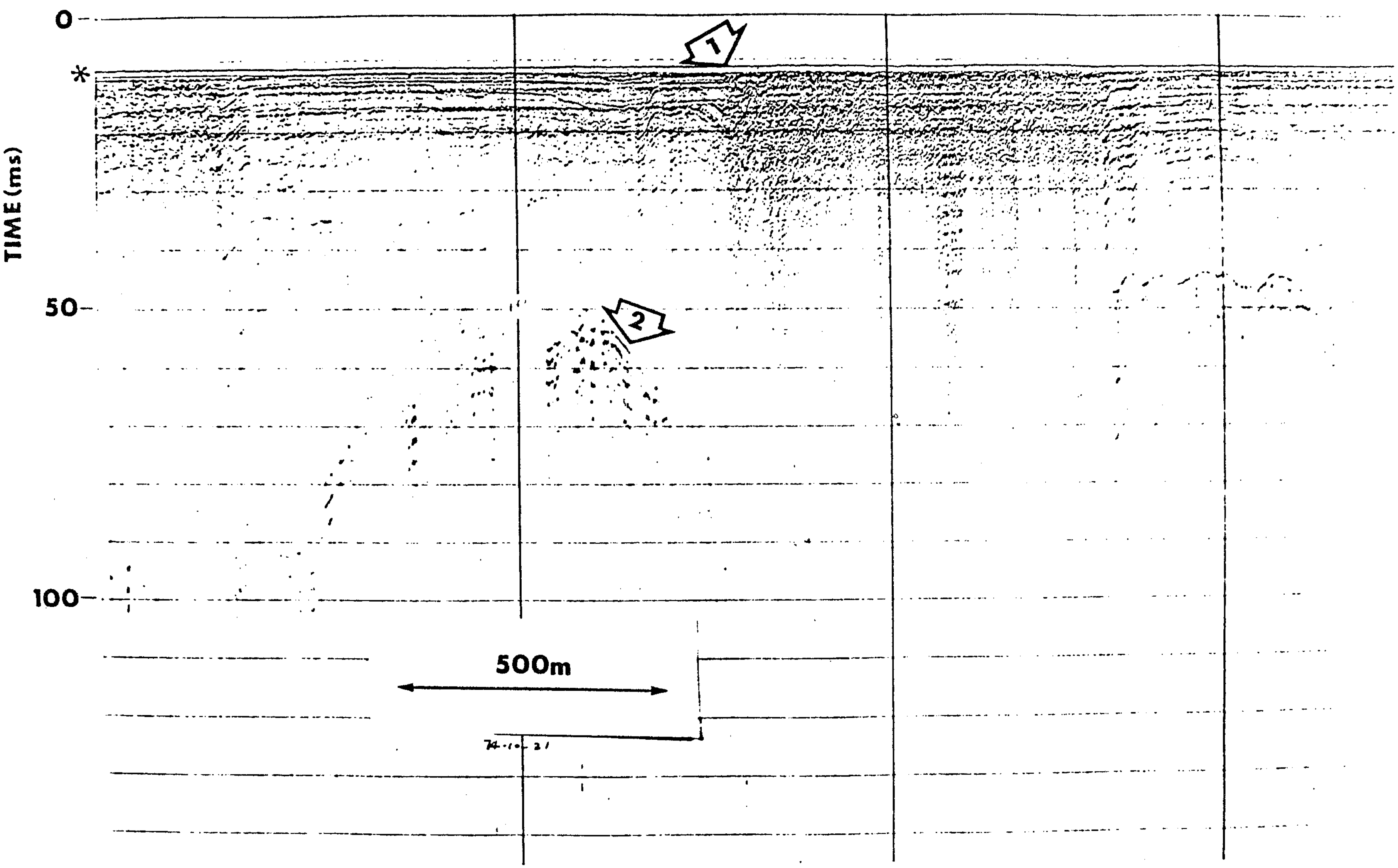


Plate 41.

3.6.1 Thermokarst Topography

Relic thaw depressions have been interpreted on some of the seismic profiles examined during this study. Plate 42, located in Kugmallit Bay at the same site as Plate 39, shows a 3 m depression (1) at the unconformity which has been infilled by subsequent deposition of a thicker sequence of horizontal strata, tentatively classified as Unit A and/or B. The interpretation is that massive ice, at some unknown depth beneath the unconformity and above the present acoustic permafrost table (2), degraded under the influence of the warmer water which flowed in Kugmallit Channel following sealevel rise. From the manner in which the strata drape into the depression, it has been deduced that development of the observed unconformity relief occurred over a significant period of time and was not a single catastrophic event.

A similar feature (1) has been interpreted beneath the seafloor on data shown in Plate 43. Here, however, there is also associated relief on the acoustic permafrost table (2) and on the seafloor itself. The latter feature suggests that sedimentation rates on the present seafloor are not sufficiently high to keep up with the rate of thaw depression. The location of Plate 43 is not known, but it is believed that the profile was collected somewhere in the vicinity of Plate 30, about 100 km north of Toker Point. Considering the observed bathymetry of approximately 50 m, it is possible that the acoustic permafrost table in this area is now either stable or aggrading and further development of the thaw depression has essentially ceased.

A number of V-shaped depressions have been mapped at the unconformity near the edge of the shelf north of Pelly Island (Plates 44 and 45).

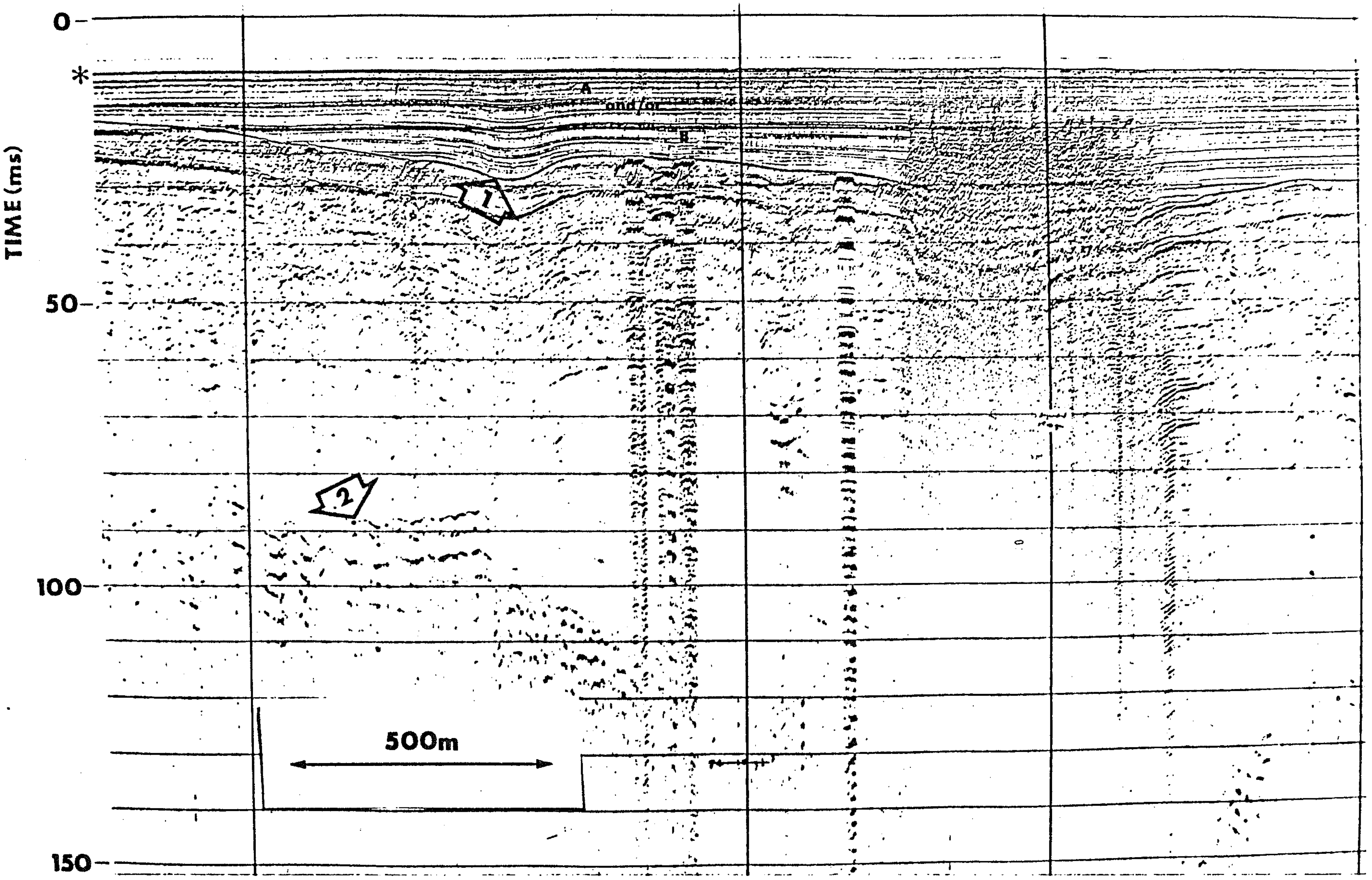


Plate 42.

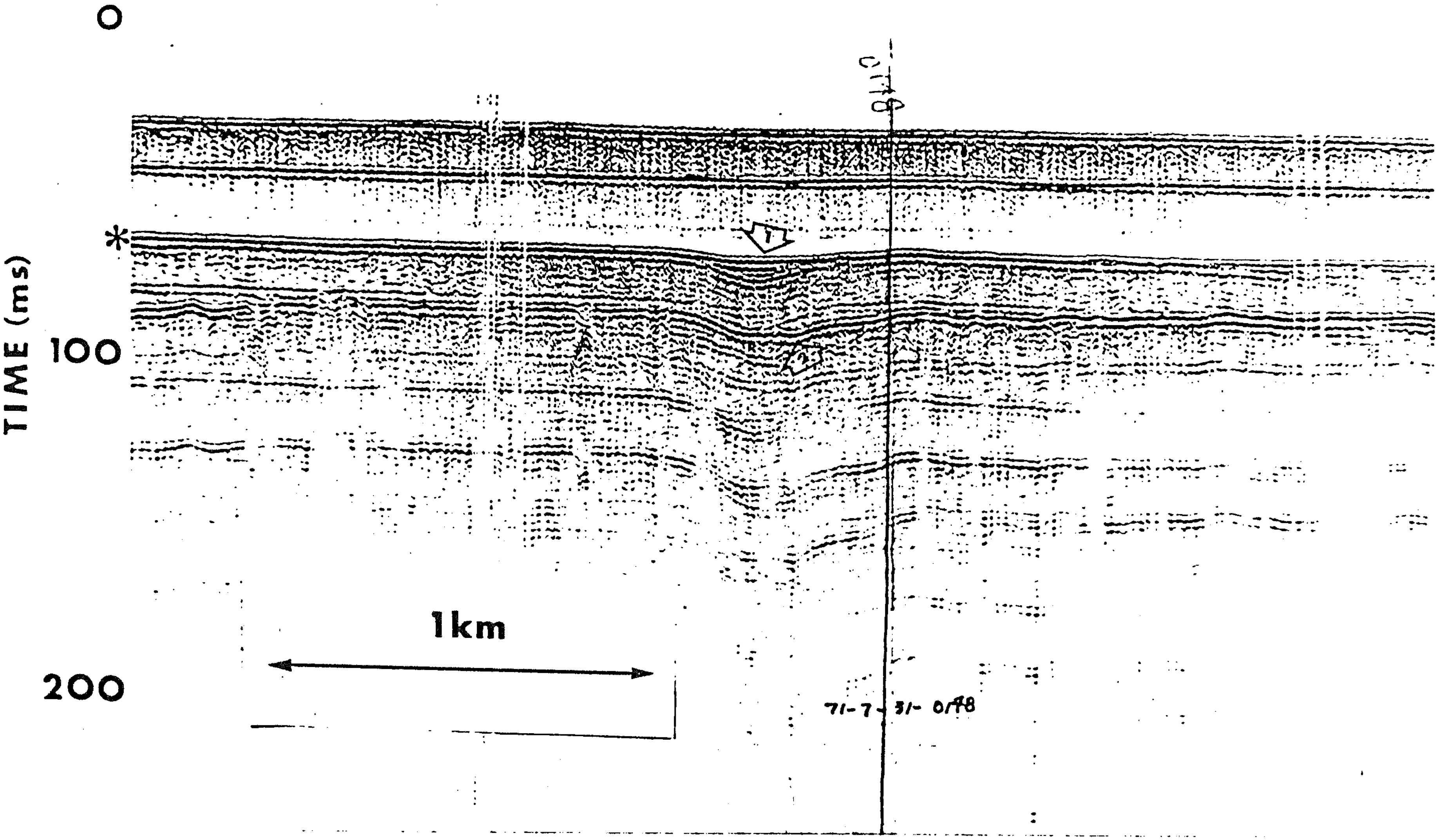


Plate 43.

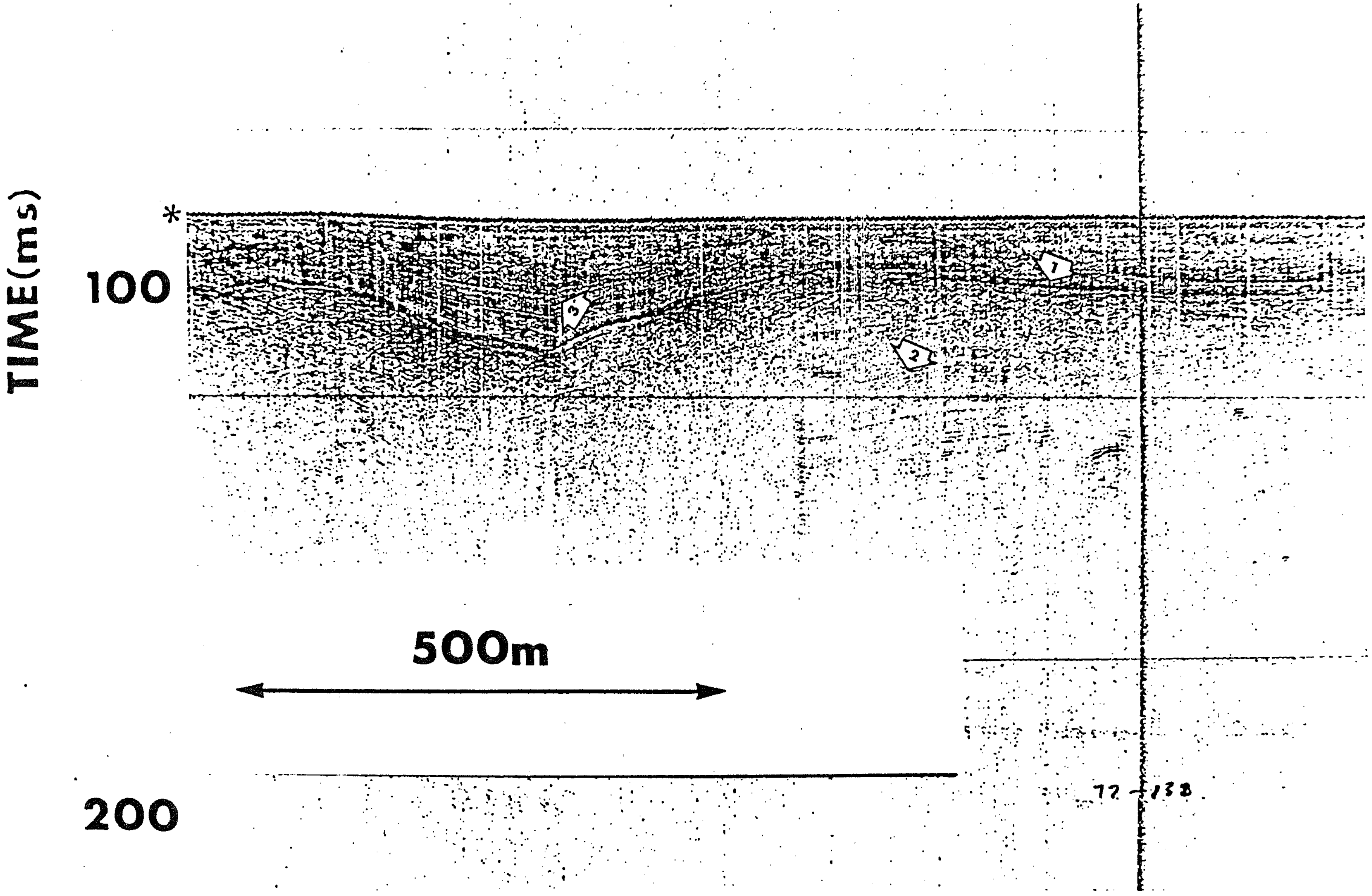


Plate 44.

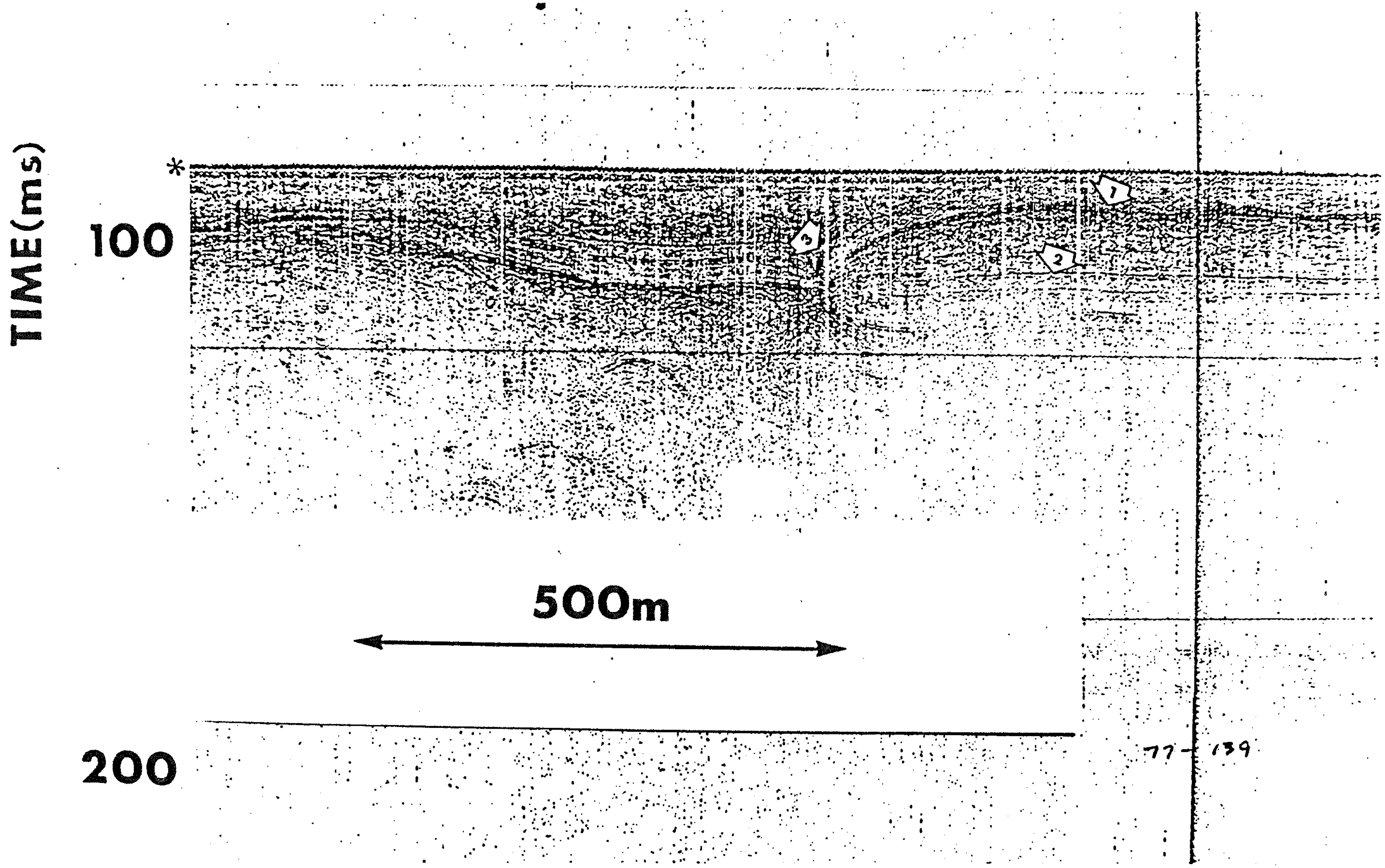


Plate 45.

In both photographs the unconformity (1) is acoustically transparent enough at some locations to reveal horizontal or gently dipping beds below (2). This suggests that it is not extensively ice-bonded. It is evident from the stratigraphy which can be observed beneath the SPZ that the bedding (3) within the lower part of the transgressive sequence is related to the unusual relief of the unconformity. While the present information is clearly not adequate enough to work out any particular geologic details, it is speculated that both features are examples of relic thermokarst topography.

3.6.2 Massive Ice

Given the fact that several relic thermokarst features have been located on the continental shelf, a brief inspection of the seismic profiles was conducted in order to identify any unique acoustic signature which might indicate massive ice in the subsurface. Although the results of the inspection were generally negative, some unusual acoustic features apparent on 1977 data northwest of Hooper Island have been interpreted as possible massive ice occurrences. A blowup of one of these features is presented in Plate 46. The SPZ here comprises both recent marine and transgressive sediments, while mainly coarse silts and sands are believed to occur beneath the unconformity (1). Although a detailed analysis of the section is not possible, it is speculated that the dark feature (2) near the centre of the photograph is related to the presence of massive ice.

Horizontal, discontinuous, high amplitude reflectors described by O'Connor (1977) may also be related to massive ice occurrences. In an equilibrium or aggrading permafrost regime they probably are due to differential ice-bonding and/or thin ice lensing due to grain size or salinity changes.

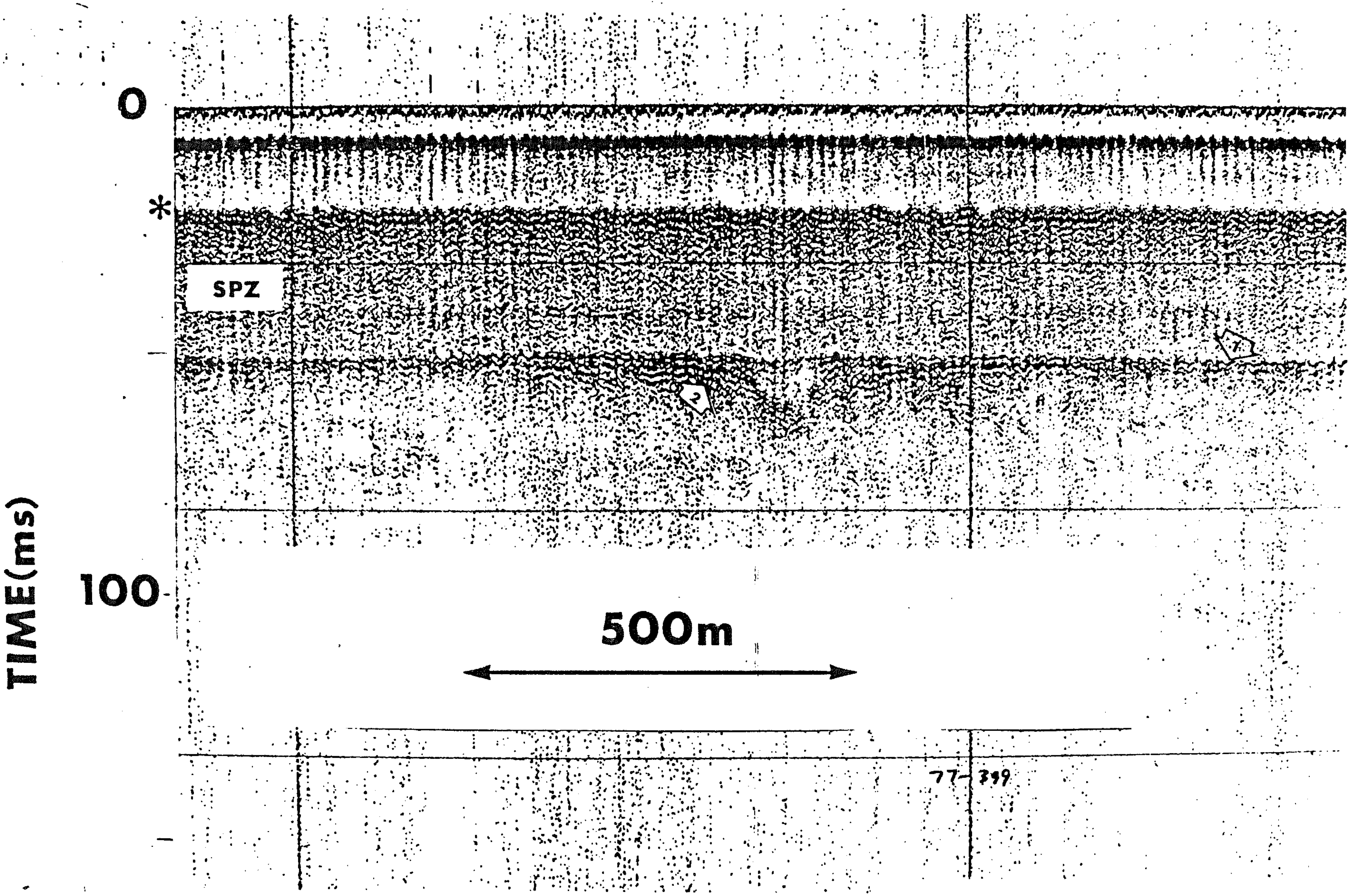


Plate 46.

In a degrading permafrost regime they may represent the top of massive icy beds whose degradation has lagged behind that of the acoustic permafrost table in the sediments below. Such occurrences might have serious consequences for the development of future seabed installations.

3.6.3 Glacial Sediments

Although sediments which probably have a glacial origin are recognized within the context of the general geologic model and appear to have been encountered during borehole and shallow coring programs, their identification on the seismic profiles has not generally been possible. A singular exception to the statement is shown on Plate 47, located about 15 km north of Pullen Island. Here transgressive sediments (B) have been deposited unconformably on and adjacent to a complicated sequence of highly disturbed beds (1) which appear, in turn, to be resting on an old unconformity surface (2). Ice-bonded permafrost is suspected at (3) and (4) and a small thermokarst (?) depression may be visible at (5). This section occurs in the same general area where the author previously achieved very little subbottom penetration using a gravity piston core. One conclusion would be that glacial sediments, perhaps similar to those encountered on Pullen Island, have been advanced to this location and then drowned during the last sea level rise.

A more recent seismic profile not shown here was obtained from an area northwest of Garry Island. Shearer (1972a) and Meagher (1978) both show the recent marine sediments to be very thin here and borehole evidence suggests the presence of a shallow till-like unit (O'Connor et al, 1979). Unfortunately, the quality of the seismic section has been severely reduced by the occurrence of shallow migrating gas, so that no detailed interpretation of the acoustic stratigraphy is possible.

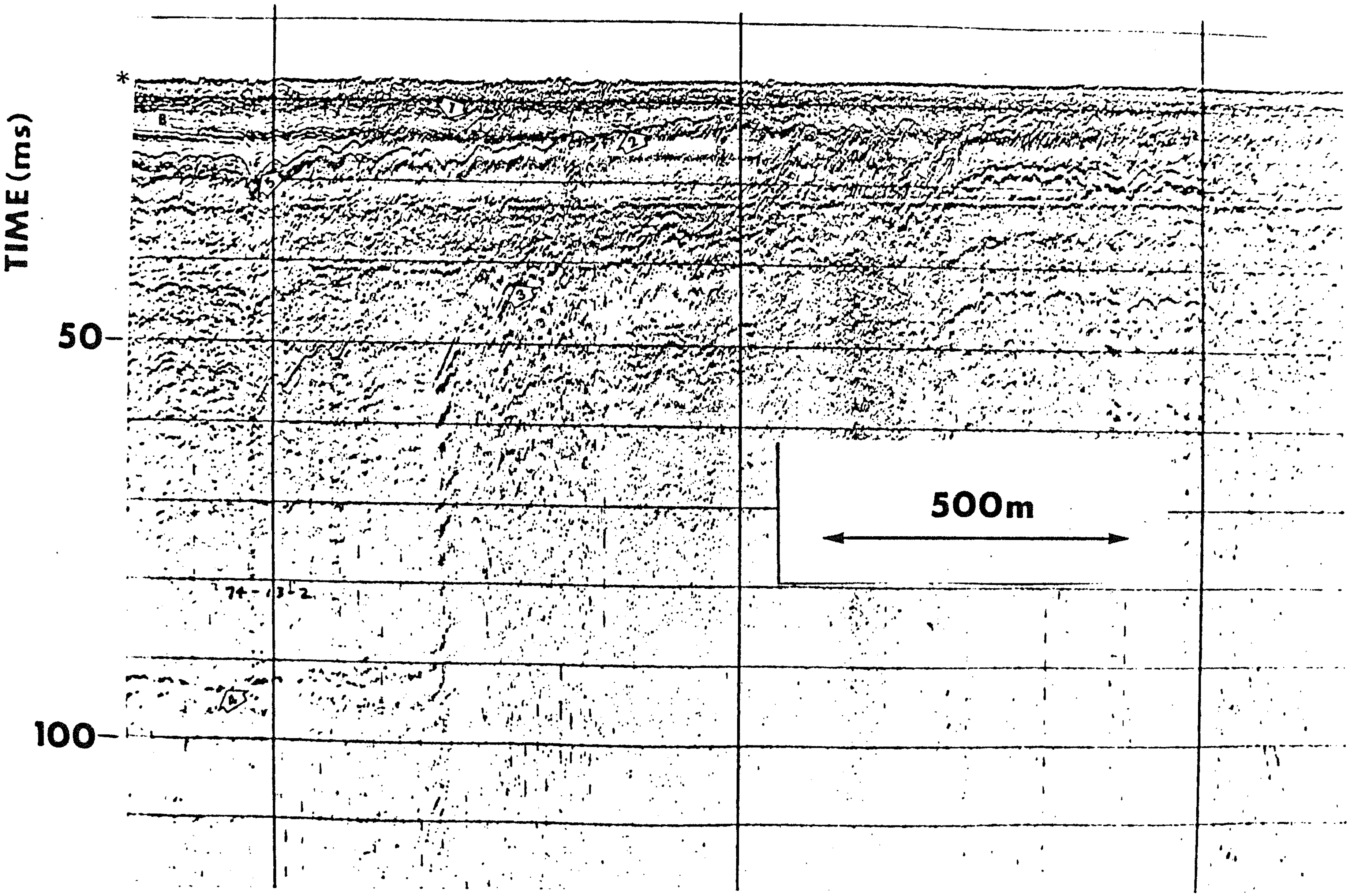


Plate 47.

3.6.4 Pingo-Like Features

Pingo-like features (PLF's) were not common on the shallow seismic profiles examined, but a few examples were noted. Plate 48 shows one PLF encountered on 1970 data north of the Tuk Peninsula, in an area where a great number of PLF's have already been mapped bathymetrically. In crossection it displays the classic features of ice-cored pingos normally observed on land: a conical hill (1) rising up from the centre of a residual pond (2). Although the top of the PLF is about 15 m above the surrounding moat, only slight relief above the present seafloor is apparent. North of the PLF is another seafloor depression (3), in the centre of which occurs relic thermokarst stratigraphy (4). The seismic evidence is not of sufficient quality to produce any detailed interpretation, but this latter feature could be associated with a relic collapsed pingo.

Plate 49 shows another seafloor depression southwest of Plate 48. The acoustic permafrost table (1) occurs from 20 m to 40 m below the seafloor, but ice lensing (2) may also be present in the shallow section. The possibility exists that this location could represent one of the few acoustically documented examples of relic permafrost overlain by recent aggrading permafrost caused by present seafloor temperatures. If the proper hydrogeologic conditions exist in the zone below the depression (3), then growth of a new pingo may be imminent.

A PLF which may be laterally associated with relic thermokarst is presented in Plate 50, a section near the northwest shelf edge. The PLF (1) appears to originate at the unconformity (2). The absence of deformed strata in the overlying recent marine or transgressive units suggests that the feature is not genetically intrusive, but has been

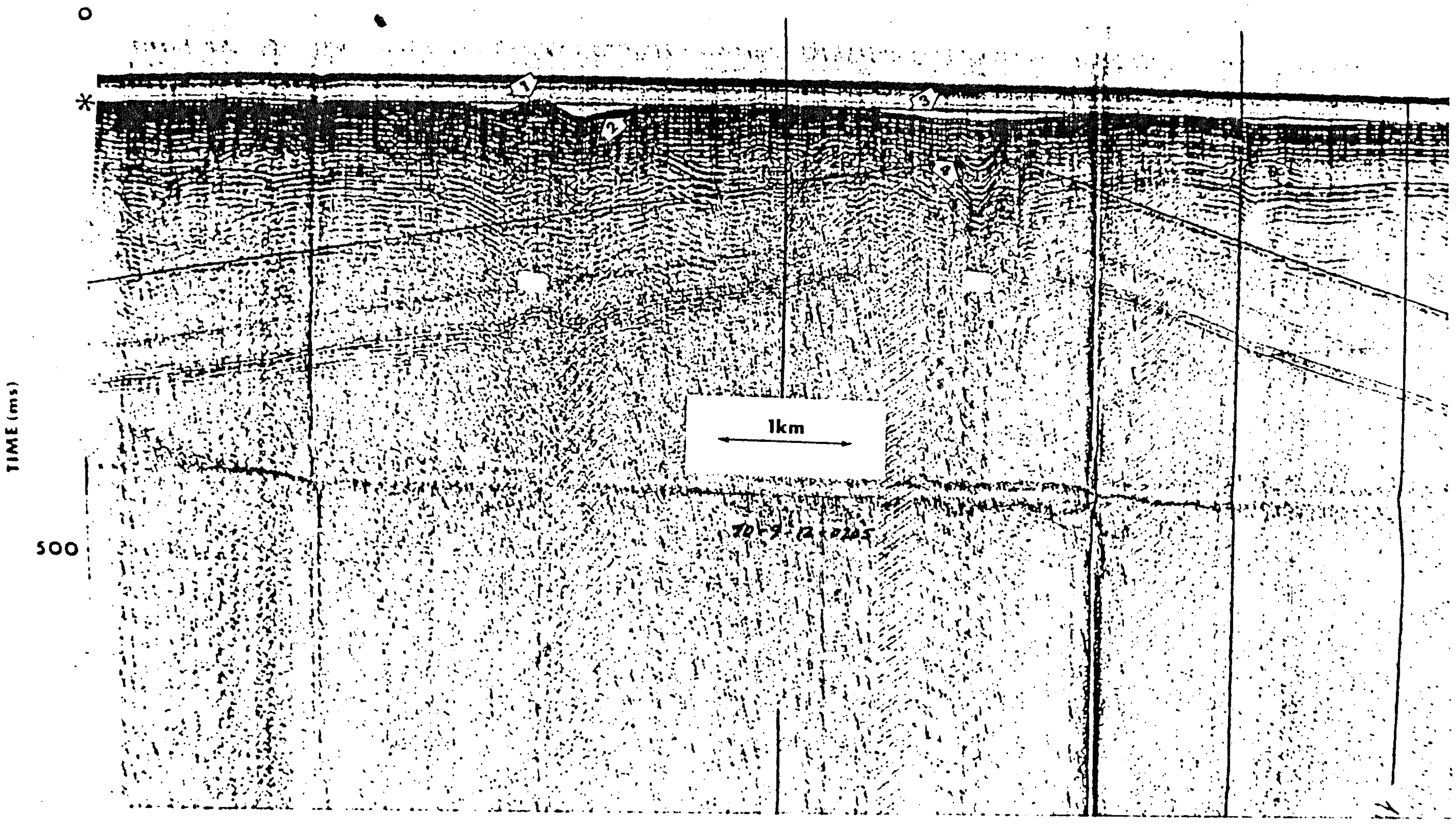


Plate 48.

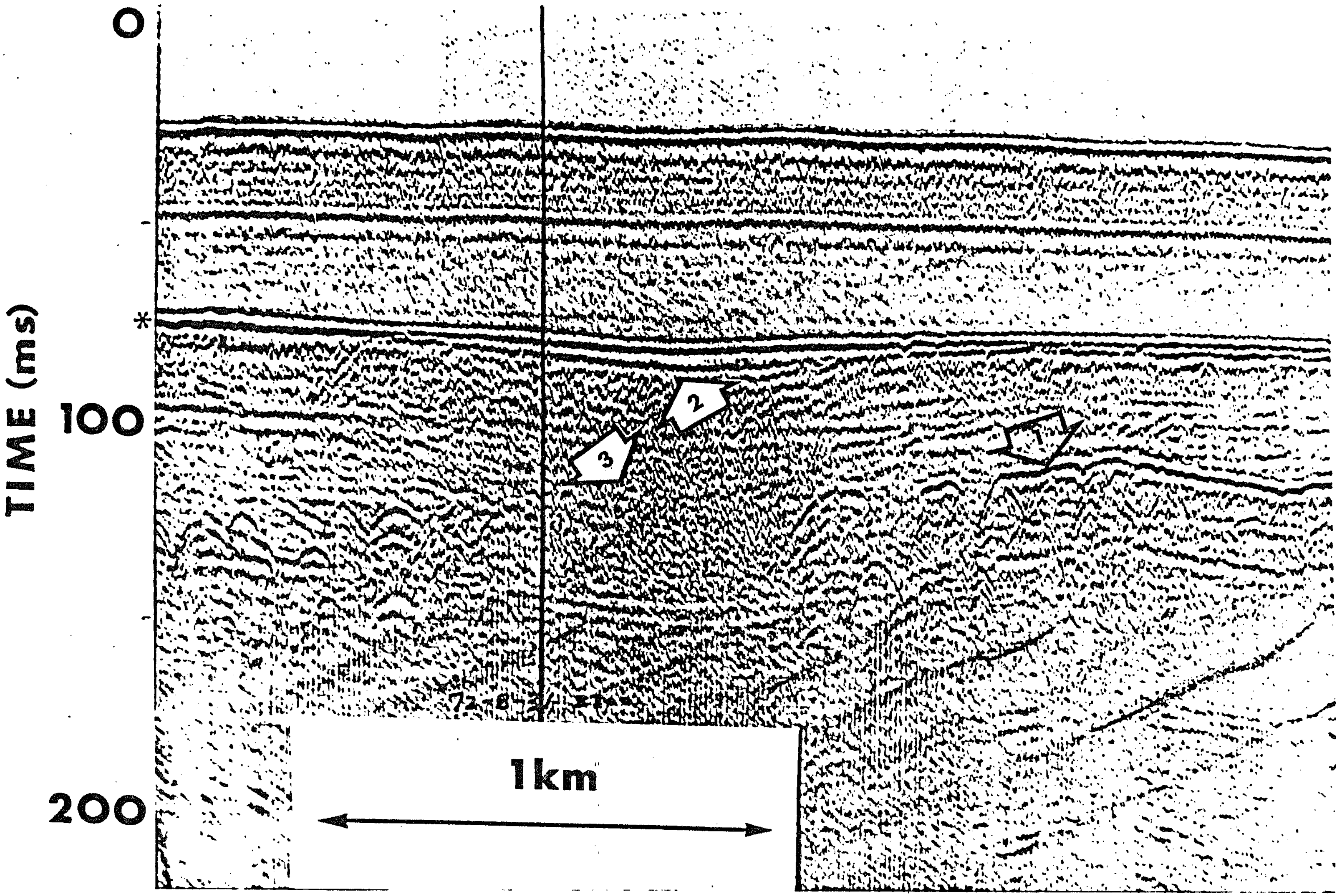


Plate 49.

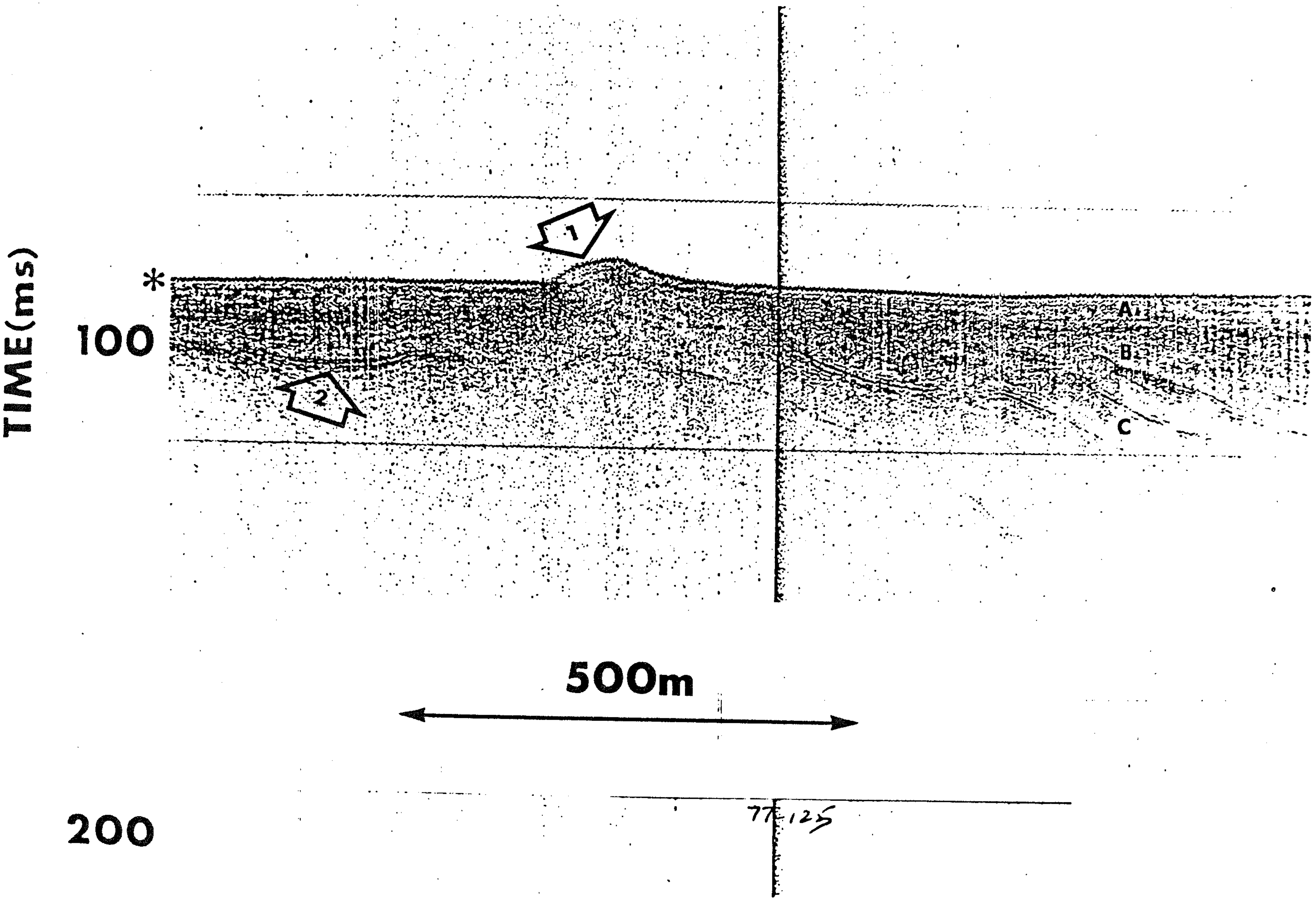


Plate 50.

buried during subsequent sedimentation. The whiter, acoustically opaque areas beneath the unconformity are believed to arise from extensive ice-bonding in the sediments. This is consistent with the nearby occurrence of a relic thaw depression (1) shown on Plate 51, since the sediments at this latter location are acoustically transparent and hence unfrozen to considerable depth (2). Note that all the overlying strata, including the seafloor, are deformed proximate to the thermokarst feature. This suggests that its development occurred recently enough so that total infilling of the structure has not yet been possible.

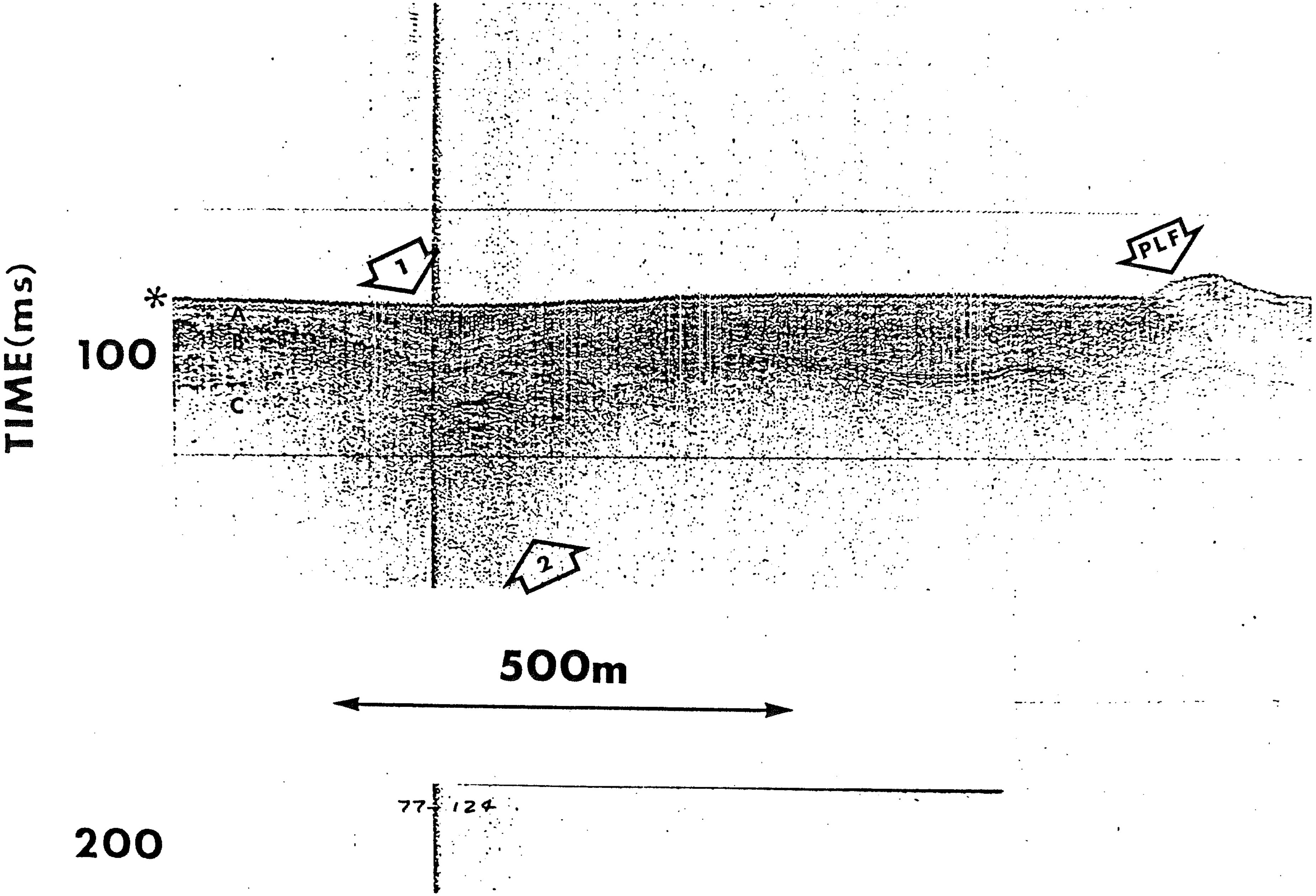


Plate 51.

4.0 DESCRIPTION OF THE SHELF EDGE MORPHOLOGY

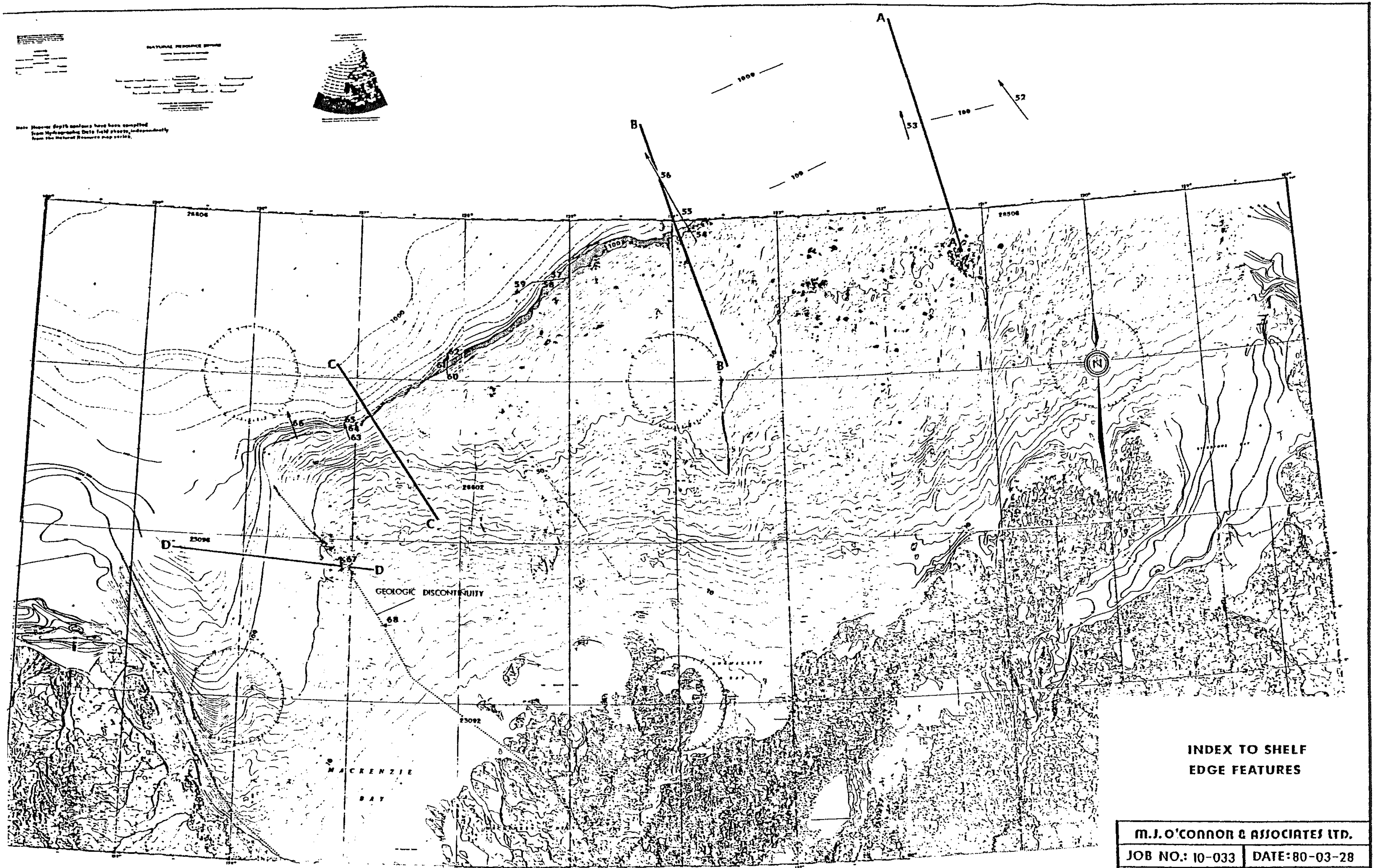
4.1 The Outer Shelf Edge

The edge of the continental shelf in the eastern and central study area occurs near the 100 m isobath, as shown by the crossections A-A and B-B in Drawings No. 4-1 and 4-2. Shoreward of this hinge line the seafloor rises to the land surface at a slope of 0.03° to 0.06°. Seaward it falls off to the continental rise at an average slope of about 1.5°. In the western region near C-C the shelf break may occur about 30 m shallower. As the drawing also shows, the shelf angle along Section C-C is about the same as that observed elsewhere, but the average continental slope is almost twice as steep.

The shelf edge is the boundary line between the neritic environment, where deposition of terrigeneous debris from the adjacent land surface is relatively rapid, and the continental slope, where (mainly) pelagic sediments accumulate at a very slow rate. As such, it represents something of a geologic discontinuity. Acoustic profiles collected across this boundary are useful in examining the changes in shelf edge morphology which occur through the study area.

Plate 52 shows the gentle nature of the shelf edge near Section A-A. Low relief structures (1) are apparent, but many of these have been intruded by PLF's (2) of undetermined origin. Where visible, bedding is parallel to the present seabottom, but most bedding is obscured by subsurface hyperbolic reflectors (3) similar in form to the PLF's.

The adjoining profile shown in Plate 53 reveals a similar seafloor structure (1) without any PLF's, but with some underlying disconformable reflectors (2) again of unknown origin.



INDEX TO SHELF EDGE FEATURES

M.J. O'CONNOR & ASSOCIATES LTD.	
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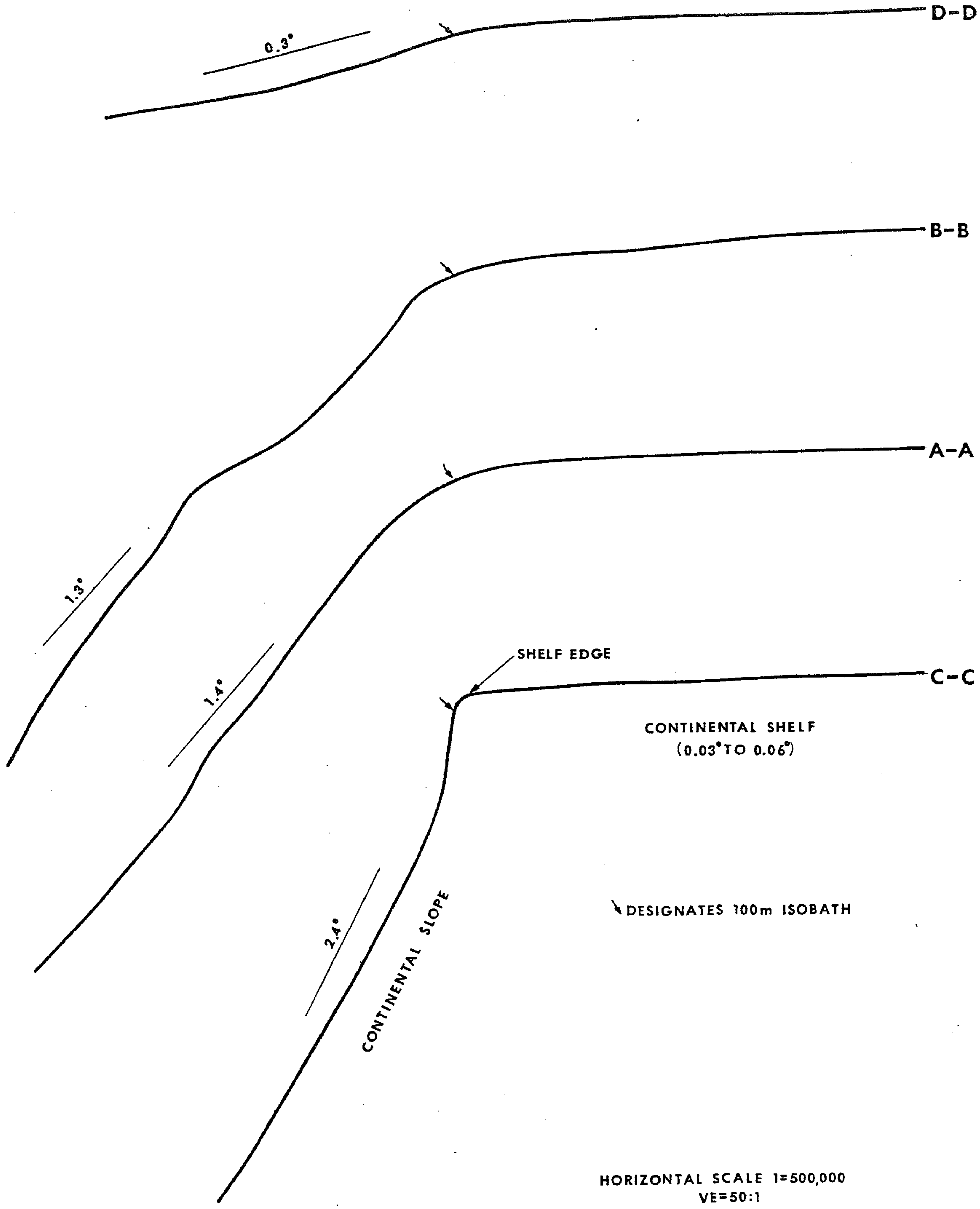
DRAWN BY: MJO.	DWG. NO.: 4-1



BATHYMETRIC PROFILES OF THE CONTINENTAL SHELF

M.J. O'CONNOR & ASSOCIATES LTD.

JOB NO.: 10-033

DATE: 80-03-27

DRAWN BY: WAO.

DWG. NO.: 4-2

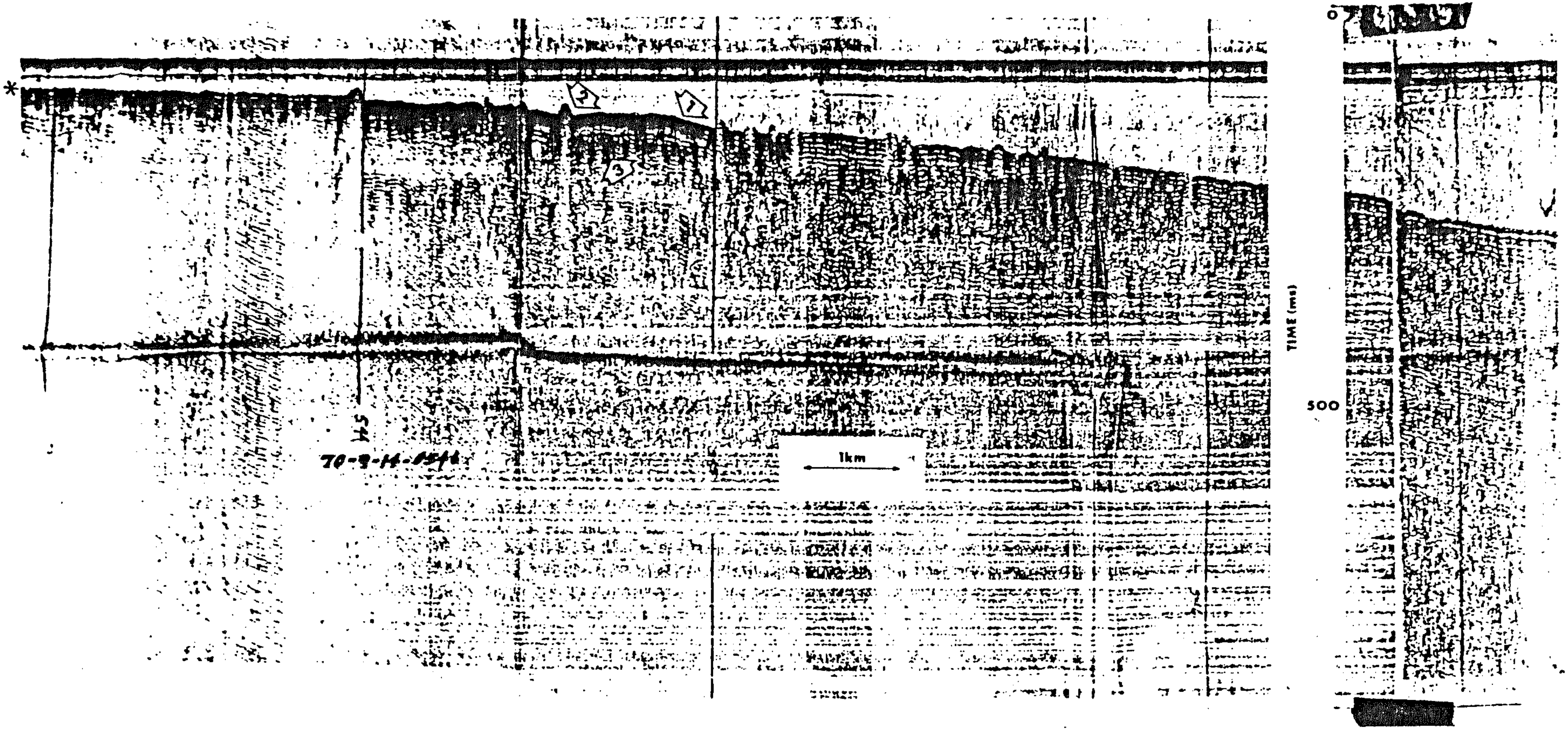


Plate 52

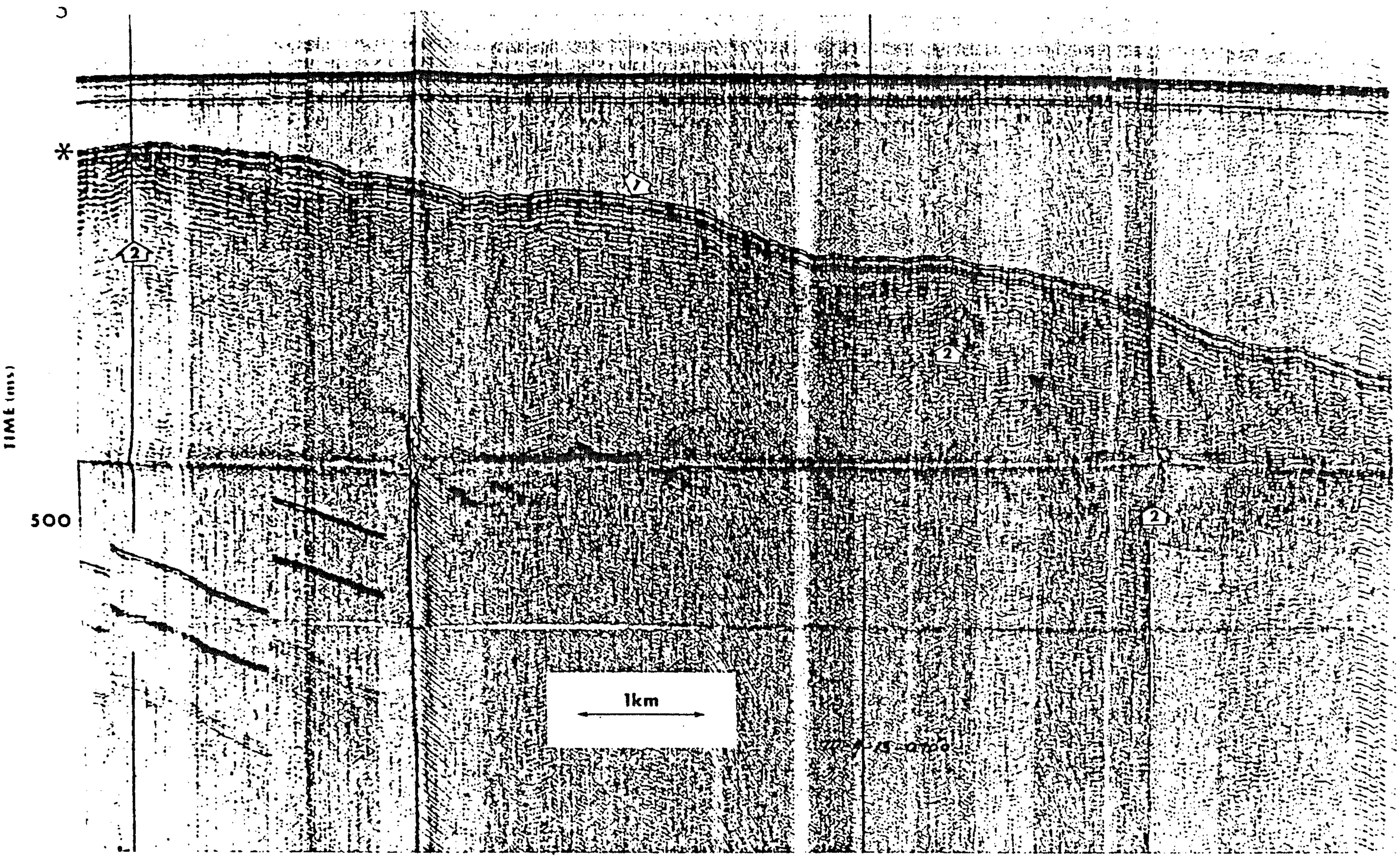


Plate 53.

Plates 54, 55 and 56 show a series of overlapping* sections on the shelf edge and continental rise in the vicinity of 134° longitude. Minor seafloor relief on Plate 54 suggests large scale downward movement of the slope seaward from (1). At (2) the subseabottom sediments are acoustically opaque, but up to 75 m of penetration was achieved at (3). Although the signal hampers any detailed stratigraphic interpretation, it appears that the surficial, thickly bedded sediments on the upper slope are disconformable with the underlying more thinly bedded, strata along a boundary marked (4).

On Plate 55 the signal penetration increases to almost 150 m in some places, but this rapidly decreases again near the 400 m isobath (1).

According to Plate 56, this is the same location where a marked increase in local relief coincides with the reappearance of acoustically opaque sediments (1) at the seafloor. This is probably the upper limit of the bulge noted in the bathymetric profile B-B plotted in Drawing No. 4-2, and may represent spoil[1] from an earlier landslide.

Plates 57, 58 and 59 form another continuous profile crossing the shelf edge at an oblique angle near 135°. As the bathymetric map suggests, the shelf edge in Plate 57 is marked by a distinct zone of hyperbolic reflectors (1). Beyond this zone Plate 58 demonstrates that the continental slope is quite uniform except for a change in subsurface acoustic stratigraphy at (1). Although the reflector (2) does not appear to be disconformable, Plate 59 reveals that it is not exactly parallel to the surficial sediments at all locations (1).

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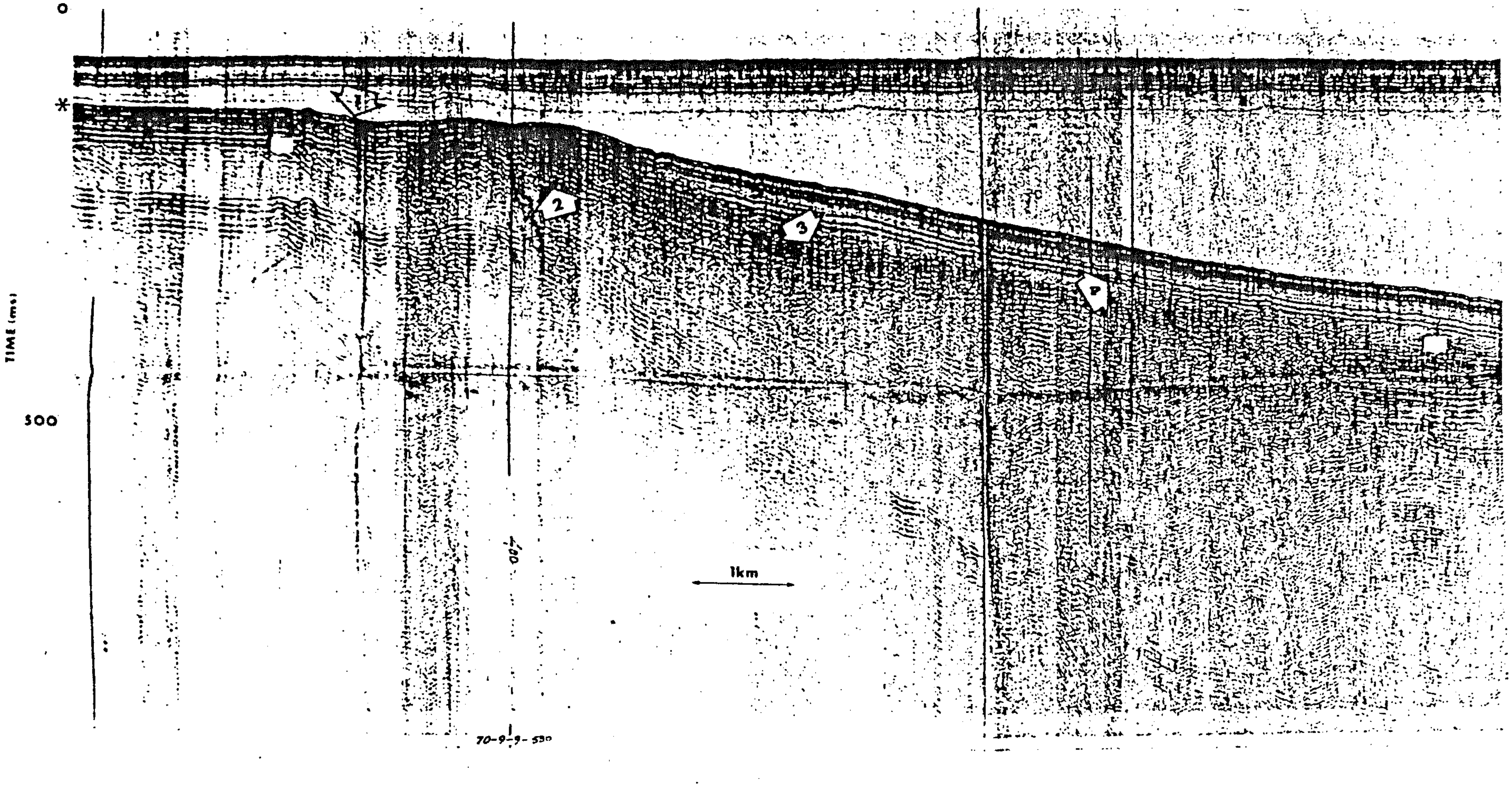
* Circles at the bottom of each section indicate match points along the profile.

[1] The word spoil is used here to indicate sediment debris involved in massive downslope movements.



①

Plate 54.

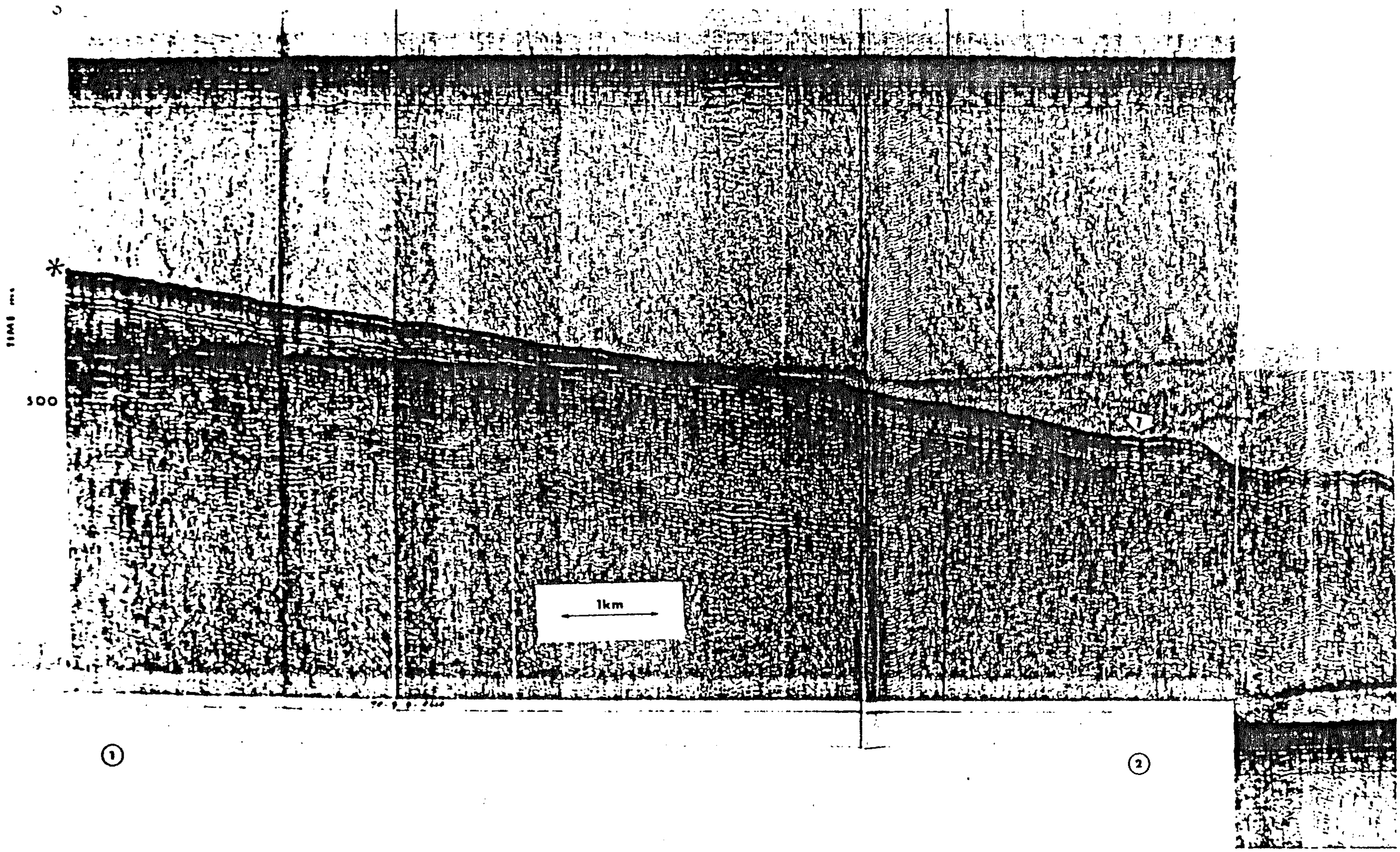


Plate 55.

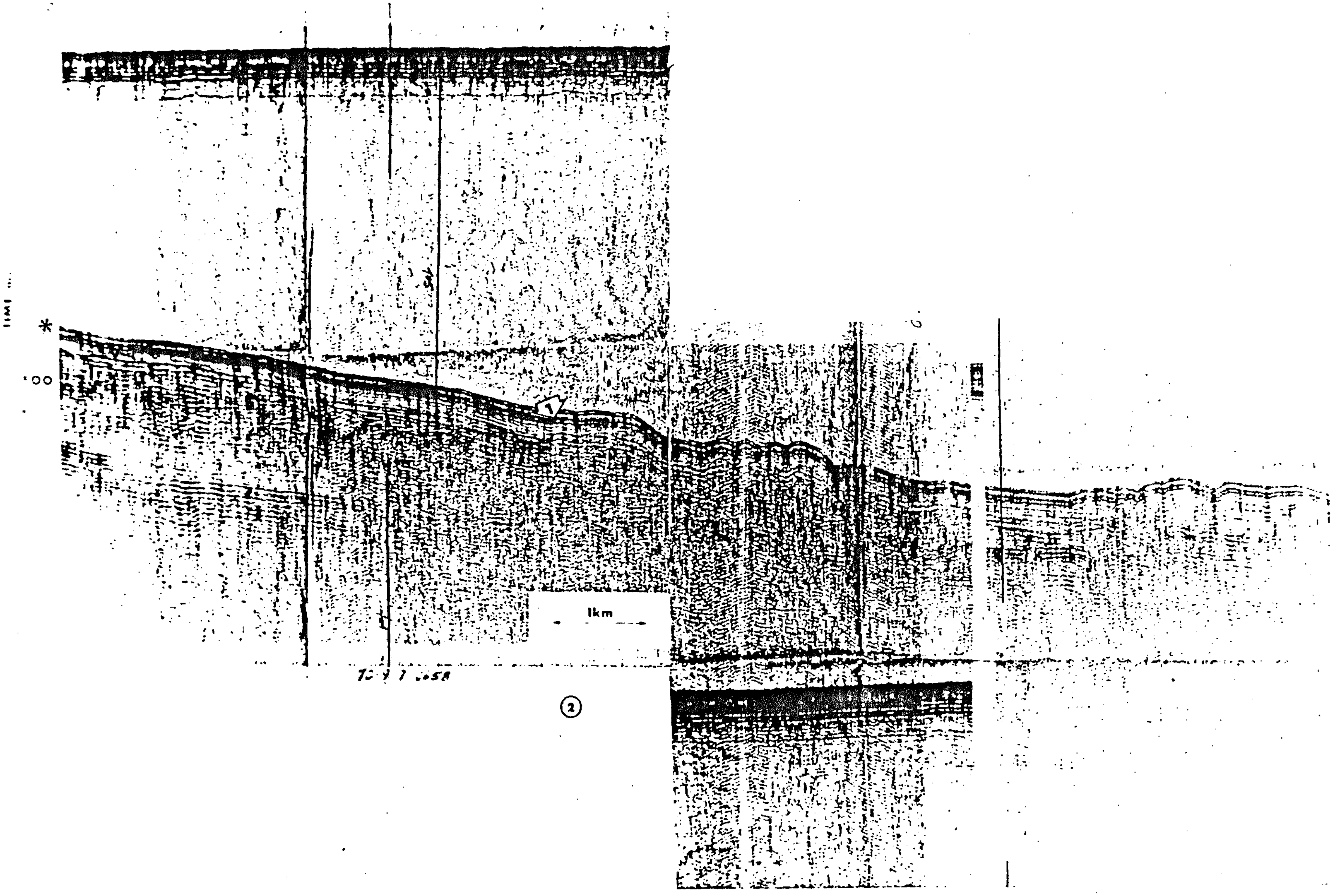


Plate 56.

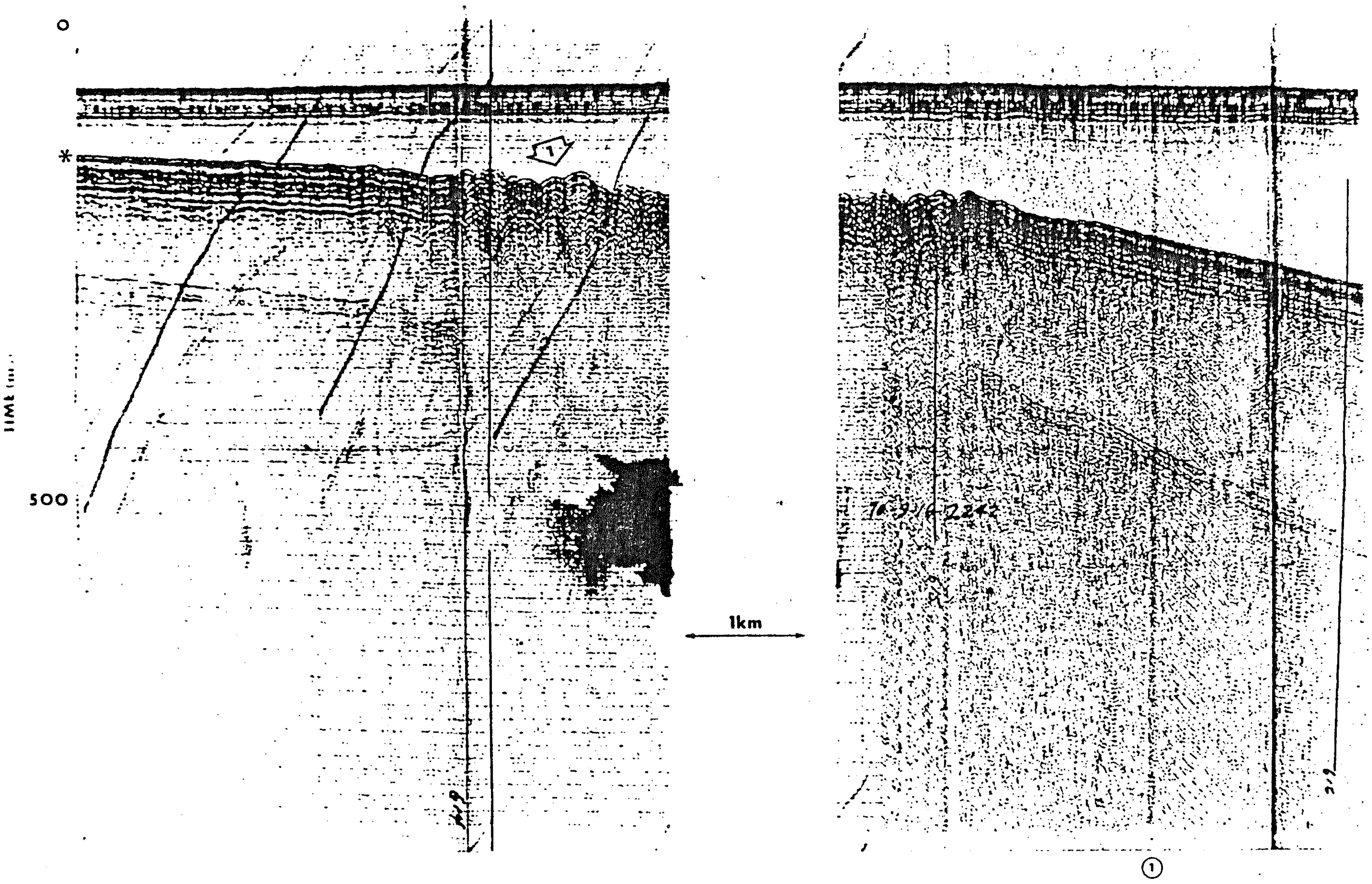


Plate 57.

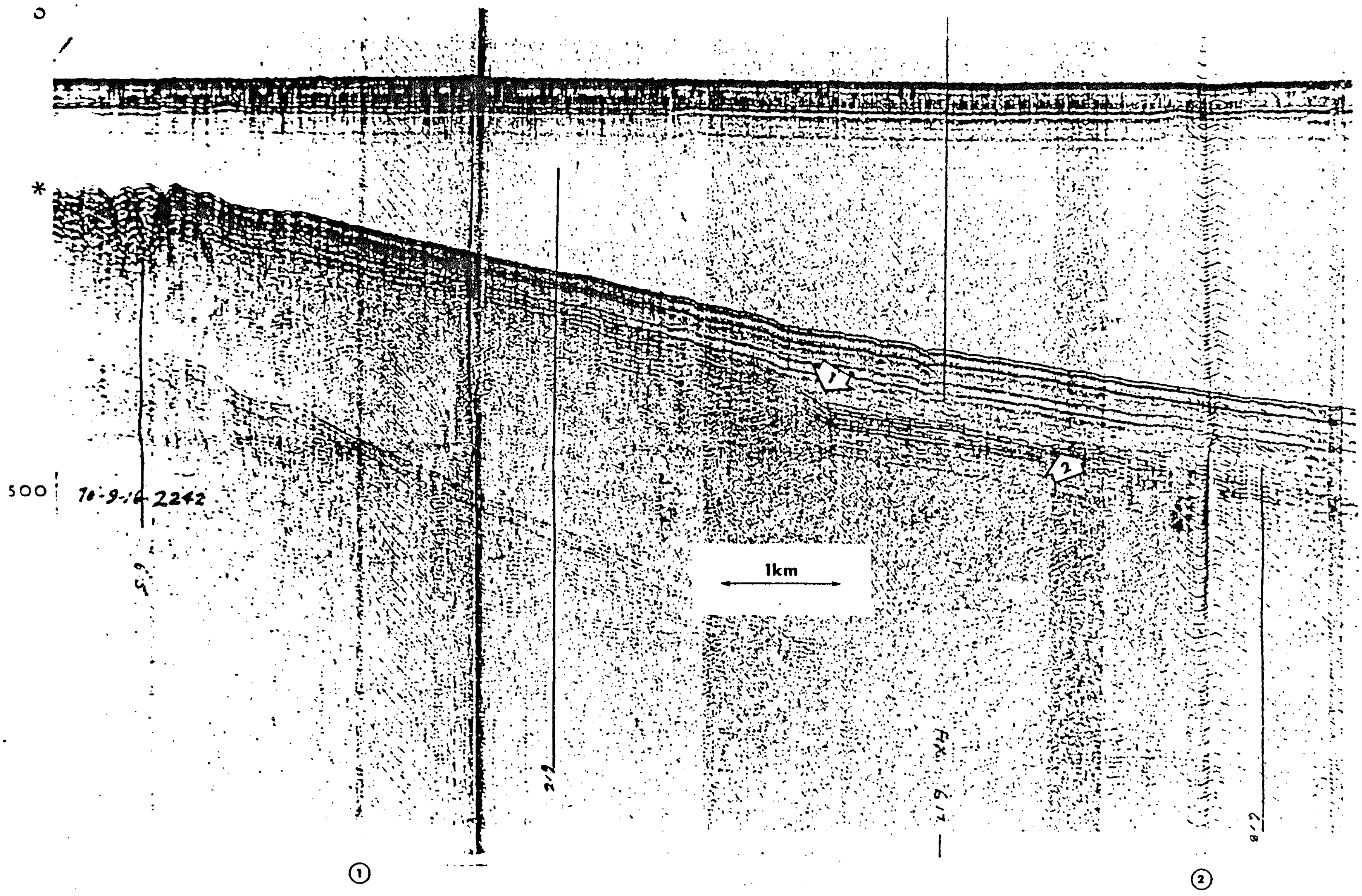


Plate 58.

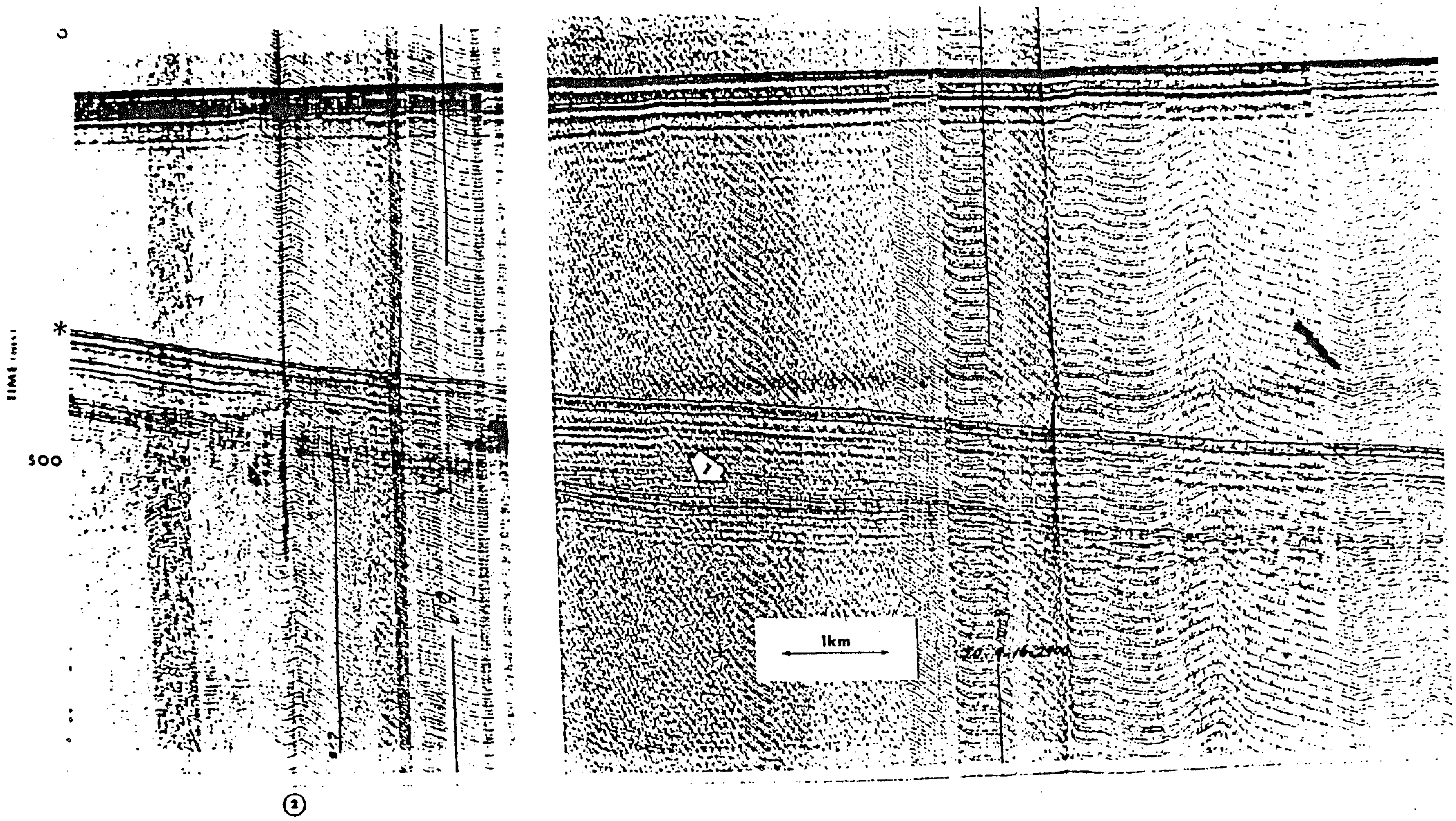


Plate 59.

An excellent north-south section was obtained west of 136° during the 1977 Nahidik cruise (Plates 60, 61 and 62). Highly disturbed sediments (1) underly the recent marine sequence (A) near the 100 m isobath on Plate 60, but subtle edge-related fault structures may also be visible on some shallower sections (see (4), (5) and (6) on Plate 7). Acoustically opaque PLF's (2) are associated with folding of the recent beds and concomitant seafloor relief(3). Opaque hyperbolic reflectors on Plate 61 also intrude a thick wedge of stratified sediments near (1), but attendant deformation is only moderate.

Plate 62 shows a 65 m high backscarp (1) formed by downfaulting of sediments on the steep continental slope. The seismic event (H) is a hyperbolic reflector generated by the discontinuity at the top of the backscarp, and does not represent the form of the actual backscarp face. Little sedimentation is apparent on top of the spoil material (2), hence the faulting must be relatively recent. Note the distinctively different acoustic signatures which characterize the spoil (2) and backscarp (3) sediments. It is not known whether this represents a fundamental difference in the nature of the materials, say due to remoulding of the spoil material, or whether this is merely a function of poor signal penetration caused by the extreme local relief on the downfaulted surface.

Faulting at the shelf edge is also apparent on a 1978 profile near 137° (Plates 63, 64 and 65). Contiguous surficial strata (1) above the shelf break (Plate 63) exhibit no evidence of any present instability, but relic relief on the unconformity (2) suggests that some faulting, sliding, or slumping of the underlying foreset beds (3) may have occurred in the past. Note that the dark line (2) which represents the unconformity has been drafted onto the section, and is not a high amplitude acoustic event.

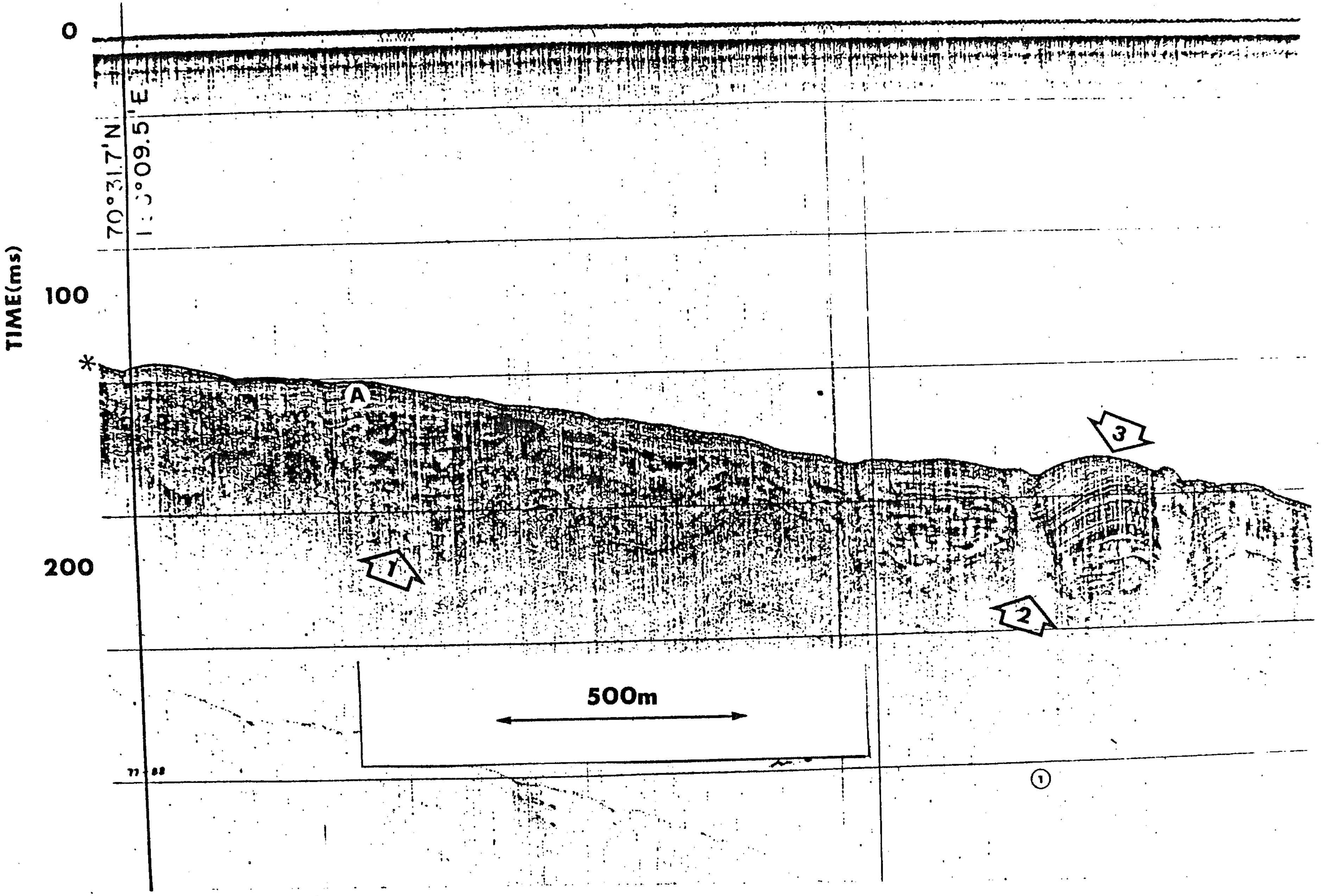


Plate 6Q

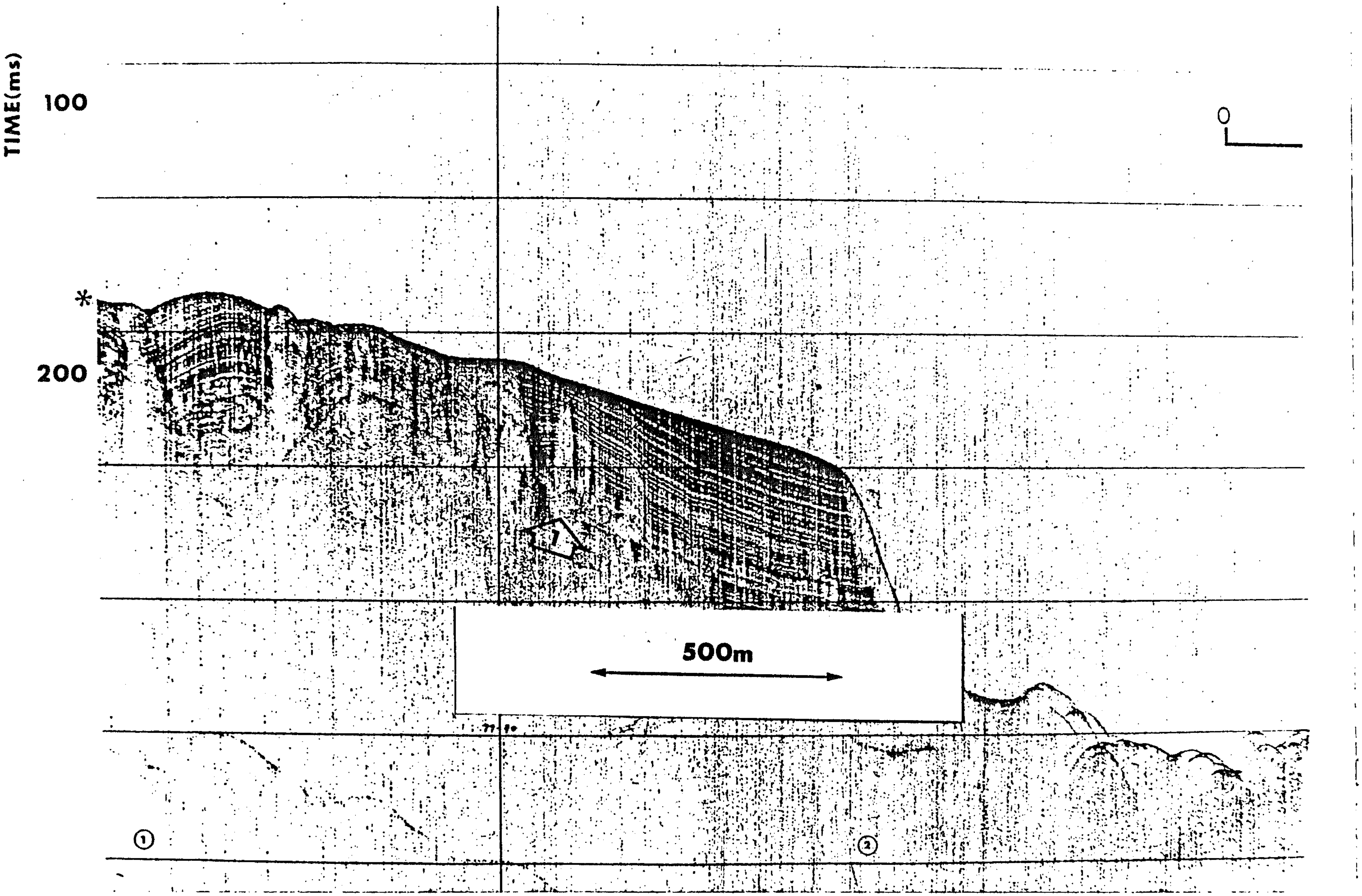


Plate 61

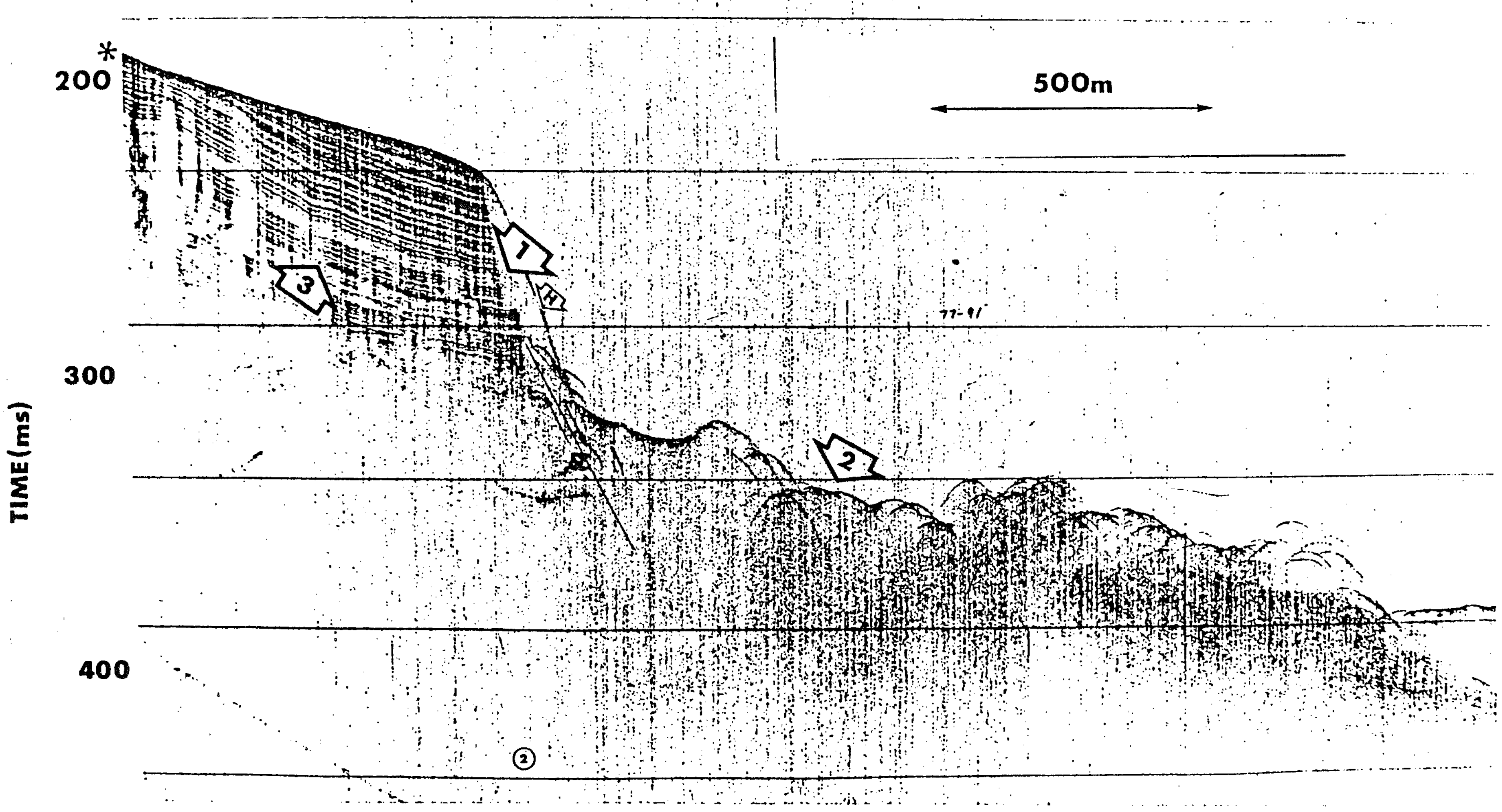


Plate 62.

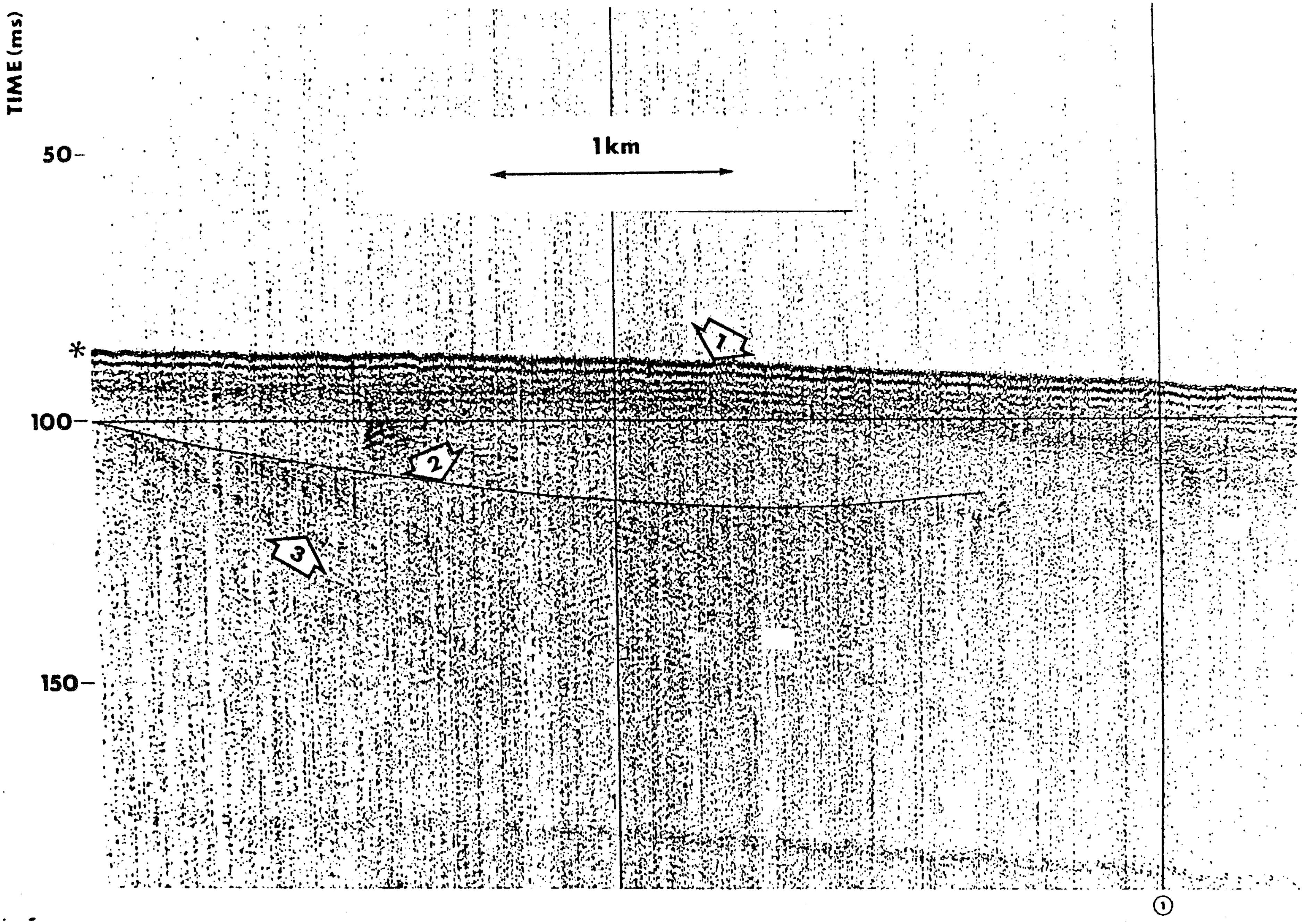


Plate 63.

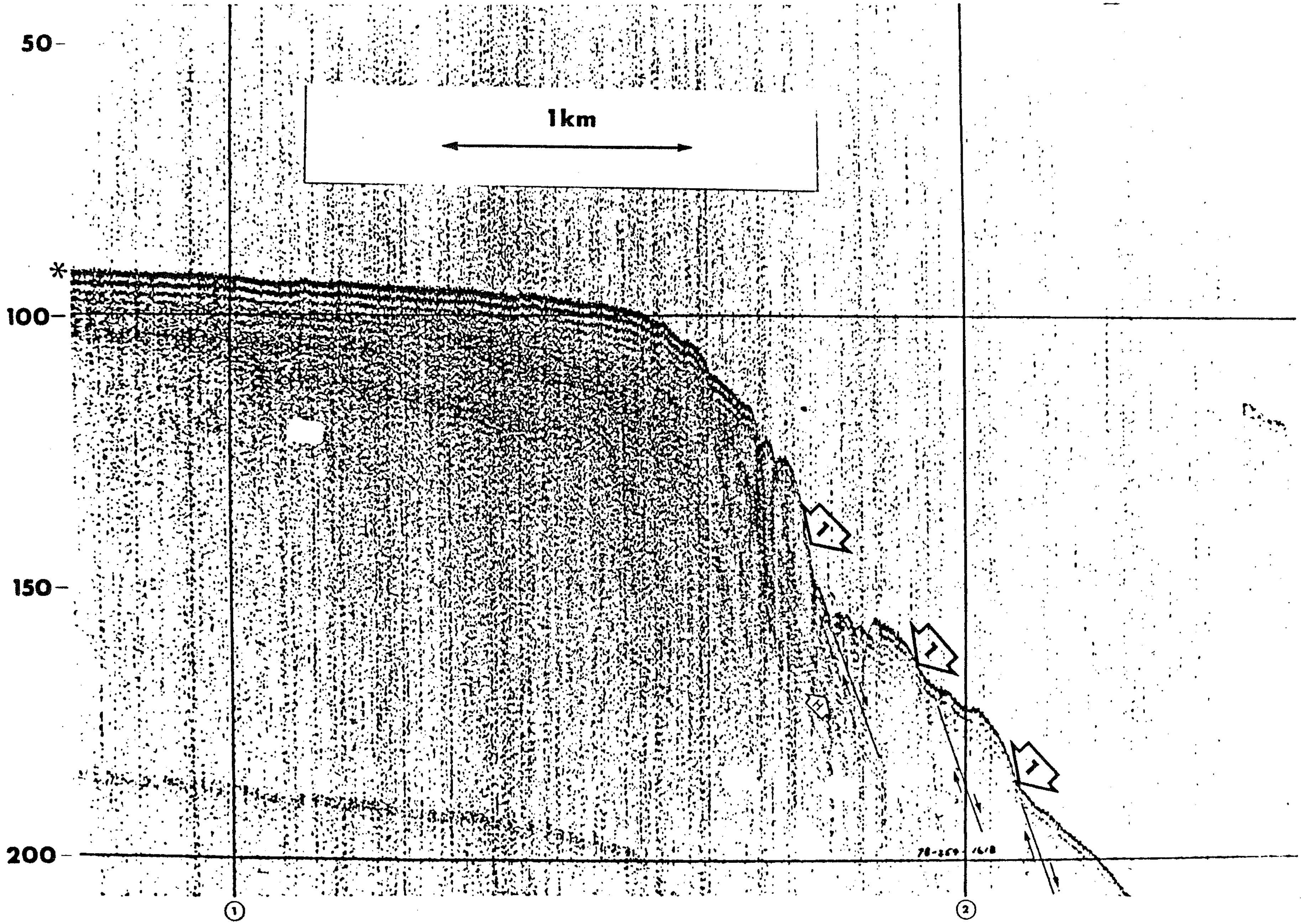


Plate 64

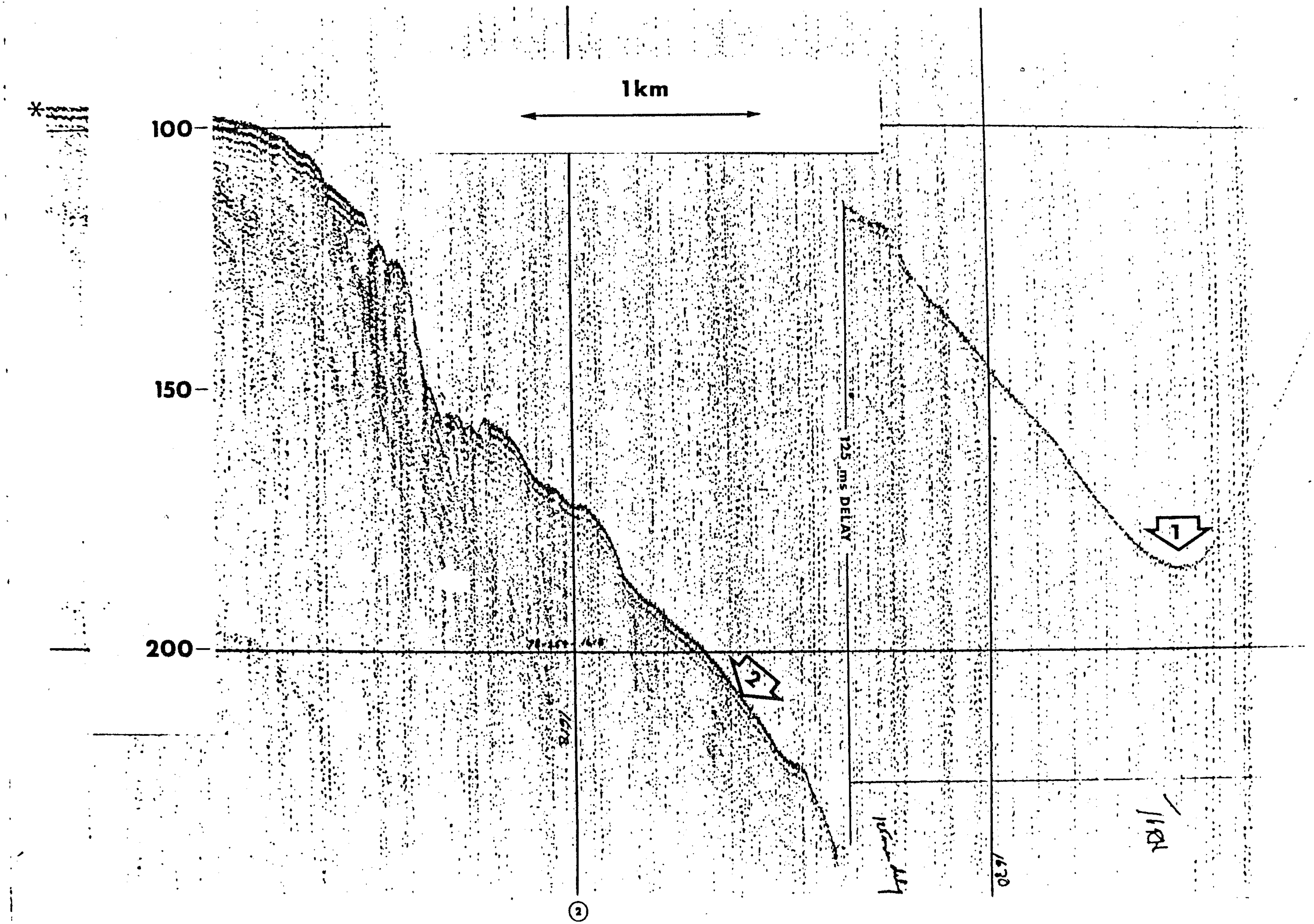


Plate 65

Plate 64 shows a series of backscarps (1) exposed by en echelon faulting of the sediments at the edge of the shelf. Note that the weak reflectors (H) are again hyperbolic and do not represent actual bedding planes. Plate 65 indicates that this profile was terminated by a turn (1) before the base of spoil (2) was encountered.

Plate 66 shows a slightly longer profile west of 137° where only minor local seafloor relief is apparent near the shelf edge (1 and 2), but relic massive faulting is evident in the subbottom stratigraphy. Since the change in acoustic character from one stratum to the next is very subtle, the interpreted stratigraphic boundaries have been shown by a dashed line drafted onto the photograph. The oldest relic spoil (3) near the top of the slope appears to have been infilled by subsequent sedimentation (4) and then buried by a second generation of shelf edge debris (5). Gentle folding of the surficial sediments (6) suggests that they, too, have been involved in recent downslope movements. It is unclear from this photograph whether the seafloor relief at (7) represents material deposited at the toe of a shallow failure plane under the slope above, or whether it is spoil material related to a much larger, deeper slide involving sediments not seen on this section.

4.2 The Mackenzie Canyon Edge

The continental shelf north of Mackenzie Bay is incised by a large embayment known as the Mackenzie Canyon (Drawing No. 4-1). Rapid post-glacial sedimentation has subsequently infilled a major portion of the canyon, creating the gentle profile seen in section D-D, Drawing No. 4-2. Detailed hydrographic surveying along the side of the canyon shows a distinctly linear bathymetric discontinuity near the edge of the shelf in this region. A shallow seismic profile collected at the same location reveals some

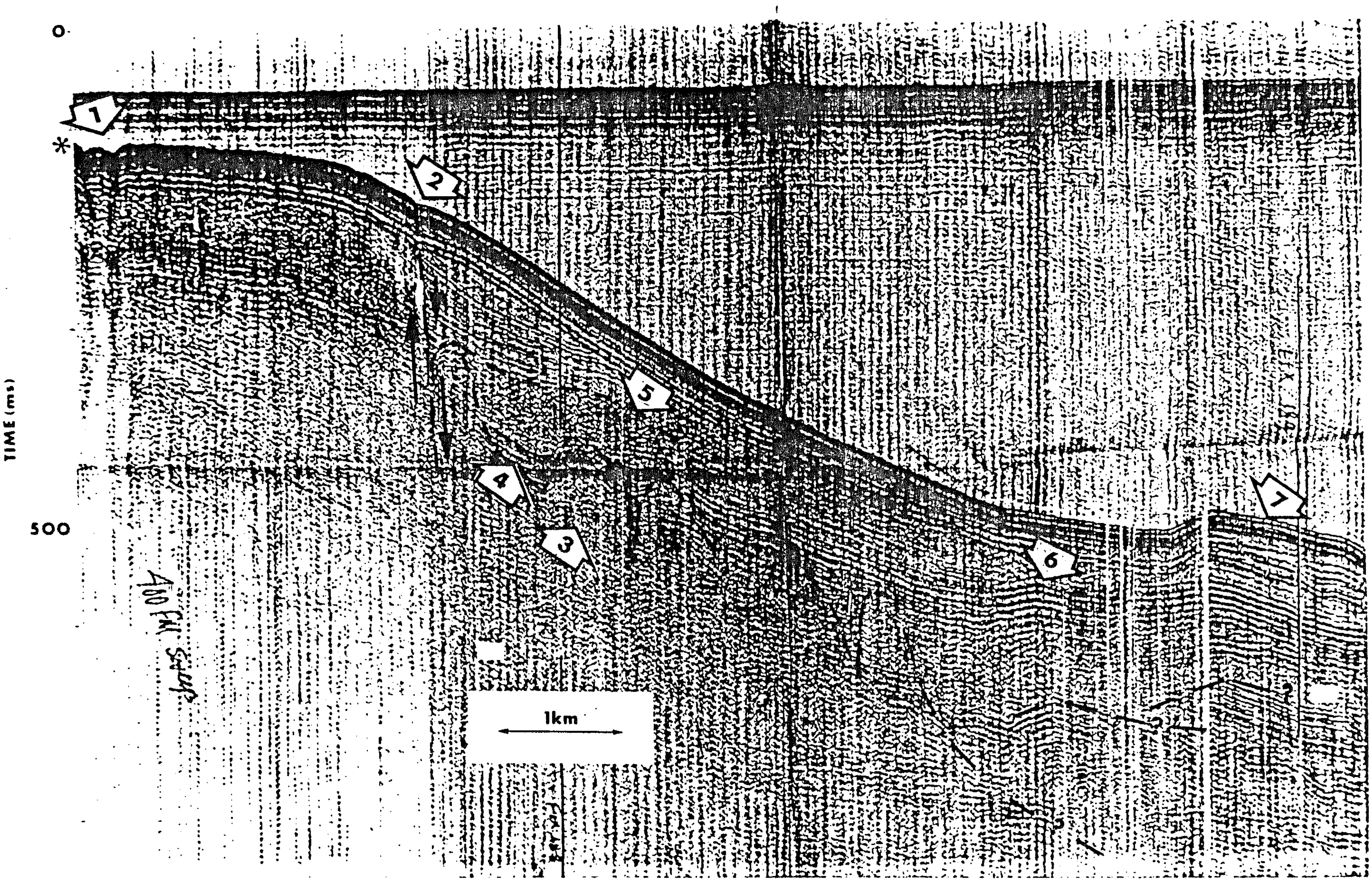


Plate 66.

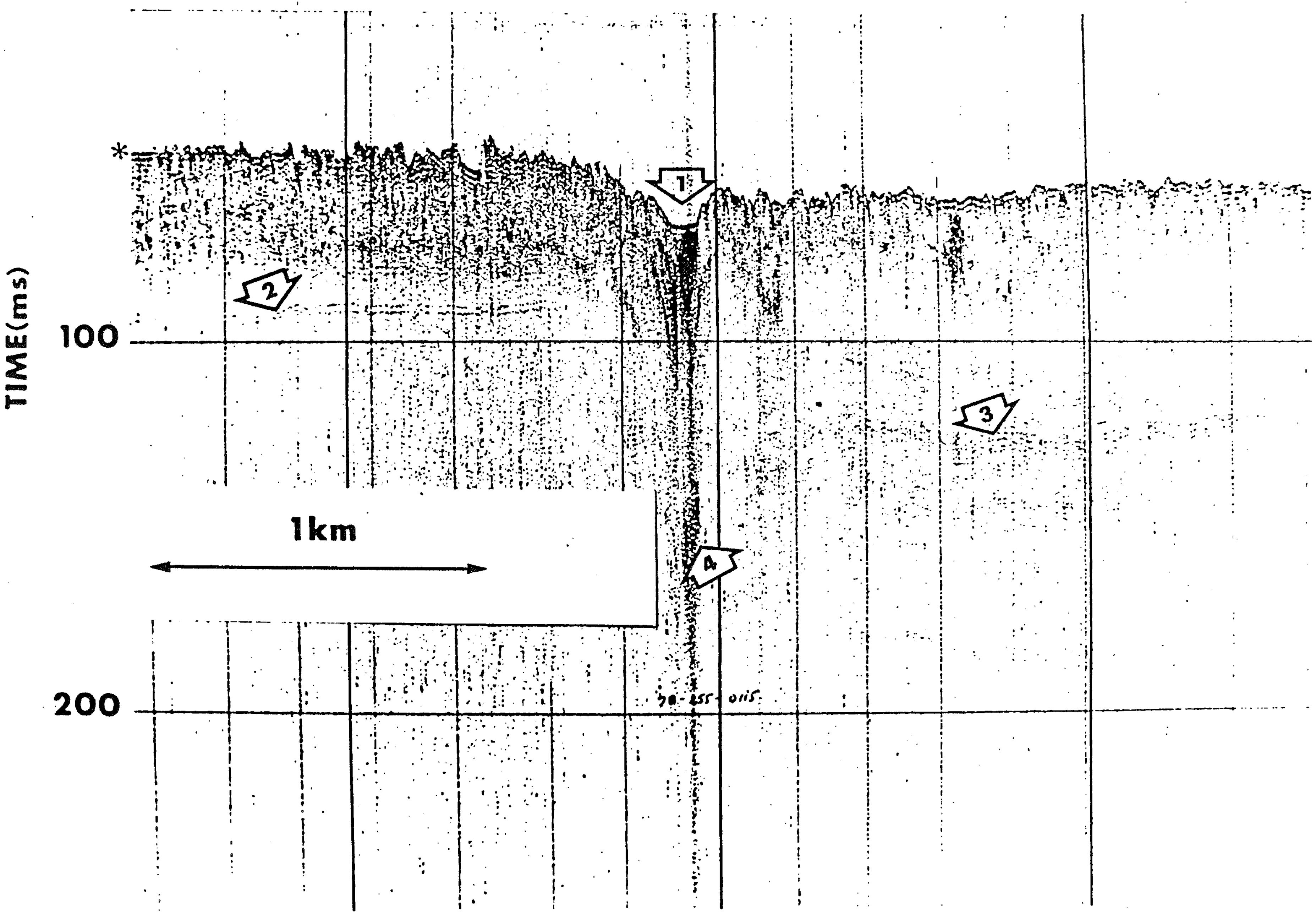


Plate 67.

important aspects of this discontinuity in more detail.

On Plate 67 the feature is characterized by a small graben (1) having approximately 15 m of throw on the east (left) side and about 6 m of throw on the west side. This results in the present seafloor being down-faulted approximately 9 m into the canyon. A thick SPZ precludes the identification of any detailed surficial stratigraphy, but some deeper horizontal reflectors are evident at (2) and (3). It is not apparent, however, whether both reflectors represent the same geologic horizon; if they do, then a minimum of 30 m net throw along the fault zone is indicated. It is further speculated that the dark acoustic character (4) observed beneath the graben is probably associated with gas migrating upwards along the fault zone. Small PLF's observed within the graben on other seismic profiles not shown here would support this hypothesis.

While the seafloor expression of this feature in shallower waters appears to have been effaced by the massive influx of recent Mackenzie River sediments, a graben-type structure (1) having identical vertical displacements was observed at the unconformity on Plate 68.

Shearer (1971) mapped faulting of the surficial sediments along the west side of Mackenzie Bay and subsequently recognized similar features on the eastern side (Shearer, 1972b). He attributed the origin of the original canyon to glacial scouring by a large lobe of ice coming down the Mackenzie River and suggested that the boundary of the relic canyon passed south of Garry Island and under the present delta, as shown by the dotted lines on Drawing No. 4-1.

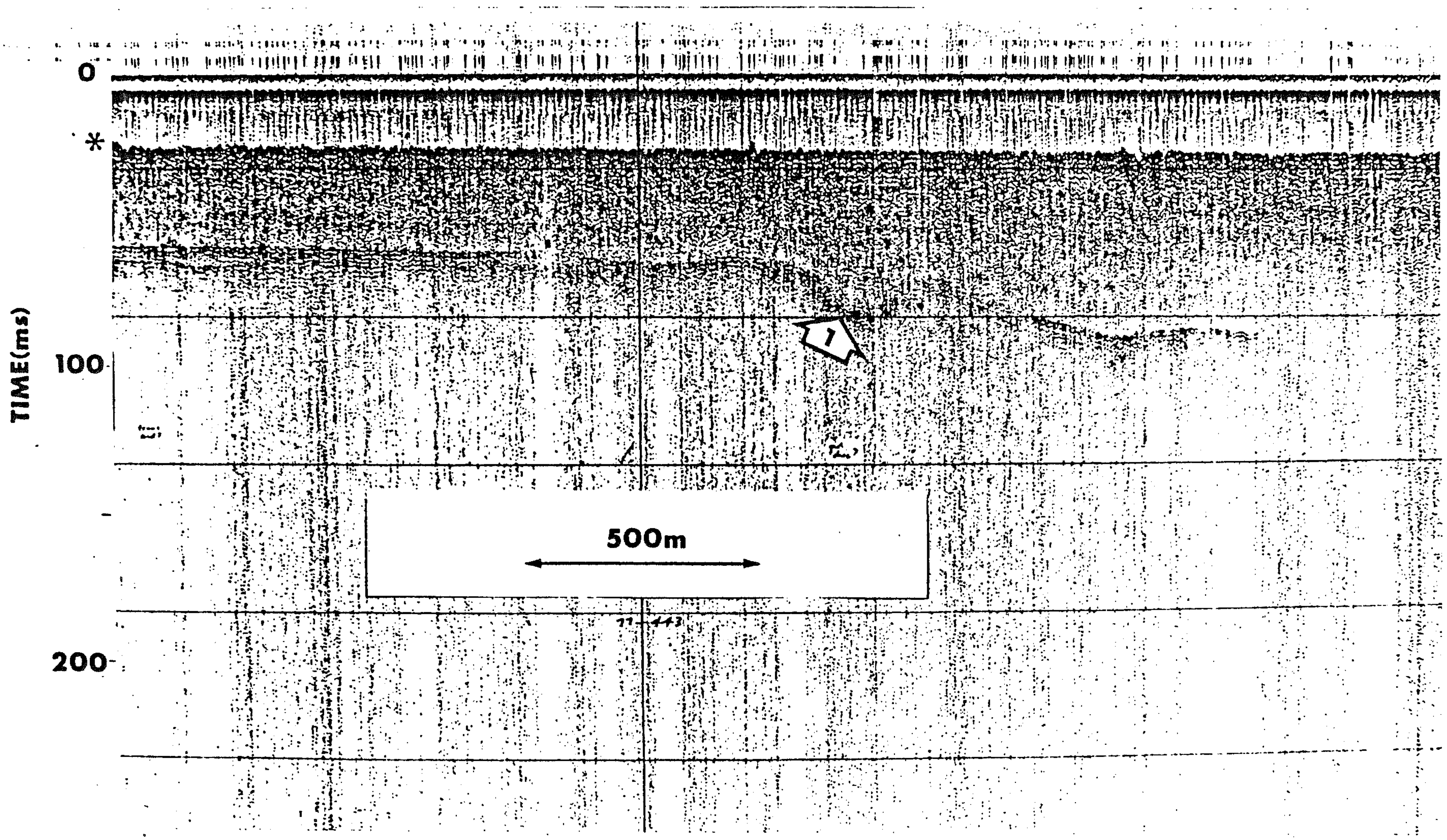


Plate 68.

While Shearer's evidence has not been reviewed during this study, the present author concurs with his premise that the observed features delineate a major geologic discontinuity related to the origin of the canyon itself. It is suggested, however, that the canyon represents a large graben bounded by deep-seated faulting, perhaps induced by seafloor spreading. Glacial processes, if they have been involved at all, are believed to have been ancillary. If the author's hypothesis is correct, then the present expression of the fault line on the seafloor over the outer reaches of the canyon may suggest that some of the faulting has been recently active.

4.3 Discussion

It is apparent from the bathymetric cross sections and example seismic profiles that a progressive change in the morphology of the shelf edge occurs across the study area. Although relic slump and/or fault related features have been recognized on both bathymetric and acoustic data east of 132°, the transition from the continental shelf to slope is a gradual one and the shelf edge is presently stable.

West of 132°, however, the upper continental slope becomes steeper and a progressive decrease in the stability of the outer shelf edge is apparent. The acoustic evidence suggests, in fact, that active, or at least very recent, faulting currently controls the morphology of the shelf edge between 136° and 137°. Furthermore, the appearance of fault-related structures on the seafloor at some distance from the shelf edge suggests that large scale movement of the sediments may be in progress in this region.

5.0 UNRESOLVED ASPECTS OF THE MODEL

The geologic model presented in this study is an expanded and somewhat altered version of the basic working model developed by the Geological Survey of Canada over the past few years.

Formalization of the model during the current project was undertaken as a mechanism to promote future discussion of this complex environment and to serve as a framework for future scientific and engineering endeavours.

The present model relies almost entirely on acoustic evidence for support. Thus by its very nature it leaves many aspects of the surficial geology unresolved. Future geological and geophysical programs must address these unresolved aspects directly:

1. Since the model is heavily biased toward the central areas of the shelf where much of the recent subbottom profiling has been carried out, what modifications of the model are necessary to account for regional variations in bathymetry, distance from shore and position on the continental shelf?

2. Ice-bonded sediments and/or gas hydrates have been mapped on both refraction and reflection records. What is the depth and aerial distribution of these features and how do the geologic factors affect their occurrence? Is there any acoustic evidence available to determine whether permafrost is aggrading or degrading?

3. How do the special features (PLF's, massive ice, glacial debris, thermokarst) identified on the shelf fit into the proposed geologic model and what other special features are not yet identified?

4. The nature of the geologic discontinuity along the east edge of the Mackenzie Canyon is presently controversial. Are there other surficial features which may also be related to deeper geological structures?

5. What is the significance of the observed acoustic stratigraphy in terms of the Quaternary history of the shelf and canyon? For instance, are all the sediments exposed at the unconformity the same age and/or representative of a uniform depositional environment? How much erosion, if any, is evident at this surface and how does this vary across the shelf? Do the till-like units represent the maximum advance of Wisconsin glaciation or were they deposited much earlier?

6. What significance do the geologic features already identified (shallow gas, massive ice, faulting, relic thermokarst) have for future resource development operations in the Beaufort Sea? How can these features be predicted, mapped and/or controlled?

So far the model has been tested only at specific locations where suitable quality acoustic information already exists. Because little in the way of groundtruth information was available for review during this study, the correlation between acoustic stratigraphy and actual geological, geothermal, or geotechnical parameters (soil type, density, temperature, ice content, etc.) remains a major question. In addition, the question must be asked whether the model, itself, will stand up when synthesized with thermal observations, palynological data, glacial geology and geotechnical information and some of the major structural features underlying the shelf. Until some of these questions are resolved, the interpretation of the geologic history presented here must be deemed speculative.

6.0 CONCLUSIONS

A generalized model of the surficial geology on the continental shelf of the southern Beaufort Sea has been developed from a review of the recent literature. The basic stratigraphy of the model is quite simple: Unit A, a recent marine sequence, overlies Units B, a transgressive sequence, which in turn lies unconformably on Unit C, an older sequence believed to have been subaerially exposed prior to the most recent sea level rise.

In order to evaluate the model, several thousand kilometres of shallow seismic profiles were reviewed. Acoustic identification of specific units of the model is complicated by the presence of ice scouring, permafrost and shallow gas. In spite of these factors, the seismic evidence appears to support the basic model at most locations, and no examples of acoustic evidence contradicting the model were encountered.

A review of seismic information pertaining to the morphology of the shelf edge was also undertaken. It demonstrates that the shelf edge is presently stable east of 132° longitude, but that the stability decreases in a westerly direction to 137° longitude, where faulting and slumping of the shelf edge has occurred in the recent past. The western (Mackenzie Canyon) edge is also unstable, but the responsible geologic mechanisms along this boundary are somewhat different.

Specific features identified on the continental shelf (massive ice, shallow gas, relic thermokarst depressions) suggest that the submarine environment may be every bit as complex as the adjacent permafrost-affected land. If such is the case, then a thorough knowledge of the active and potentially active geologic processes is warranted before extensive resource development can be undertaken safely.

7.0 RECOMMENDATIONS FOR FUTURE STUDIES

It is evident that significant quantities of data concerning the continental shelf already exist within the Geological Survey of Canada, the Earth Physics Branch, EMR, and the petroleum industry. Much of this information, however, has not been synthesized into any single format for evaluation and review.

As a starting point for future discussion, we recommend that a rigorous effort be made to incorporate the existing data into the geologic model proposed here. The first step in this synthesis must be the integration of all information (geotechnical, geophysical, geological, geothermal) onto a standard series of maps such as 1:500,000 scale traverse mercator projections. This would greatly facilitate future cross-correlation of data from different sources and, in so doing, would undoubtedly result in a revised and expanded model which more clearly describes the geological processes responsible for continental shelf development.

Future geological and geophysical studies should focus on those aspects of the current geologic model which are presently unresolved. Most important are those aspects which directly relate to the geological hazards of resource development.

Finally, we recommend that additional scientific information be obtained in those specific areas where offshore development is presently occurring, so that the Geological Survey will be well equipped to supply back-up information to the responsible regulatory agencies on a timely basis.

Respectfully submitted,
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