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The geology of ice scour.

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THE GEOLOGY OF ICE SCOUR

by

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SUMMARY

Ice scour is the phenomenon that occurs when the keel of a floating mass of ice (iceberg, sea ice or freshwater ice) touches, penetrates and continues to move forward through unlithified seabed or lakebed sediments. The typically curvilinear excavation made by the scouring keel is called a scour mark. Scouring ice keels present logistical problems to the safe installation and operation of, for example, oil and gas production pipelines and power and telecommunication cables in several cold ocean regions.

The typical surface morphologies of modern iceberg scour marks on the Labrador continental shelf are described, and mechanisms that operate at or near the sediment surface during the period of ice/seabed interaction are suggested. Scouring action also disturbs sediments beneath the seabed or lakebed. Sub-scour deformation is accommodated by compression and pore space-reduction beneath the scour mark, by corresponding volume increase adjacent to the trough and by folding and faulting. Deformation structures are described from beneath ancient large scale (30-40 m-wide) iceberg scour marks exposed in clays of the former glacial Lake Agassiz in southern Manitoba, and from small scale (< 5 m wide) contemporary scour marks that form on tidal flat sediments in Cobequid Bay, Nova Scotia, and the St. Lawrence estuary, Quebec. Structural data from the Lake Agassiz features are presented and discussed with respect to scour mark-forming mechanisms.

Criteria for the recognition of ice scour marks and of ice keel turbates are developed. The criteria are discussed with respect to observations, frequently of striated bedding plane surfaces, contained in the published works of others. The analysis reveals that possible ice scour marks and ice keel turbates may occur in glacimarine and glacilacustrine sediments of Precambrian, Ordovician, Devonian, Carboniferous and Permian age at a number of localities worldwide.

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career, and that burns ever more strongly within me today. I can never thank you enough Gwynn.

I give thanks to all of the above people, but to Carla, and to Victoria, Nicholas and Tristan I give my love.

To my grandfather

Tressilian Charles Nicholas, M.A., O.B.E., M.C., F.G.S.

August 17th, 1888 - November 13th, 1989

Geologist

ABSTRACT

In contemporary Arctic and Antarctic polar and sub-polar seas, icebergs drifting in oceanic and wind-driven currents may impinge upon the seafloor in water depths up to and occasionally exceeding 500 m. Where seafloor sediments are unconsolidated the ice keels penetrate and plough forward creating curvilinear iceberg scour marks that are commonly tens of metres wide, 1-2 m deep and often several hundred metres (or even several kilometres) long.

Icebergs may come into contact with the seabed in one of two ways. They may drift onto shoaling bank top areas, scouring or grounding occurring as draft exceeds water depth. Alternatively they may increase their draft by unstable roll, caused by combinations of ablation, minor calving events, or as the result of splitting of tabular icebergs that may cause large increases in draft. During the period of iceberg-seabed interaction, which may last from a few minutes to several days or even years, both the seabed and iceberg keel undergo modifications.

When observed from submersible soon after their formation, scour marks that are developed in fine-grained sediments exhibit morphological characteristics not seen in old, degraded scour marks. The flat-bottomed trough of a new scour mark, between two berm ridges, is characterized by the presence of ridge-and-groove microtopography (up to 30 cm relief) developed parallel to the scour mark axis. These features are formed at the trailing edge of the keel by clastic material embedded in the ice and by open fissures in the ice. In places along the inner berm margins ridges and grooves may be developed at an angle to

the scour mark axis reflecting lateral displacement of material towards the berm as the iceberg moves forwards. Pits up to 1 m deep and 2 m wide occasionally truncate the ridges and grooves. Pits are formed by the dissolution of small (a few m^3) masses of debris-laden ice that were mechanically broken off from the base of the keel and pressed into the seabed by the scouring iceberg. Depressed areas within the scour mark trough may preserve seafloor that has not been affected by ice/seabed interaction. In these regions deposition of bulldozed sediment from the surcharge at the leading edge of the keel may partially fill the narrow voids developed between the seabed and the keel.

Scour mark berms consist of *in situ* fractured but intact blocks of material on the inner flanks, and disarticulated blocks 1-2 m high along the berm crest. The outer berm slopes generally consist of pieces of larger blocks spalled from the berm crest resting in relatively finely comminuted, reworked material. The reworked material originates in the leading edge surcharge before being displaced to either side of the keel. Scour mark berms have irregular topography ranging in height from a few centimetres to as much as 6 m above the seabed.

Excavations through Quaternary-age scour marks developed in clays of glacial Lake Agassiz reveal intense reworking of the lakebed to depths of at least 5 m beneath the deepest part of the scour mark trough. Horizontal thrust faults and low angle normal faults are found beneath the scour marks. Scour-induced displacements of at least 3.5 m have occurred along the polished and slickensided surfaces of low angle faults. Fine laminae are generally obliterated by the scouring event, and chaotically-arranged, dislocated fold hinges are seen in the reworked groundmass.

Structures associated with contemporary small-scale scour marks from tidal flats of the St. Lawrence estuary and Cobequid Bay are well developed and easily seen because of well-developed sedimentary layering. Some of the structures are compared with similar structures from a large-scale scour mark, and similar deformation mechanisms are implied.

Relict scour marks occur over large areas of high-latitude and polar seafloors, therefore it can be reasonably extrapolated that iceberg scouring in Quaternary glaciomarine sediments has been an important process over a considerable extent of the global oceans. Ice scour is likely to have been important in pre-Quaternary glaciations, and thus its effects should be preserved in lithified sediments. Although such lithified features as bedding plane striations have in rare instances been tentatively assigned a drift ice origin, scour marks have been recognized recently from only two localities in the world, and ice keel turbate facies have not been described at all.

Scour marks and ice keel turbates remain invisible to enquiry because the characteristic types and associations of structures unique to scouring have not been recognized in the context of formation by floating ice. This thesis presents descriptive criteria that should enable workers to recognize the effects of ice scour.

TABLE OF CONTENTS

CHAPTER 3

THE SURFACE MORPHOLOGY OF SCOUR MARKS,

AND THE PROCESSES OF SCOURING 28

CHAPTER 6

CHAPTER 7

LIST OF FIGURES

Chapter 1

Chapter 3

Chapter 6

LIST OF TABLES

Chapter 3

Chapter 4

Chapter 5

Chapter 6

CHAPTER 1

INTRODUCTION AND SUMMARY

The keels of drifting icebergs or sea or lake ice pressure ridges that plough through seafloor or lacustrine sediments generate characteristic curvilinear furrows referred to as iceberg scour marks (Lewis and Woodworth-Lynas, 1990). There exists a considerable body of work on the phenomenon of scouring by floating ice masses. Although the scouring phenomenon was known beforehand (e.g. United States Coast Pilot, 1947; Carsola, 1952; Rex, 1955), the vast majority of research has been carried out only in the last fifteen years. It was only in the early 1970's that scour marks, formed by the keels of sea ice pressure ridges and to a far lesser extent, ice islands (tabular icebergs), were initially identified from sidescan sonographs in the Canadian Beaufort Sea by Skinner (1971), Kovacs (1972) and Pelletier and Shearer (1972). Shortly after, iceberg scour marks were first reported on the seafloor of the continental shelves of Norway (Belderson and Wilson, 1973) and eastern Canada (Harris, 1974; Harris and Jollymore, 1974). These initial discoveries stimulated a decade of intense work in Canada and Norway directed at mapping the distribution and size of the scour marks.

Previous work

Lyell (1845) was the first to describe striations formed by ice scour. He observed straight parallel and diverging furrows 1.25 cm wide incised into soft sandstones at Cape Blomidon, Nova Scotia. He theorized that the grooves were formed by the mechanical action of stones embedded in the bottom-touching keels of contemporary sea-ice. Harding (reported by Lyell, *op. cit.*) also described shore-parallel ice scour marks developed on the tidal mudflats near Wolfville on the Bay of Fundy.

With remarkable foresight Darwin (1855) theorized that scouring icebergs could traverse isobaths:

"... in an iceberg 1000 feet (300 m) thick, as the whole floats, there will of course be no pressure on a surface exactly level with its bottom, and if driven over a prominence standing up at the bottom of the sea some 50 or 100 feet (15 or 30 m) above the base line of the berg, only the weight of as much ice as is forced up above the natural level of the floating mass, will press on the prominence. It may therefore, I think, be concluded that an iceberg could be driven over great inequalities of surface easier than could a glacier."

Geikie (1865) theorized on the action of icebergs in contact with the seabed, relating

his discussion to a diagram (Figure 1), to this author's knowledge the first pictorial representation of a scouring iceberg:

> *"When such current-driven masses grate along the sea-bottom they must tear up the ooze and break down and scratch the rocks. In the course of long ages a submerged hill or ridge may get its crest and sides much bruised, shorn, and striated, and the sea-bed generally may be similarly grooved and polished, the direction of the striation being more or less north and south according to the prevalent tread of the drifting ice."*

Dawson (1868), based on observations in the Strait of Belle Isle, Newfoundland, hypothesized that icebergs act as:

> *"polishers of the seafloor" and that they "smooth and level the higher parts of the sea bottom, and mark it with furrows and striae indicative of the direction of their own motion."*

Dawson (*op. cit.*) also described the overturned keel of a previously grounded iceberg as having a "flat and scored surface covered with sand and earthy matter." Kane (1857) made a similar observation in the vicinity of Disko Island on Greenland's west coast:

> *"Many of the bergs were covered with detritus... Some of them* (rocks and pebbles) *were marked with well-defined striae, without angular crossings, smooth, and occasionally*

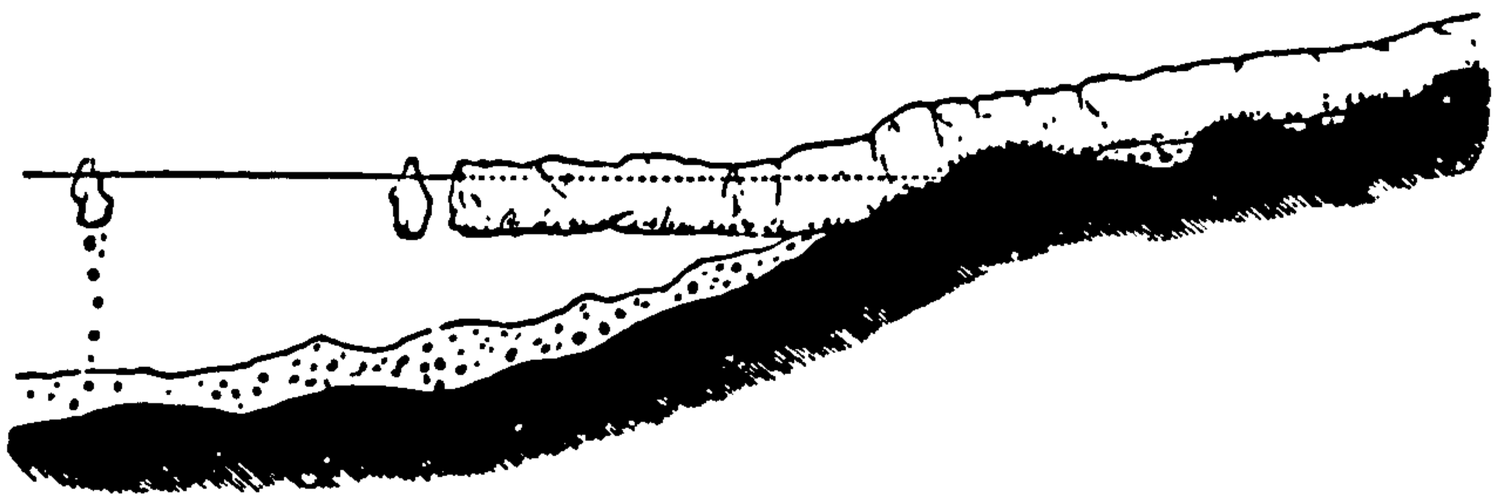


FIG. 4.—SECTION OF A SHEET OF LAND-ICE,
going out to sea, breaking off there into bergs, and forming *boulder-clay*, partly on land, and partly in the sea.

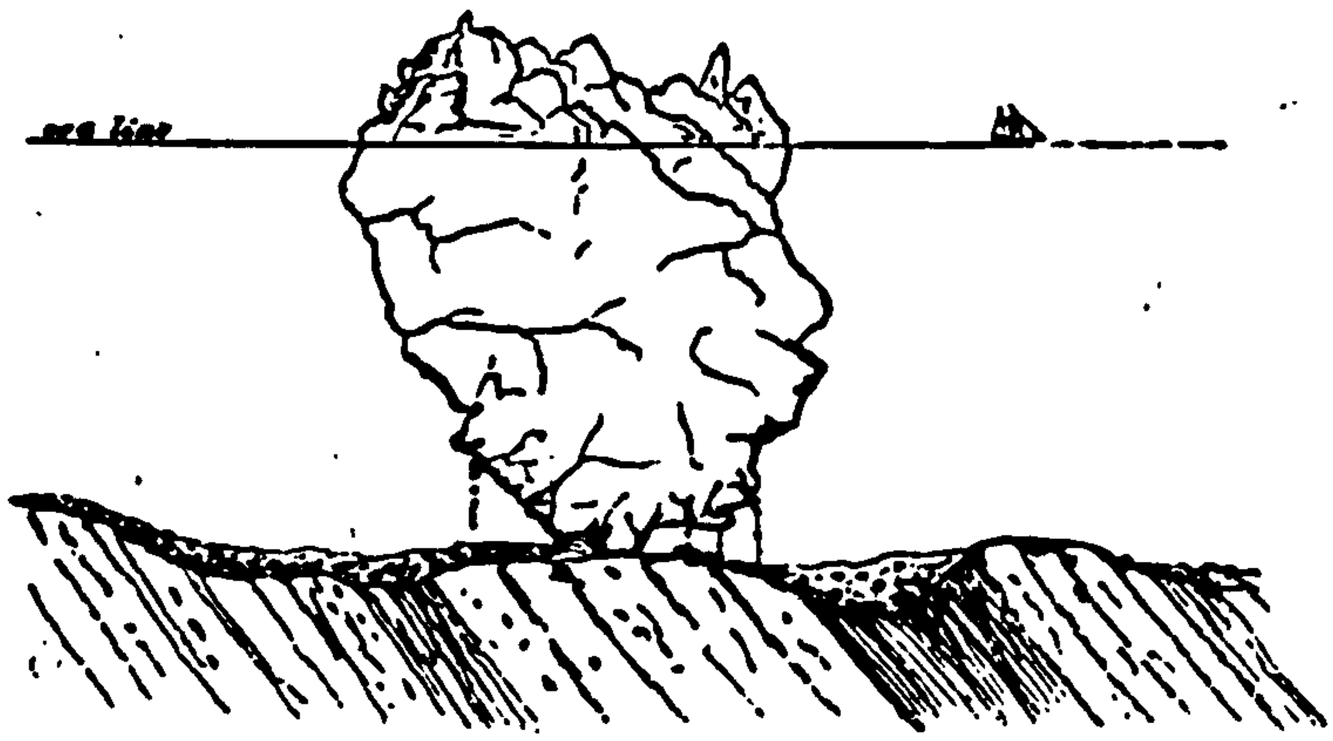


FIG. 5.—ICEBERG grating along sea-bottom, and depositing mud and boulders.

Figure 1. Conceptual cross-sections of a tidewater glacier margin and an iceberg that is both scouring and "depositing mud and boulders" (a deposit that would be classified as a "berg till" by Dreimanis, 1979). From Geikie (1865).

polished even highly: others were cut in facets of more or less regularity. They varied in size from large blocks to mere pebbles, conglomerated in the ice with finely powdered gneissoid material. The berg had evidently changed its equilibrium: and it seemed as if these rocks had been cemented in its former base, and there had been subjected to attrition during its rotary oscillations against the bottom of the sea."

These descriptions are strikingly similar to recent observations of an overturned iceberg keel that had been in contact with the seabed near Makkovik, Labrador (Hodgson *et al.* 1988).

Iceberg scour

Relict iceberg scour marks are found on the continental shelf of British Columbia where they occur in water depths up to 200 m (Luternauer, 1982; Luternauer and Murray, 1983). Relict scour marks are abundant in Hudson Bay in modern water depths up to 185 m, where they may have formed when water depths were as great as 500 m (Josenhans and Zevenhuizen, 1990). Relict scour marks are numerous also in deep water along the eastern Canadian shelf, occurring in Hudson Strait, on the southeast Baffin shelf in depths up to 715 m (Praeg, 1987), Flemish Pass (Pereira, 1985), the Laurentian Channel and western Grand Banks (King, 1976) and the outer St. Lawrence Channel (pers. comm. D. Piper, 1985). On the Norwegian continental shelf the entire scour mark population is relict (Belderson and

Wilson, 1973; Lien, 1982; 1983; Vorren *et al.* 1983) the last icebergs having been produced from the waning continental ice sheet in the early Holocene. Relict scour mark populations occur also in the Barents Sea (Solheim, 1988), and in parts of the North Sea and northeastern Atlantic (Belderson, 1973; Stoker and Long, 1984), and have been discovered in water depths as great as 915 m west of the Faeroe Islands (Werner, 1989).

In Canada relict scour marks have also been documented on the exposed floors of the former glacial Lake Agassiz (Horberg, 1951; Clayton 1975; Dredge, 1982; Mollard, 1983) Lake Ojibway (Dionne, 1977) and Lake Iroquois (Gilbert *et al.* 1992), and have also been identified on the modern lake floor of Lake Superior (Berkson and Clay, 1973). Scour marks are also seen on subaerially exposed seafloor areas on King William Island (Hélie, 1983; Woodworth-Lynas *et al.* 1986b), Victoria Island (Sharpe, pers. comm. 1987), and on Amund Ringnes Island and Ellef Ringnes Island (Hodgson, 1982) in the Canadian Arctic, and on Coats Island (Aylsworth and Shilts, 1987; Josenhans and Zevenhuizen, 1990) and Mansel Island (Josenhans, pers. comm. 1990) in Hudson Bay.

In the northern hemisphere modern scouring by icebergs still occurs on the continental shelves of eastern Canada and west Greenland (Lewis, 1979; Brett and Zarduski, 1979) to water depths of about 230 m (Hotzel and Miller, 1983) and with estimated frequencies as high as 4.3% (Woodworth-Lynas *et al.* 1985). Scouring occurs on the eastern continental shelf of Greenland, possibly to water depths as great as 490 m (Gravesen, 1990), and in Scoresby Sund possibly in maximum water depths of 600 - 700 m (Dowdeswell *et al.*

1992). In the Barents Sea active iceberg scouring occurs between Spitsbergen and northern Norway (e.g. Moign, 1976; Solheim and Pfirman, 1985) in water depths up to about 200 m (Solheim, 1988) in the northern Barents Sea, and with recent offshore oil and gas exploration in this region, interest in the process of iceberg scouring has increased. Kovacs (1972) reported that Russian mariners had long noted icebergs grounding in water depths up to 600 ft. (180 m) in the Laptev Sea, and showed the cross section of one such scour mark with an apparent width of 200 yd. (180 m) and incision depth of at least 10 ft. (3 m).

Comparatively little work has been carried out in the southern hemisphere, where reports of iceberg scouring on the Antarctic continental shelf have been made by Lien (1981) and Lien *et al.* (1989) who described very large scour marks (up to 250 m wide and 25 m deep) in water depths of less than 400 m from the eastern Weddell Sea. Barnes (1987) also described iceberg scour marks and other grounding-related features in water depths exceeding 500 m on the continental shelf area adjacent to Wilkes Land. Barker (pers. comm. 1990) reports that iceberg scour marks on the west side of the Antarctic Peninsula are restricted in their occurrence to the outer continental shelf. Keys and Fowler (1988) reported an iceberg grounded in a water depth of 273 m on 'Iceberg bank' 100 km north of McMurdo Sound, southwestern Ross Sea, and grounding of very large icebergs on the Belgrano Shoals in water depths of probably around 225 m is still occurring (Ferrigno and Gould, 1987): the large iceberg 'Trolltunga' (110 x 60 km) remained aground on these shoals for five years (McClain, 1978).

Barnes and Lien (1988) suggest that active scouring occurs in water depths up to 500 m on the Antarctic shelf areas. This depth is probably a rarely achieved maximum because from 60 - 80% by volume of Antarctic icebergs are tabular, having calved from flat-topped, floating ice shelves, and most of these icebergs have drafts generally less than 300 m (Keys, 1990). Deeper-drafted icebergs are produced from fast-flowing outlet glaciers around Antarctica and Greenland, because thinning due to basal shear stress-relief and to melting have not reduced their thickness to the same extent (e.g. Dowdeswell, 1987; Dowdeswell *et al.* 1992).

Pressure ridge scour

Active scouring by sea ice pressure ridge keels and rare tabular icebergs (calved from ice fronts such as the Ward Hunt ice shelf) is also occurring in the Canadian and American sectors of the Beaufort Sea (e.g Pelletier and Shearer, 1972; Reimnitz *et al.* 1972) in water depths up to 60 m (Reimnitz *et al.* 1984). Documentation from the Russian arctic ocean is sparse but scour is known to occur in water depths of 10 m in the vicinity of a proposed pipeline route in Baydaratskaya Guba (Inlet) southwest of the Yamal Peninsula (Kamyshev, 1990). Presumably scour has also occurred on the vast continental shelf areas of the Chukchi and Kara Seas of the Soviet Union, and also the Laptev Sea where features described as thermokarst depressions by Klyuyev and Kotyukh (1985) are probably sea ice scour marks. Scouring by first year pressure ridge keels is an active process in coastal

waters near Great Whale river in Manitounik Sound, James Bay, occurring in water depths to approximately 30 m (pers. comm. G. Gilbert, Canadian Seabed Research, 1991), and it is likely a modern process in similar water depths throughout James Bay (Meagher, 1976) and Hudson Bay. Scouring by first year ice occurs in water up to 11 m deep in Northumberland Strait (Fader and Pecore, 1990), in the vicinity of the proposed causeway between New Brunswick and Prince Edward Island. Scouring by first year pressure ridge keels in water depths up to 20 m is a concern for offshore petroleum activity on the east coast of Sakhalin Island (pers. comm. Stanislav Vershinin, Chief of Scientific and Technical Complex, Vnipimorneftegas, Moscow, 1990). Active scouring by lake ice pressure ridges occurs in water depths up to 25 m in Lake Erie (Grass, 1984; 1985), where their seasonal occurrence has been a factor in the decision not to lay power transmission cables between Ontario and Pennsylvania. Scouring by ice floes during spring breakup is also common in very shallow water (<3m) of the northern Caspian Sea (Koshechkin, 1958) and in Great Slave Lake (Weber, 1958), and probably in other large lakes whose surface waters are subject to seasonal freezing. Relict sea ice scour marks have been interpreted on a buried surface in the central North Sea (Stoker and Long, 1984).

Scouring by sea ice is an important process during the spring breakup in intertidal zones in the St. Lawrence estuary (e.g. Dionne, 1988). It is an important process during both winter and spring in Cobequid Bay and Cumberland Basin in the Bay of Fundy region (Knight and Dalrymple, 1976; Dalrymple *et al.* in press; Gordon and Desplanque, 1983) and along Arctic coastlines in Canada (e.g. Tarr, 1897; Laverdiere, 1981). Although not

reported, scouring is probably an important process along the Arctic coasts and river mouths in the Soviet Union. Scouring also occurs along more temperate shorelines, such as the East Friesian islands of the North Sea (Reineck, 1976; Ehlers, 1988).

In Canada scour research has been driven in large part by petroleum exploration companies who were beginning an intense period of offshore exploration in areas where sea ice and icebergs abound. In particular there was considerable concern about the potential damage to seabed facilities (such as wellheads, pipelines and mooring systems) by scouring icebergs. Two critical questions needed to be addressed: 1) What is the frequency of modern day scouring? 2) How deep are the effects of scouring felt beneath the seabed?

Modern scouring frequency has been approached using six different methods. These are: 1) determination of the inception of the present period of iceberg scouring using geological methods. In this method scouring rate is determined from the ratio of seabed scour mark concentration to the inferred age (derived from sedimentological and micropaleontological data) of the scour mark population (Lewis, 1987). 2) direct calculation of grounding rates using historical information for iceberg flux and draft distribution (d'Apollonia and Lewis, 1986; Lewis, 1987). 3) repetitive mapping of the seabed (using sidescan sonar) over known periods to determine new scour mark additions and other seabed changes (Woodworth-Lynas and Barrie, 1985, for the Canadian east coast) (Hnatiuk and Brown, 1977; Reimnitz *et al.* 1977; Barnes *et al.* 1987; Lewis, 1978; Hnatiuk and Wright, 1983; Shearer *et al.* 1986, for the Beaufort Sea). 4) evaluation of the rate of scour mark

degradation as an indicator of the rate of formation (Lewis, 1978; Gaskill *et al.* 1985; Gaskill, 1986, for the Canadian east coast, and Weeks *et al.* 1985; 1986; Lanan *et al.* 1986, for the Alaskan Beaufort Sea). 5) direct evaluation of grounding and scouring frequencies derived from interpretation of iceberg radar trajectories (El-Tahan *et al.* 1985; Woodworth-Lynas *et al.* 1985). 6) estimating the relative age of scour mark populations using cross-cutting relationships and inserting this into an absolute age framework (Woodworth-Lynas, 1983). The first four methods have been used to estimate the long term frequency of scouring. These are evaluated by Lewis *et al.* (1987).

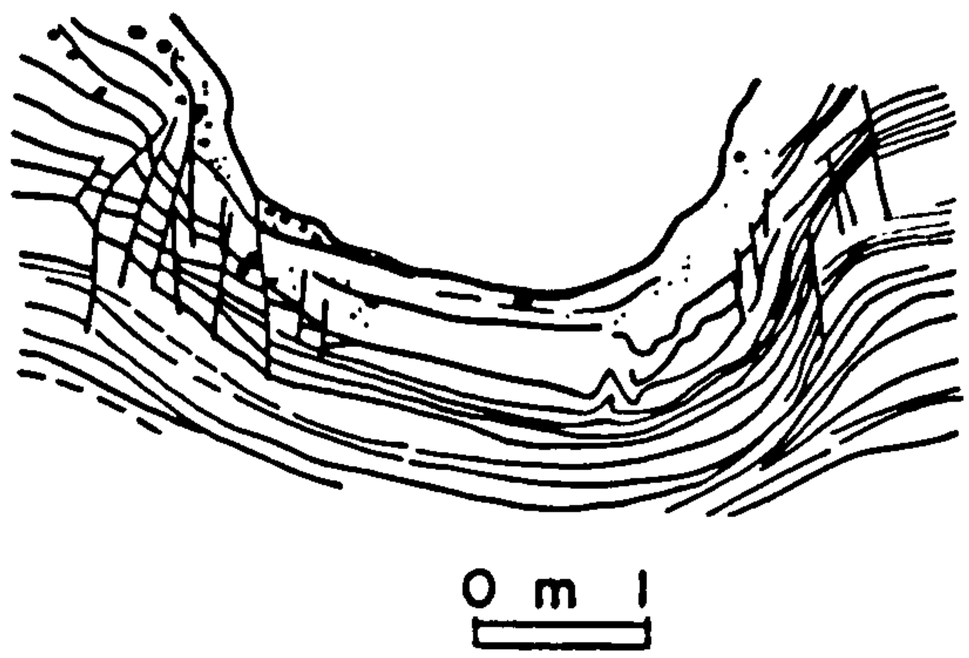
Subscour effects

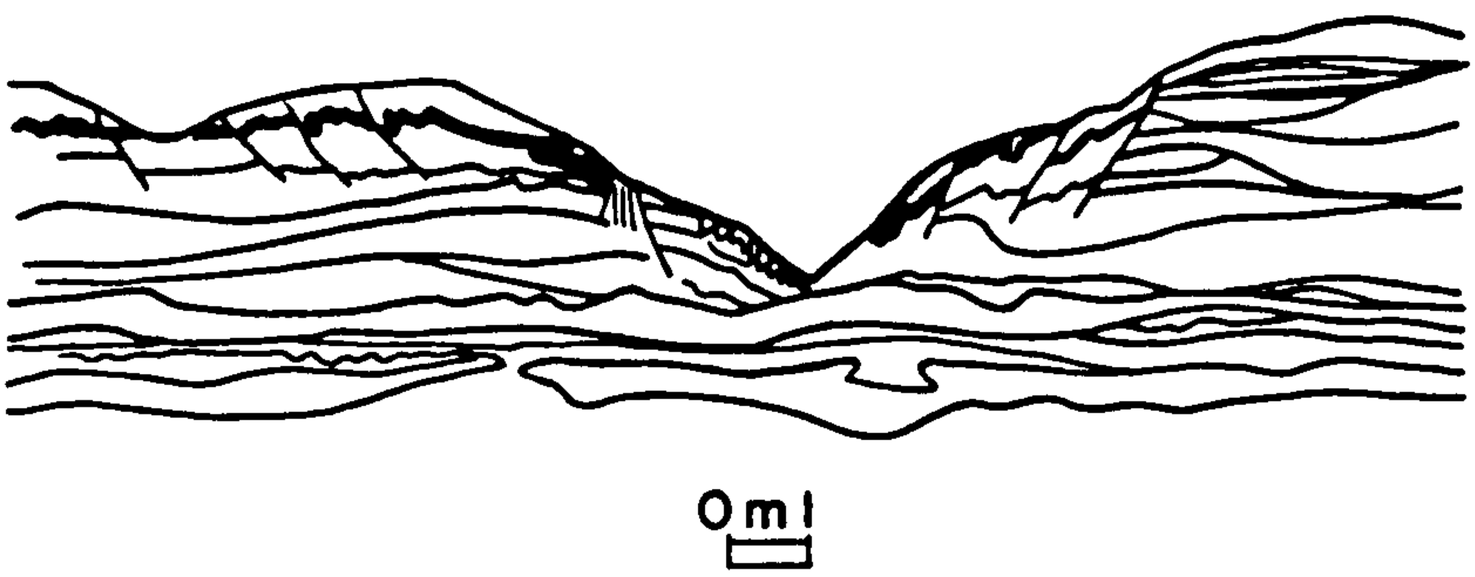
Fischbein (1987) described deformation structures observed in unoriented vibrocores retrieved from an area affected by sea ice scouring in the Beaufort Sea. He related the structures directly to ice scouring and used these descriptions to suggest a hypothetical model of what ice scour marks may look like in cross-section. His study is hampered by lack of knowledge of the positions of the cores with respect to individual scour marks, and by the coring method itself which does not give a complete picture of the sub-seabed cross-section below individual scour marks.

Thomas and Connell (1985) described a 10 m long grounding structure, at least 2 m deep, from glacio-lacustrine sediments exposed in a Scottish quarry. They observed small

scale reverse faults below the inner margins of the trough and showed "downfolded" strata extending to at least 1.3 m below the trough (Figure 2a). They interpreted the structures to be the result of ice/sediment interaction during a grounding event caused by a slow lowering of water level, with no horizontal keel movement, processes that are not typical of most iceberg scour marks. This feature is analogous to modern "scour pockets" created by grounding icebergs during annual breakout floods (Fahnestock and Bradley, 1973). Eyles and Clark (1988) described a well-preserved scour mark, approximately 9 m wide and 2.5 m deep at Scarborough Bluffs, Ontario. They interpreted the scour mark, incised into delta front sandy lake sediments, to have been made by a pressure ridge keel in water depths of 20 m about 60 000 years ago. They described thrust and normal faults, load casts and folds below and on either side of the scour mark trough (Figure 2b), and suggested that sediments have been affected by shearing up to 2 m below the scour mark trough during the scouring event. At other locations Eyles and Clark (1988) described striations that may have been formed by direct ice/sediment contact. These structures correlate with similar striations associated with ridge and groove microtopography described from modern scour marks (Hodgson *et al.* 1988)

In Norway, Longva and Bakkejord (1990) have reported on excavations of two iceberg scour marks and an iceberg pit that were formed during a glacial outburst flood in the Romerike area about 9,200 years ago. Sections beneath the scour marks revealed evidence of folding, faulting and sediment liquefaction (Figure 2c). Deformation in sub-scour sediments occurred to approximately three times the depth of scour mark incision





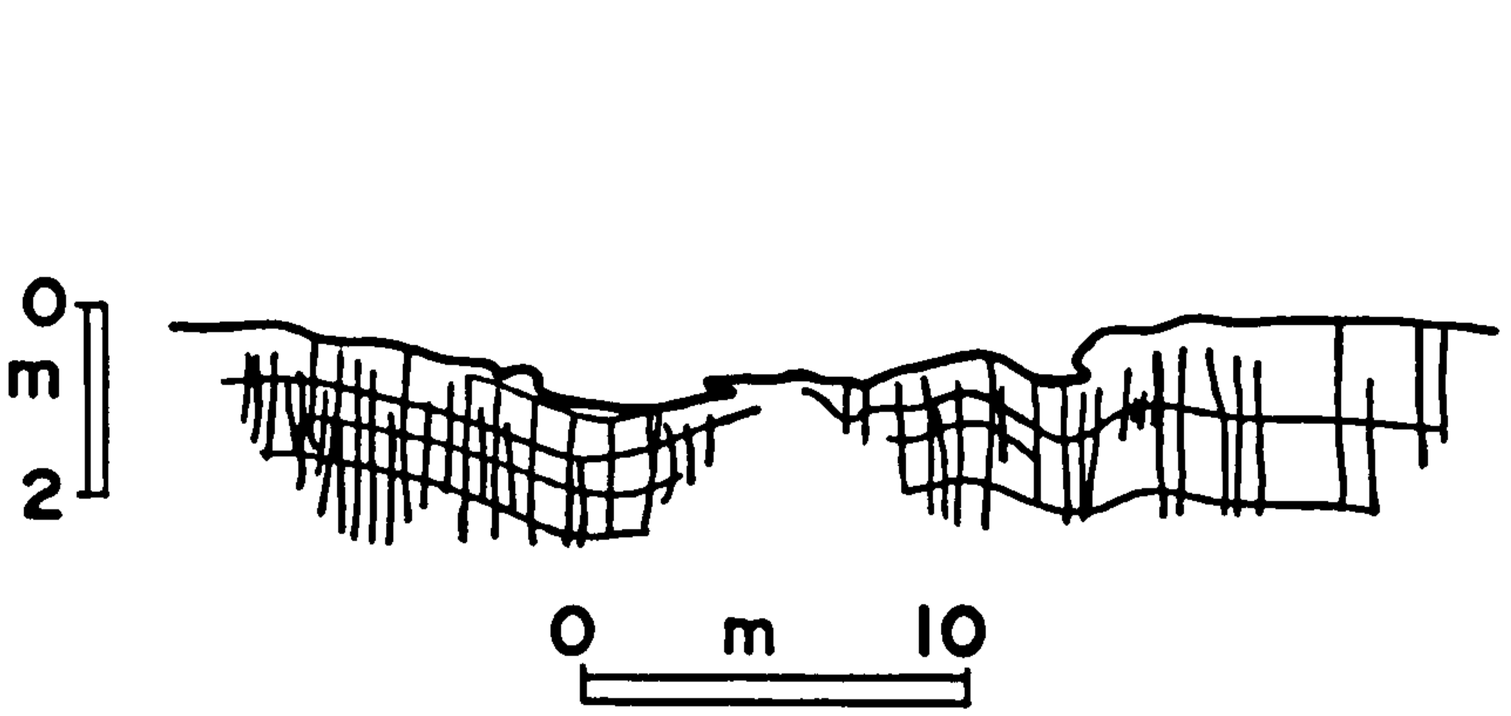


Figure 2a. Cross-section of a 10-m-long iceberg grounding structure developed in laminated silts, sands and gravelly sands, from a quarry north of Aberdeen, Scotland. Adapted from Figure 6 of Thomas and Connell (1985).

b. Cross-section of a 9-m-wide scour mark trough in delta-front sands, Scarborough Bluffs, Ontario. Adapted from Figure 10a of Eyles and Clark (1988).

c. Cross-section of a 30-m-wide scour mark in laminated glacimarine clay, Romerike, southeast Norway. Adapted from Figure 6 of Longva and Bakkejord (1990).

(Oddvar Longva, pers. comm. 1986).

Van der Meer (1990; pers. comm. 1991) reports sedimentary deformation by iceberg scouring from a Wisconsin-age pro-glacial lake in Patagonia but detailed descriptions are not given.

Goals and objectives of this study

Goals of the study are:

- to interpret the morphologies and structures in sediments beneath scour marks in terms of the processes of ice keel/sediment interaction

- to define zones of sediment movement and suggest possible effects of movement on sub-seabed facilities such as oil and gas pipelines and wellheads

- to describe a number of diagnostic morphological and structural features that define ice keel turbate facies

- to propose use of these features so that scour marks, or the effects of ice scouring, can be recognized in pre-Quaternary geological sections

- to demonstrate that ice keel turbates probably are common facies in glacigenic sediments, and thus that many massive diamictons have acquired their internal structure and form by post-depositional mechanical reworking in an aquatic environment.

To achieve these goals, the objectives of the study are:

- to examine scour marks from a variety of environmental and sedimentological settings

- to map out in detail the cross-sectional morphology of scour marks

- to map and take structural readings from deformation structures preserved in sediments beneath scour marks

- to discuss, with specific examples, descriptions and interpretations of pre-Quaternary glacigenic sediments by other workers to demonstrate possible re-interpretations in terms of ice scour marks and ice keel turbates.

CHAPTER 2

METHODOLOGY

Offshore studies

Geophysical methods and navigation

On the eastern Canadian continental shelf most data from which information on scour mark statistics, such as width, depth, orientation and spatial distribution, are derived comes from interpretations of geophysical analog records. Width, partial length and orientation are measured from sidescan sonographs. Since 1974, when iceberg scour marks were first discovered on the eastern Canadian continental shelf, much of the data have been gathered using the Bedford Institute of Oceanography (BIO) 75 kHz system operating at a slant range of 750 m (Jollymore, 1974). The resolution of a sidescan system can be broken into two components:

1) transverse resolution (Rt), defined as the minimum distance between two objects parallel to the line of travel that will be recorded on paper as two separate objects. The minimum distance is equal to the beam width at any point on the seabed, resulting in a steady decrease of Rt towards the outer ranges (Flemming, 1976). Thus:

Rt (in metres) = sin (beam width) X slant range (in metres).

2) range resolution (Rr), defined as the minimum distance between two objects perpendicular to the line of travel that will be recorded on paper as separate objects. Assuming that a minimum spacing of 1 mm on the recording paper is needed to plot two objects separately, and with a paper width per channel of 125 mm (standard for most surveys), Rr will be 1/125 of the slant range. Thus:

Rr (in metres) = slant range (in metres) ÷ 125.

Operating with a horizontal beam width of 1.5°, the BIO system has a theoretical transverse resolution of 19.6 m at 750 m slant range and 0.39 m at 15 m slant range. Corresponding range resolution is 6.0 m at 750 m slant range, and 0.12 m at 15 m slant range. Other data have been gathered using commercial 100 kHz systems operating at slant ranges of 200 m (such as the Klein Hydroscan system used during the Dynamics of Iceberg Grounding and Scouring [DIGS] experiment. DIGS is described in Chapter 3). These systems operate with horizontal beam widths on the order of 1°. Thus, in comparison to the BIO system, transverse resolution is enhanced to about 0.26 m at 15 m slant range and 3.5 m at 200 m slant range, and the range resolution is comparable. The SeaMARC mid-range sidescan operates at frequencies of 27 kHz (port) and 30 kHz (starboard) up to a slant range of 2.5 km (Chayes, 1983) and has been used to collect seabed morphological data on relict scour marks in water depths greater than about 500 m in Hudson Strait (Josenhans and Woodworth-Lynas, 1988) and Laurentian Channel. This system has a theoretical transverse resolution of 5.9 m at 200 m slant range, and 74.2 m at 2.5 km slant range, and range resolution (on paper with 240 mm width per channel) of 0.8 m at 200 m slant range

and 10.4 m at 2.5 km slant range.

Information on scour mark depth and near-surface acoustic stratigraphy is obtained from high resolution sub-bottom profile records, many of which have been collected using a Huntec Deep Tow System with a boomer source (Hutchins *et al.* 1976). This system has a pulse length of between 90-120 microsec. resulting in a generally-accepted vertical resolution of 25-30 cm (R. Parrott, Atlantic Geoscience Centre, pers. comm. 1992). All scour mark statistics from the eastern Canadian continental shelf have been measured from sidescan and sub-bottom profile records, and compiled into the east coast Regional Ice Scour Database by the Atlantic Geoscience Centre, Dartmouth (e.g. King and Gillespie, 1985).

Navigation during BIO geophysical surveys is accomplished using BIONAV, a system integrating Loran C and satellite navigation. The positional accuracy of this system is about ± 500 m. Navigation during the DIGS experiment was carried out integrating three methods: Loran-C, SatNav, and a commercial trisponder line-of-sight Sercel Syledis system, providing position accuracy to about ± 5 m during clear weather.

During surveys the sidescan towfish generally has a greater amount of cable in the water than the profiling system because of the operational requirement that the sidescan be close to the seabed (generally 15-20 m above) for optimal scanning. Consequently the displayed data from both systems is offset, the Huntec passing over and insonifying seabed

features before the sidescan. This offset discrepancy is additionally complicated by different paper speeds on the respective recorders so that there are differences in horizontal scale. However, Huntec and sidescan records can be integrated visually by matching pronounced seabed features, such as large scour marks, thus facilitating correlation of the interpretation of both datasets. During DIGS the correlation problem was reconciled by attaching a 50 kHz sidescan to a Huntec towfish system, and running both recorders at the same paper speed. Both datasets were thus matched and of equal horizontal scale.

It is clear that sidescan systems are unable to resolve discrete seabed features of less than about 0.5 m in the near ranges, and that Huntec reflection profile data can resolve sub-bottom features with vertical expressions no smaller than about 25-30 cm. These resolutions are acceptable for general statistical descriptions of ice scour mark dimensions and densities but are insufficient for the level of detail necessary to resolve the precise geometry and structure that are required for an analysis of the scouring process. Detailed resolution can only be achieved by combining direct visual examinations of scour-affected sediments from submersible with on-land studies of ancient scour marks.

Submersible

The Canadian federal Department of Fisheries and Oceans three-person research submersible (mini-submarine) *PISCES IV* was used in 1985 in collaboration with the DIGS

experiment to carry out dives on new iceberg scour marks identified from sidescan sonographs. *PISCES IV* is a single-chambered vehicle that maintains an internal environment of one atmosphere. The vehicle is battery-powered and in 1985 was operated from a tender vessel, M.V. *Pandora*, with which it communicated using a 12 kHz acoustic voice channel. Navigation of the submersible was carried out using a Hydrostar system operated from the *Pandora*, instructions on course direction and distance to specified targets being relayed to the submersible pilot via the acoustic voice channel. On-the-bottom navigation is aided by a gyro compass and forward-scanning sonar. Sidescan sonographs of specific iceberg scour marks recorded shortly before a dive were taken in the submersible and used successfully as maps to navigate between features. Three small windows in the submersible allow exterior viewing. The central window is for the pilot, who kneels in a well and flies the submersible using a joystick control unit. Two observers are accommodated on either side of the pilot lying on two horizontal benches. Seabed observations are made using an externally-mounted, forward-looking video camera which continuously records on a VHS videocassette recorder in the cabin. One of the observers records observations onto the video tape using a microphone. Other observations are made using standard 35 mm cameras held against the observation windows, frame numbers being recorded orally onto the video tape. Viewing is aided by forward-projecting floodlights depending on water depth and visibility. The submersible is propelled at speeds between 2-3 knots by two swivel-mounted thrusters, one on each side. Dive duration may be up to 6 hours.

An external, frontal cluster of instruments allows seabed samples to be taken using

an hydraulic manipulator arm. Small push cores, up to 50 cm long, can be retrieved and stored in a rack, and loose surface samples can be obtained using a suction tube attached to the arm. Suctioned material is stored in a circular, revolving, compartmentalised carousel. Core and suction samples are retrieved and stored after the dive.

On-land studies

King William Island

Aerial photographs were used to select scour marks for study. Seven were cursorily examined by on-site visual inspection to observe similarities in surface expression and sediment type. One scour mark was selected for more detailed study. Trenches were hand-excavated using shovels, exposing structures in the trench walls that were described, and sediment samples were taken for grain size analysis. Excavations were limited to depths of about 1 m because of the presence of permafrost at this depth. Drilling, using a generator-powered heavy-duty electric drill attached to a small core barrel, failed to obtain cores from within the permafrost. The scour mark was surveyed over a distance of 660 m at 30 m intervals. Cross-profiles of the scour mark were surveyed at each 30 m interval using a Brunton compass/clinometer and tape measure, and the relative altitude of each survey station was recorded using an altimeter. Although sub-scour effects could not be documented because of problems with excavating and sampling within the permafrost, the

study was useful because it represents the only on-land documentation of a scour mark developed in poorly sorted sediment.

Manitoba

Relict iceberg scour marks are exposed at surface over a large area of farmland in southeastern Manitoba. These scour marks formed during the last phase of glacial Lake Agassiz. Using aerial photographs scour marks were pre-selected for study based on the clarity of surface expression, and the excavation sites on the scour marks were chosen in areas where there appeared to be little or no interference from nearby or cross-cutting scour marks. This precaution was taken to ensure that sub-scour deformation structures could be associated reasonably with the scour mark being investigated. Exact positions of proposed excavation sites were measured from enlargements of the aerial photographs. Four scour marks were accurately surveyed and levelled from a known landmark using a theodolite, and the excavation sites clearly marked with coloured stakes.

The clay sediment was easily trenched to 3 m using a tracked backhoe, and this depth was increased to 4.5 m by removing up to 2 m of surface material with a bulldozer in one large excavation. Trench walls are unstable in this material and provincial safety guidelines concerning working in open excavations required the use of steel trench cages. The initial excavation was made large enough to insert two trench cages positioned such that a vertical

working face of about 1.5 m was left exposed between them. Lumber shoring, held apart with screw jacks, was erected in the centre of the working face to prevent trench collapse. One side of the trench was selected for study for the entire cross-section. After the working face was cleaned off using Dutch garden hoes a laser level, set up above a control stake of known elevation, was used to mark spot elevations on the trench face. From these spot elevations, a grid was marked on the wall, and a hand-drawn diagram of the working face was constructed on graph paper showing structural and sediment textural features. Positions of block and bulk samples for subsequent analysis, and of photograph locations were marked on the diagrams. Faults were excavated where possible and measurements were made of their orientation and associated slickenside plunges using a compass-clinometer. Orientations were measured at a distance from the metal cages to avoid deflection of the compass needle.

Once a working face had been mapped, the shoring was removed, and the small area covered by the lumber was quickly cleaned and mapped. The trench was then advanced about 2 m by the backhoe. The trench cage furthest from the hoe was attached to the bucket with a chain, and the cage pulled forward until it touched its neighbour. The cage nearest the hoe was then attached to the bucket and pulled forward 1.5 m thereby creating a fresh working face. Whilst the new face was cleaned and measured the trench behind the rear cage was backfilled. In this way only a small section of ground was opened at any one time.

Cobequid Bay

Scour marks formed by pan ice during spring breakup are well preserved in the tidally-laminated silty sediments of the estuary. Approximately two months after the breakup, ice scour marks near the surface could be easily identified in well exposed bluff sections at the eroding margin of the main Salmon River thalweg. These scour marks are essentially unaffected by post-scour processes, because they are formed in a depositional setting and generally are protected by a thin mantle of silt from subsequent tidal cycles. In addition the general form and dimensions of the scour marks are similar to fresh features observed at the time of formation (Dalrymple, pers. comm., 1991, Queen's University). In all cases the cross sections of the two-month old scour marks could be correlated with a linear (partially filled) trough on the present depositional surface.

Scour marks were identified during on-foot reconnoitring of the middle to upper reaches of the tidal flats during the ebb tide. The scour marks were hand-excavated using a spade. At the Black Rock Section and on Masstown Flats scour marks were investigated by digging shallow pits, the long sides of which were oriented normal to the scour mark axes. The pits were excavated to depths of about 1 m beyond which little or no appreciable scour-related deformation could be observed. One of the long sides of the trench was chosen for study and cleaned off vertically with the spade. In places where laminae were hard to define they were either marked by drawing a sharp knife point along the layer, or enhanced by carefully pouring water from a plastic container down the prepared surface. The water

washed material out of sandy laminae leaving a well defined etched surface that often revealed fine structures not previously visible. At the Irving Oil Dock scour marks were displayed not only in plan on the mudflat surface but in section along the top of a continuous bluff that was actively eroding with each tidal cycle as the axis of the Salmon River thalweg moved towards the south margin of Cobequid Bay. This fortuitous situation meant that between 1-2 m of nearly vertical fresh section was exposed at the top of the bluff above the debris apron. Sections were straightened and cleaned off with the spade and etched with water. Photographs were taken of the cleaned sections and later were compiled into mosaics. Prominent layers and faults were identified and traced, and from these layer deflection and changes in layer thickness were measured. Contoured undrained shear vane data were transposed onto the traced sections.

Once a section had been prepared, a string was drawn tightly and levelled, using a string-mounted spirit level, between two aluminum pegs driven into the mudflat surface above the vertical trench wall. The horizontal string was used as an arbitrary datum line. At increments along the datum line, usually of 5 or 10 cm, vertical distances to marked layers were measured using a steel tape measure. The measurements, considered accurate to within 0.5 cm, were entered in a log book and later used to construct cross-section diagrams.

At the position of the next section (for scour marks that were sectioned more than once) and prior to excavation, a direct-reading hand-vane tester was used to obtain

undrained shear strength data of the sediment along the profile at depth increments of 5 cm (see Appendix for a discussion on measurement). The four blades on this type of shear vane are 26 mm long and 19 mm in total width, and the shear strength measurement obtained for each point therefore represents an average value for a cylinder of sediment of the same length and diameter. This should be borne in mind when examining the contoured data because the small x's, although used as the contour points, indicate the position of the bottom part of the vane blades and not discrete point measurements of shear strength. The sampling effect of the vane thus results in contours that do not always correspond to well defined sedimentary layers. The instrument should have been calibrated by removing the blades, inserting the shaft into sediment and recording values. This procedure records the frictional resistance of the shaft at each sampling depth, and the average reading from a number of samplings can be used to correct the vane data. Unfortunately the calibration procedure was omitted. The resulting contoured shear strength values are thus likely to overestimate the actual strength values. However, comparison of results for uncorrected and corrected shear vane data collected from the St. Lawrence estuary using the same instrument suggest that although the corrected values are smaller the shape of the contours will be almost identical. Thus, although the contoured data from Cobequid Bay are uncorrected they serve to indicate the general shape distribution of contoured shear strength values which are useful when comparing trends between scour marks.

St. Lawrence estuary

Small scour marks formed by ice pans and compound, pressured ice are formed during the spring breakup and are exposed on intertidal mudflats. Profuse scour marks became easily visible as the tide receded, and often an individual feature could be related to the grounded ice block that created it. The scour marks were reached on foot at low tide. Criteria for selecting a scour mark for study were that it was freshly incised with sharp relief, and thus likely to have formed during the preceding ebb tide, and that the part selected for study was developed in an area of the mudflat unaffected by other scour marks. This latter point was important so that the interpretation of shear vane measurements could be reasonably related to a single scouring event. The surface morphologies of several features were examined, and two scour mark cross-sections were investigated in detail. The elevation of the incision surface was measured using a levelled string and ruler, and shear strength measurements obtained with the hand-operated shear vane. Shear vane measurements were collected up to 1 m below the scour mark incision surface, however, the presence of numerous pebbles at about 20 cm often prevented penetration of the vane beyond this depth. The contoured shear strength values for these scour marks were corrected.

CHAPTER 3

THE SURFACE MORPHOLOGY OF SCOUR MARKS, AND THE PROCESSES OF SCOURING

This chapter describes observations of iceberg marks made during the Dynamics of Iceberg Grounding and Scouring (DIGS) experiment carried out on the Labrador continental shelf in 1985 (Hodgson *et al.* 1988) (Figure 3). Visual observations were made of five new iceberg scour marks from the Department of Fisheries and Oceans research mini-submarine *PISCES IV* ("Bertha" scour mark, "Big Makk" scour mark, asymmetric scour mark, "Caroline" scour mark and Baffin Shelf scour mark) (Table 1). In addition an iceberg ("Gladys") was observed to impact the seafloor but no subsequent seabed observations could be made. Visual observations were used in conjunction with good quality high resolution sidescan sonar (using a Klein Hydroscan system operating at 100 kHz) and with acoustic sub-bottom profile data (acquired using a Huntec Deep Tow Seismic system).

The "Bertha" scour mark was examined from the submersible two weeks after the iceberg un-grounded in 107 m of water on Makkovik Bank (Figure 4). The feature consisted of a pit where the iceberg had initially grounded, and three "skip" marks made by the oscillating iceberg as it lifted off from the grounding pit. "Big Makk" was discovered in 150 m water depth as a fresh feature during a detailed sidescan sonar survey of a portion of northwestern Makkovik Bank (Figure 5), and was subsequently investigated during two submersible dives. The scour mark was approximately 315 m long and 50 m wide. "Big

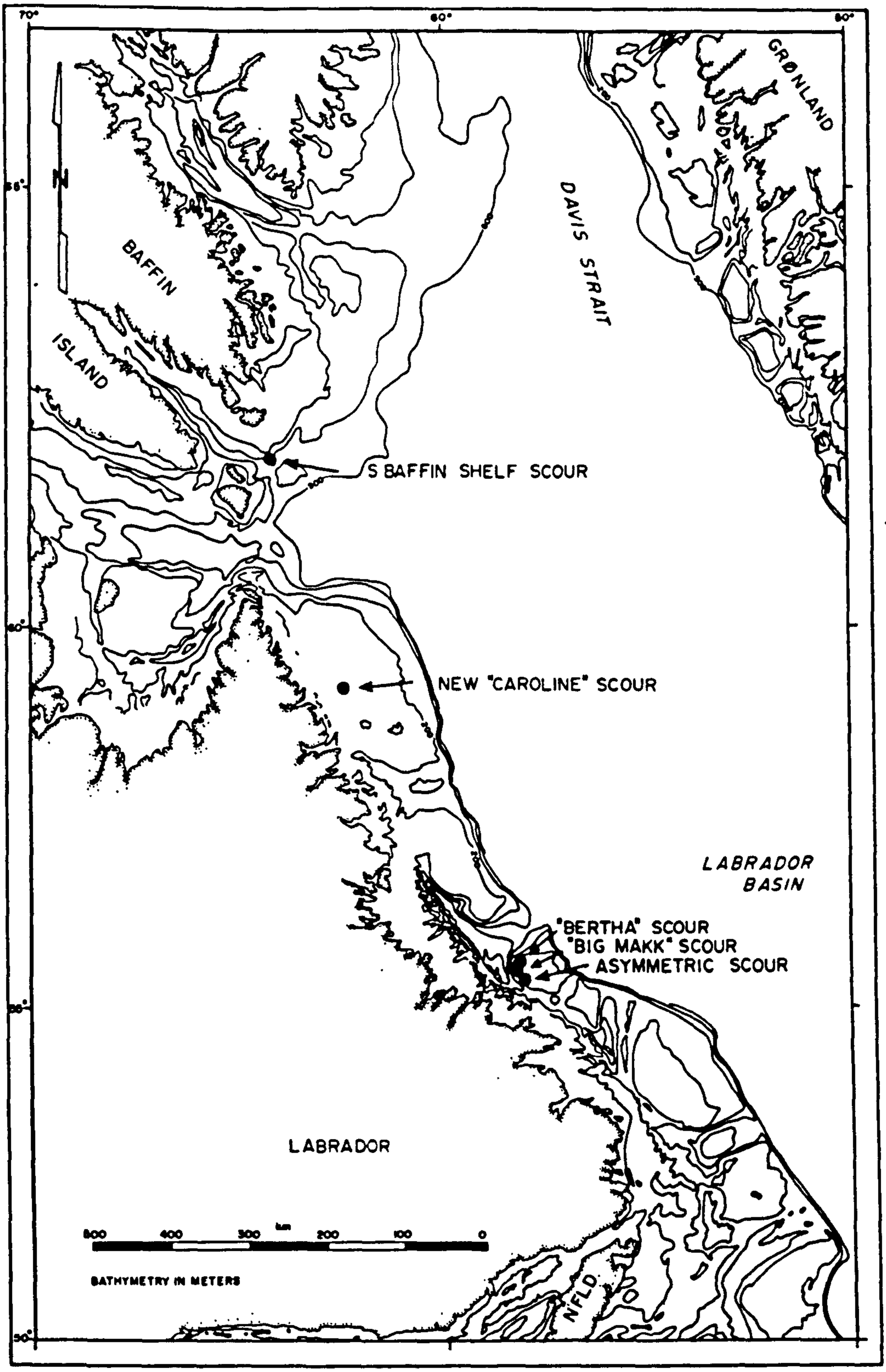


Figure 3. Location map of five new scour marks in the Labrador Sea.

Table 1. Summary description of five new scour marks observed during the Dynamics of Iceberg Grounding and Scouring (DIGS) experiment in 1985, Labrador Sea.

Site	*Water depth*	*Sediment Unit*	*Common elements*	*Unique elements*
"Bertha" scour	107 m	Upper Till	RGM.* Berms FBT#	Ice & boulder embedded in seafloor. Disjunct RGM* in first impact mark
"Big Makk" scour	150 m	Qeovik Silt Fm.	RGM* Berms FBT# Meltout pits	Surcharge Flat-topped mounds
Asymmetric scour	137.5 m	Upper Till	RGM* Berms FBT#	Berm on down-slope margin only
New "Caroline" scour	120 m	Qeovik Silt Fm.	RGM* Berms FBT# Meltout pits	Disjunct RGM* on inner berm flanks
S. Baffin shelf scour	230 m	Fine sand	RGM* Berms FBT#	

* RGM = Ridge-and-groove microtopography
# FBT = Flat-Bottomed scour Trough

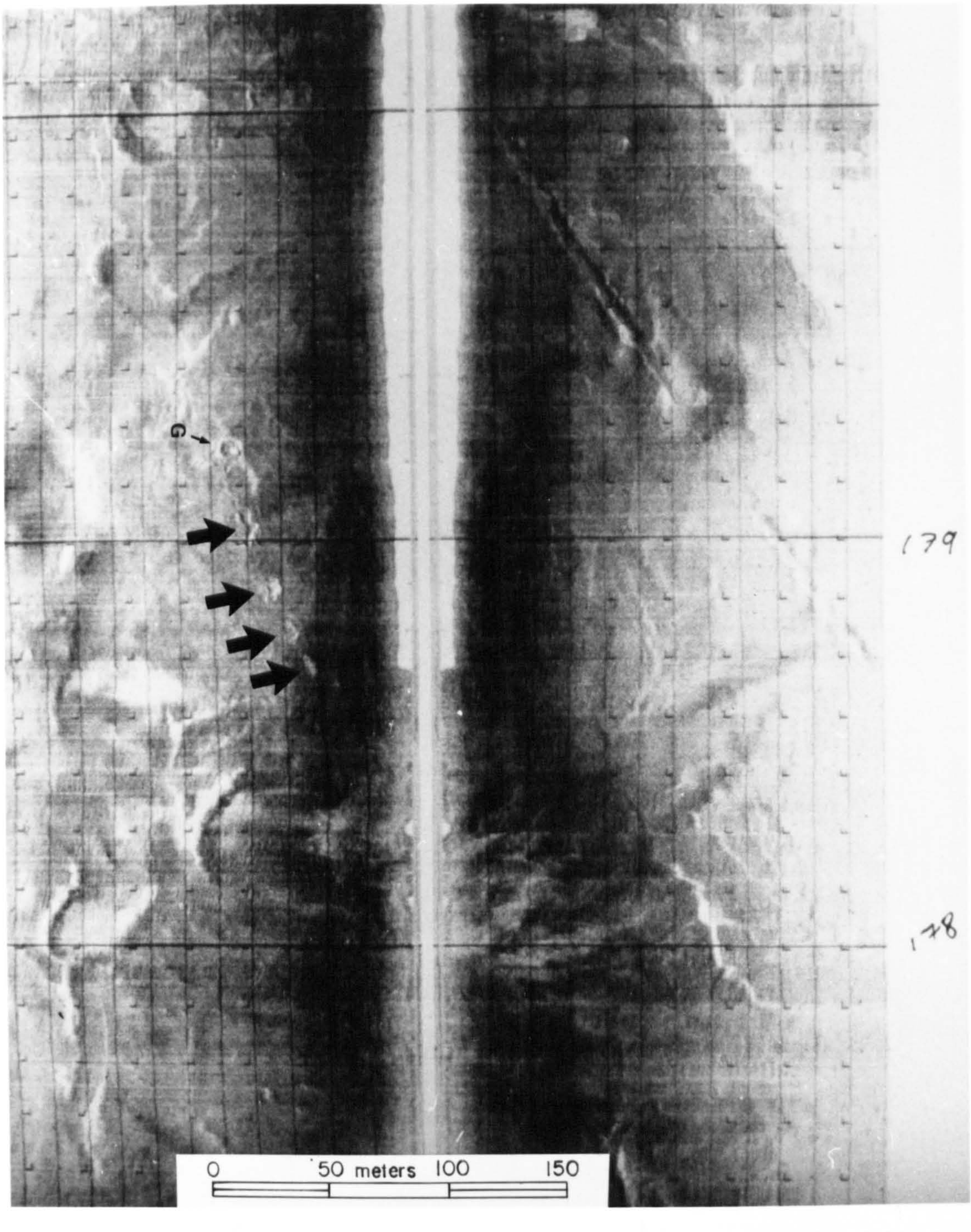


Figure 4. Initial grounding pit (G) and three (possibly four) "skip" marks (arrows) made as iceberg "Bertha" ungrounded.

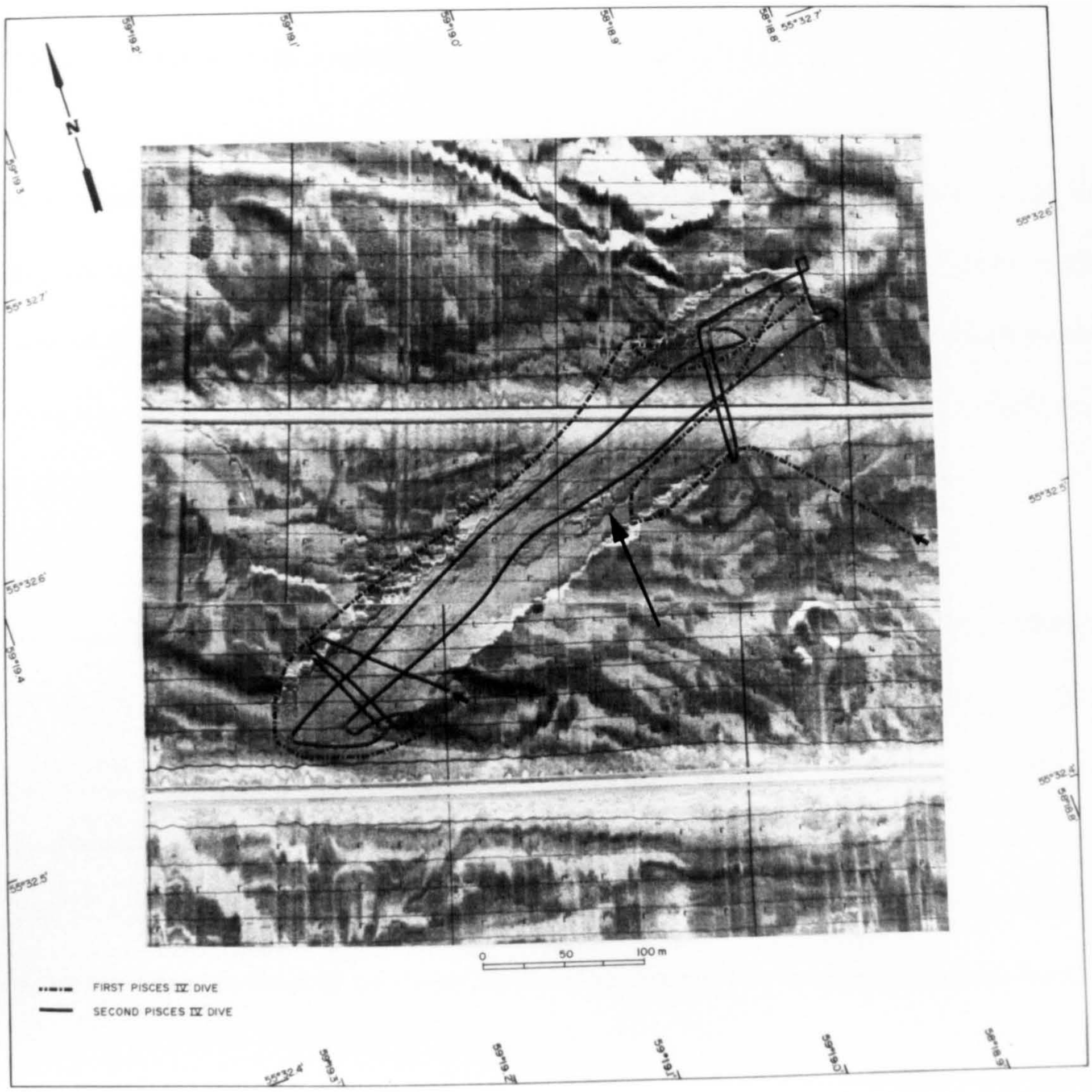


Figure 5. 100 kHz sidescan sonar mosaic of the "Big Makk" scour mark cut into the Qeovik Silt Formation at a water depth of 150 m on Makkovik Bank, Labrador Sea. A region of flat-topped mounds (arrow) in a depressed area approximately 100 m long and 20 m wide is evident within the scour mark trough. Apparent waviness of the ridge-and-groove microtopography within the scour mark trough is an artifact caused by towfish roll.

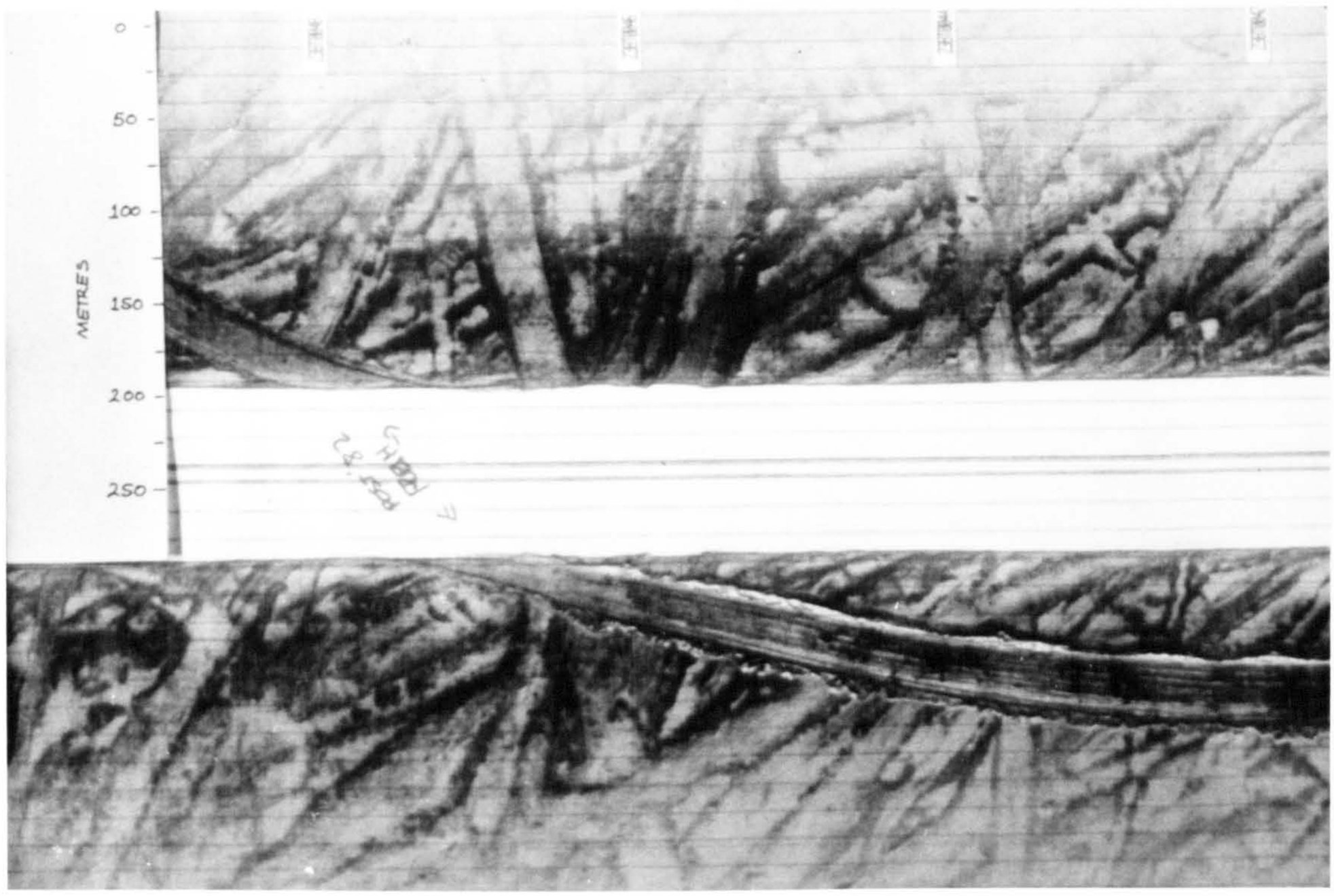


Figure 6. 100 kHz sidescan sonograph of the new "Caroline" scour mark, cut into the Qeovik Silt Formation at a water depth of 120 m on Saglek Bank, Labrador Sea. Scour mark trough-parallel ridge-and-groove microtopography is clearly seen in the trough. Individual ridges and grooves can be traced up to 500 m before dying out.

General geology, Labrador shelf

The area of most intense scouring by icebergs in the Labrador Sea occurs on the tops of the six large, flat-topped banks comprising the outer continental shelf. Water depths generally range from 120 m to 300 m. The banks are separated by transverse valleys or "saddles" up to 500 m deep (see Figure 3). The bank tops are blanketed by post-glacial marine sediments of the Sioraq Sand Formation (fine sand to muddy sand) and Sioraq silt and gravel Formation (gravelly, muddy silt) that overlie a series of at least three till units (Josenhans *et al.* 1986). Iceberg scour marks described in this chapter are developed in these overlying units.

Elements of new scour marks

Flat-bottomed scour mark troughs

Visual observations made from *PISCES IV* showed the troughs of all five scour marks to be essentially flat. Similar observations were made by Fader (1989) from a large, relict scour mark in the Avalon Channel offshore Newfoundland. Flat scour mark troughs indicate that the bases of the scouring keels were also flat. This interpretation was strengthened by observation of an overturned iceberg nearer to shore, that presented to view a sediment-covered, flat surface interpreted to be the former keel which had previously been

in contact with the seabed (Figure 7). The reason for making the interpretation of a sediment-impregnated keel is outline below.

There are three ways to explain how icebergs may contain sediment. One is that sediment was entrained in the parent glacier. Such englacial sediment is inherited by calving icebergs and is later exposed, usually in bands within the iceberg, due to capsizing caused by minor calving, ablation and melting. A second explanation is that sediment may be incorporated and frozen on to the sole of the glacier. An iceberg calved from such a glacier would be characterized by a veneer of glacial material on its keel (for example see Bellair, 1960). A third explanation is that debris exposed on a flat surface may have been accumulated recently by mechanical incorporation and freezing of seabed sediment during a scouring or grounding event. In the case of the observed iceberg, glacial origins for the sediment are rejected. In the first place, englacial debris was not observed as a band or bands in this or in any other iceberg on Makkovik Bank. Origin of the observed material from the sole of a glacier is also rejected. The nearest tidewater glacier is 900 km to the north in Frobisher Bay, but more reasonably about 2,000 km, which is the distance to the first significant concentration of iceberg-producing glaciers on mid-Baffin Island. After drifting such long distances, ablation would probably have resulted in meltout and deposition of the sediment long before the iceberg was observed. Local origin of sediment from a recent scouring or grounding event is the preferred theory because sediment on an exposed ice surface would be deposited rapidly due to ablation, and therefore its observation on an iceberg is considered reasonable proof of recent origin (see also Chapter 8, Ice-rafting).

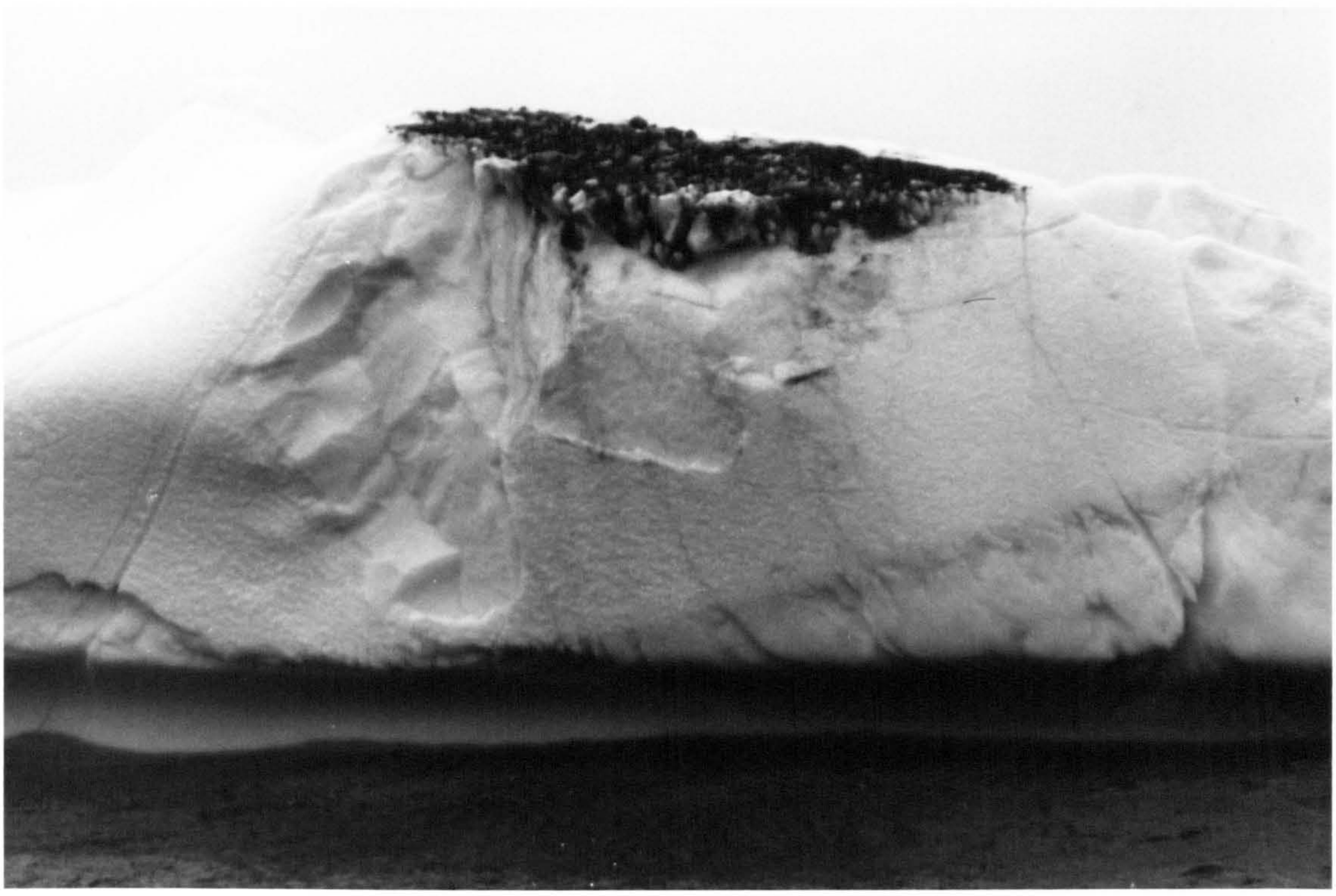


Figure 7. Photograph of an overturned iceberg whose flat, sediment-covered keel had been in contact with the seabed. Sediment grain size ranges from large boulders (approx. 1 m diameter), cobbles, and probably gravel and fines. Fine-grained sediment is concentrated along pronounced fractures in the ice at the edge of the keel.

Evidence for ice keel deformation

During the study iceberg "Gladys", an 8.9 million tonne tabular iceberg, split in two. One half immediately rotated and grounded in 134 m of water. About 7 1/4 hours later an underwater calving event released several sediment-laden growlers from the grounded keel. The growlers contained seabed sediment entrained along numerous fractures, and probably originated from the edge of the keel where fractured ice, as in the overturned keel described above, would be likely to break off. Samples of the growler ice were collected and kept frozen. Thin section analysis show zones of fine-grained, euhedral, polygonal crystals in sharp contact with zones of large-grained crystals of undeformed glacier ice. The undeformed ice contains linear trains of elliptical air bubbles not seen in the fine-grained ice (Figure 8). Also, thin (approx. 1 mm wide) fractures, filled with fine sediment, penetrate the zones of glacial ice crystals but do not occur in the fine-grained ice. However, fine sediment is concentrated along grain boundaries throughout the zones of fine-grained ice.

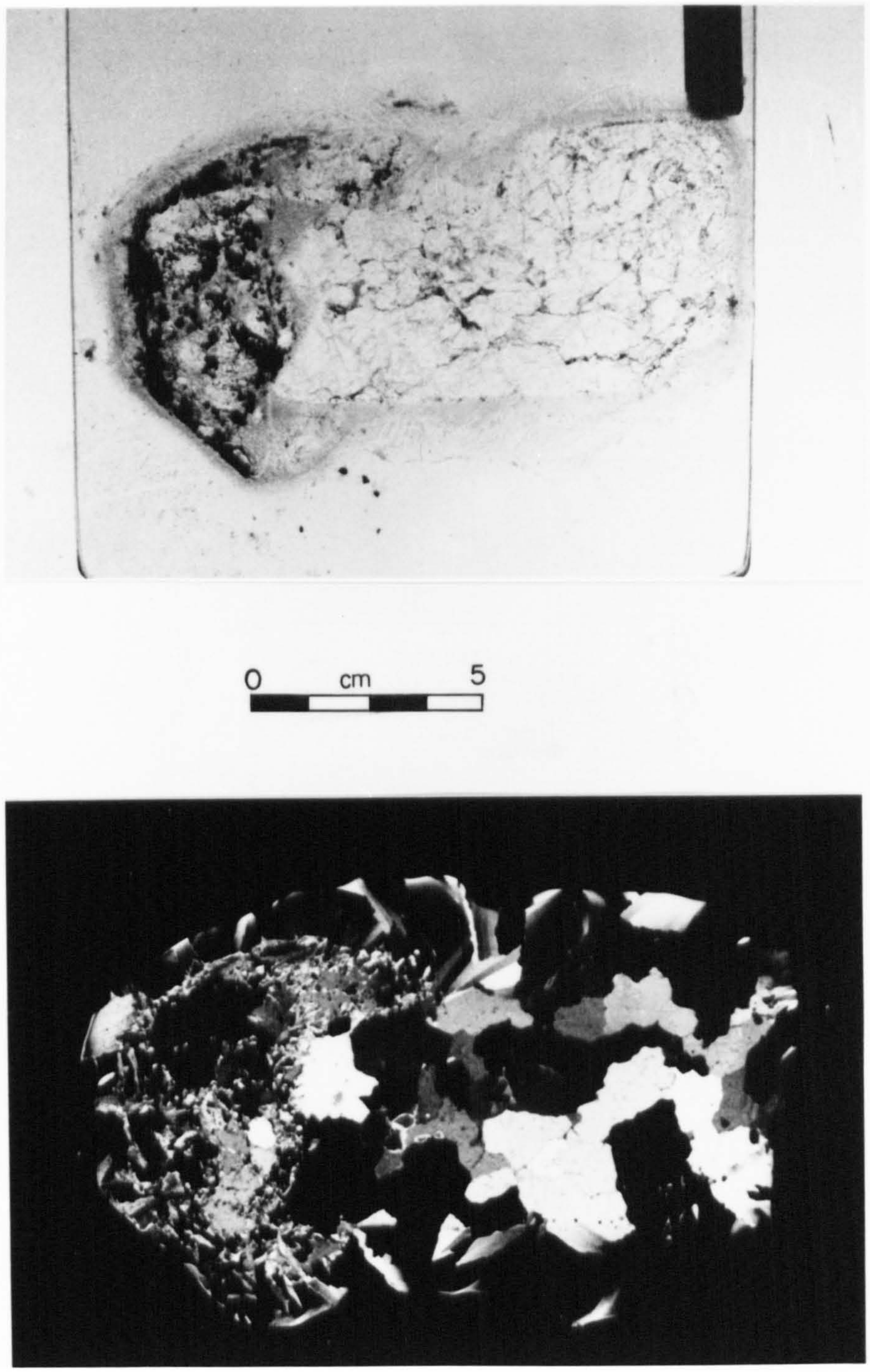


Figure 8a. Photomicrograph of thin section of ice from sediment-laden growler that calved from the grounded keel of iceberg "Gladys". Note pervasive fracture planes that cross the section. Fine-grained sediment is confined to fracture planes affecting original glacier ice crystals and to the grain boundaries in the fine-grained ice. Large porphyroclasts of relatively undeformed glacial ice are clearly evident and contain no sediment (photo approx. at scale).
b. Same section as above, polarized light.

Features within the scour mark trough

Ridge-and-groove microtopography

Common to all five new scour marks are the presence of scour mark-parallel ridges and grooves. With relief and widths ranging from a few millimetres to 30 cm, these features are developed on the inner berm flanks and in the scour mark troughs. The larger ridges and grooves may be seen on 100 kHz sidescan sonographs (Figure 6) and can be traced for at least 500 m. The smaller ridges and grooves, seen only from *PISCES IV* (Figure 9), are less continuous often dying out within a few metres. From *PISCES IV* fine striations can be seen on the flanks, tops and bottoms of ridges and grooves.

As they are traced along the scour mark axis the morphology of individual ridges and grooves often changes (Figure 10). Typically these changes involve increases or reductions in amplitude between a ridge crest and the bases of adjacent grooves. Changes in width, possibly of several centimetres, and corresponding changes in cross-sectional shape are seen. Smooth ridges may deteriorate over several meters, the ridge walls appearing progressively more "ragged", as if an insufficient volume of sediment was available for their construction. Ridges and grooves that change shape may regain their original, or similar, morphologies. Occasionally, new ridges may start abruptly on one side of a single boulder or cobble, whose cross-sectional shape may be mirrored by the ridge. Along the inside berm flank ridges and grooves may be developed rarely at angles up to 45° to the scour mark axis, but these

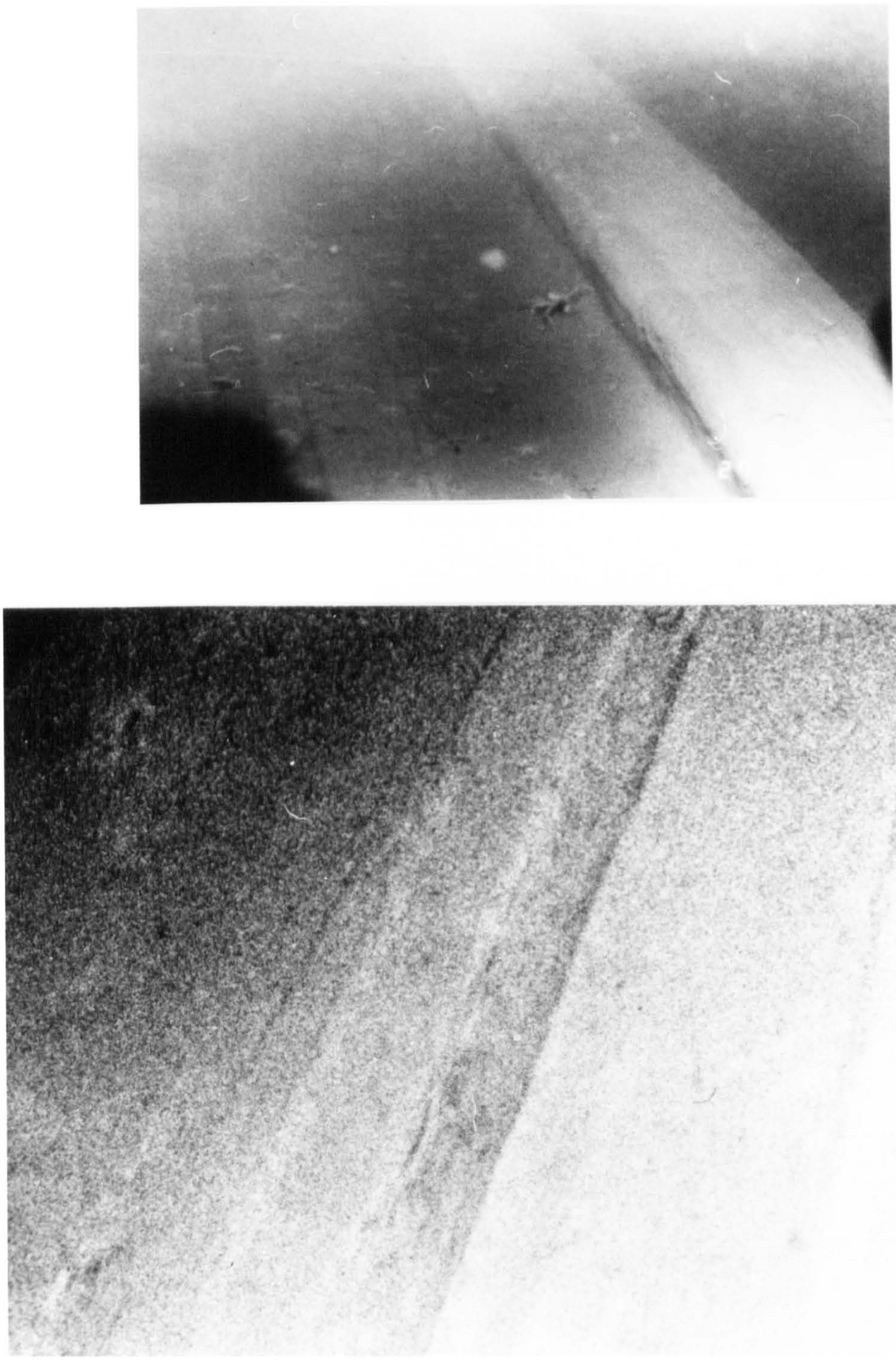
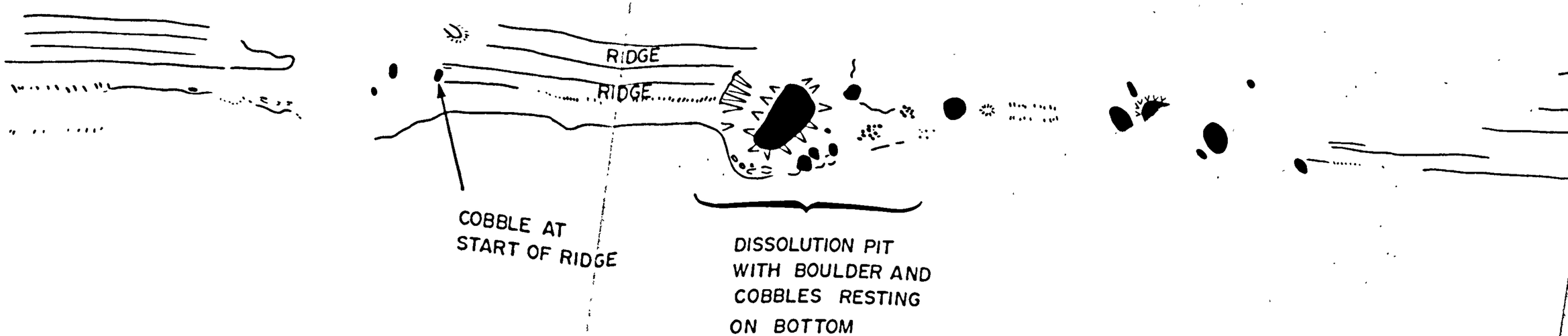


Figure 9. Typical ridge-and-groove microtopography as seen from *PISCES IV* in the scour mark troughs of the new "Caroline" and "Big Makk" scour marks, Saglek Bank and Makkovik Bank respectively. Lateral field of view about 3 m.


RIDGE
RIDGE
COBBLE AT
START OF RIDGE
DISSOLUTION PIT
WITH BOULDER AND
COBBLES RESTING
ON BOTTOM

RIDGE

RIDGE

RIDGE

'RAGGED'-APPEARING RIDGE

INFERRED MOVEMENT DIRECTION OF SCOURING ICEBERG

2m

KEY

Lumps of sediment

Cobbles and boulders

Edge of dissolution cavity - long and short arrows indicate deep and shallow cavities respectively.

Ridge and groove Microtopography and striations defined/approximate

Slope with relief <20cm

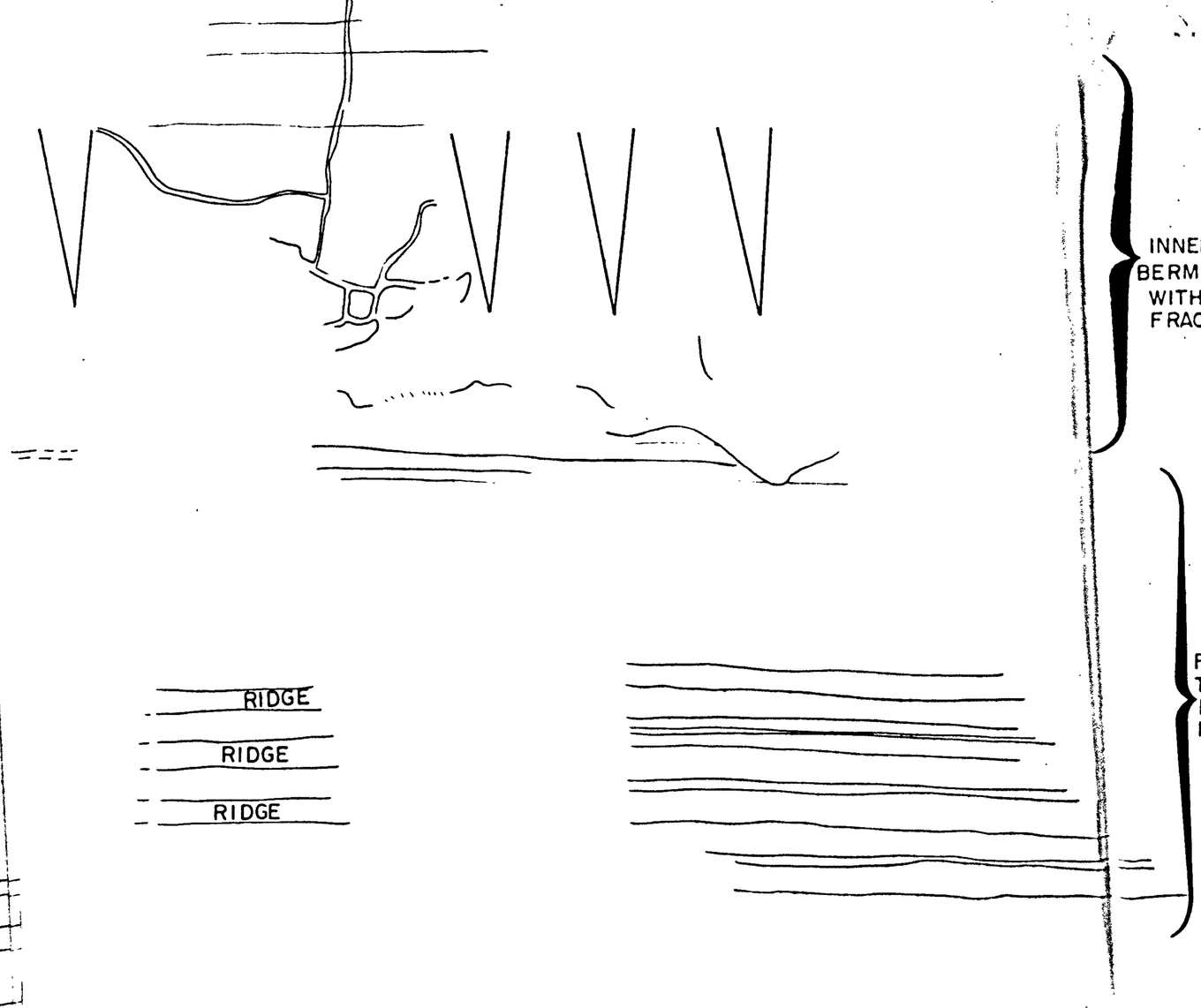
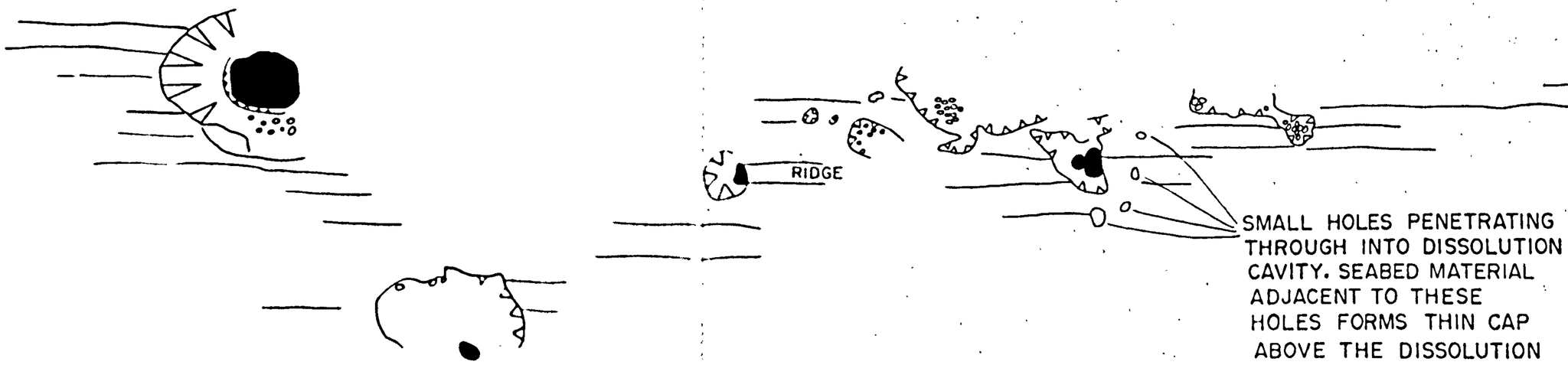


Figure 10a. Map of ridge-and-groove microtopography and fractures on inner berm flank from the new "Caroline" scour mark, Saglek Bank. Drawn from video playback.


RIDGE
SMALL HOLES PENETRATING THROUGH INTO DISSOLUTION CAVITY. SEABED MATERIAL ADJACENT TO THESE HOLES FORMS THIN CAP ABOVE THE DISSOLUTION CAVITY.

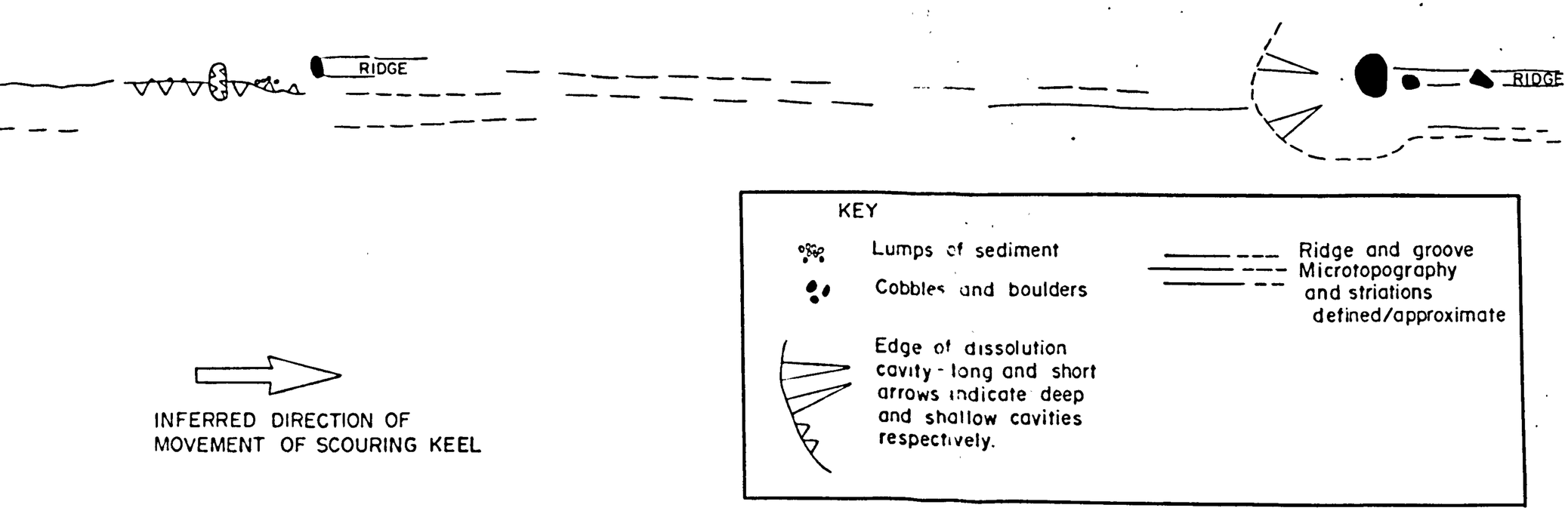


Figure 10b. Map of ridge-and-groove microtopography and fractures on inner berm flan from the new "Caroline" scour mark, Saglek Bank. Drawn from video playback.

are characteristically smaller scale than ridges and grooves in the scour mark trough. In a small area in one of the impact marks made by iceberg "Bertha" ridges and grooves were developed as two discordant sets almost at right angles. Although the dominant set can be related to the movement direction of iceberg "Bertha", the other cannot.

Embedded ice and voids

In the floor of the grounding pit made by iceberg "Bertha" (Table 1) a partially buried boulder, rimmed by iceberg ice, was observed from *PISCES IV* (Figure 11). The iceberg had moved off two weeks previously, illustrating how ice, which is buoyant, can remain trapped in seabed sediment.

Subsequent to this discovery small voids, up to 1 m deep and 2 m wide, were occasionally found in other scour mark troughs. The irregular-sided features interrupt ridge-and-groove microtopography that may partially cap some voids as delicate overhangs around the edges. Boulders and cobbles are commonly found resting on, but not embedded in, void floors.

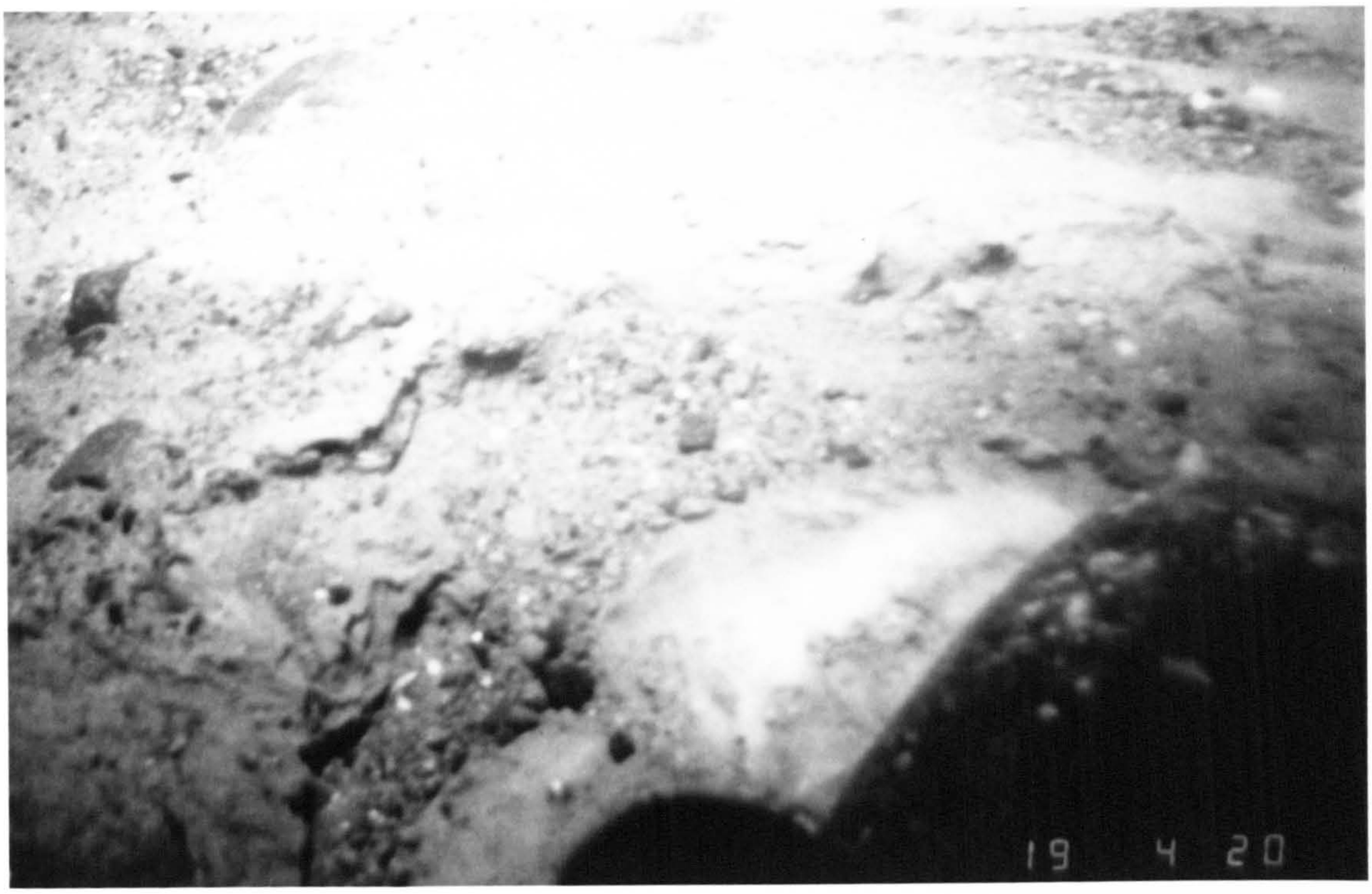


Figure 11. Boulder (dark mass, bottom right), rimmed by ice, in seafloor sediments in the grounding pit made by iceberg "Bertha" on Makkovik Bank. Water depth 107 m. Lateral field of view about 3 m.

Flat-topped mounds

Irregularly-shaped flat-topped mounds, ranging in height from 0.5-0.75 m, were observed from *PISCES IV* in low areas below the general level of the trough surface in "Big Makk" and are clearly defined on the 100 kHz sidescan sonograph of the scour mark (Figure 5). Ridge and groove microtopography is developed on the flat mound surfaces. In the low area the seabed, upon which the mounds are located, is characterized by concentrations of undisturbed gravel and shell debris, similar to undisturbed seabed immediately outside the scour mark (Figure 12).

Features at the scour mark margins

Berms

A mixture of consolidated cohesive and unconsolidated sediments form berm ridges on either side of the scour mark, rising from as little as a few centimetres to as much as 6 m above the undisturbed seabed. Berm height is often variable ranging, in one instance (asymmetric scour mark, western Makkovik Bank), from 1 m to 6 m over a distance of only a few metres along the berm crest. Berm width may vary from 0 m to 20 m. The asymmetric scour mark was remarkable in that there was no berm on the upslope side of the scour mark. Berm slopes may reach angles as steep as 45°.

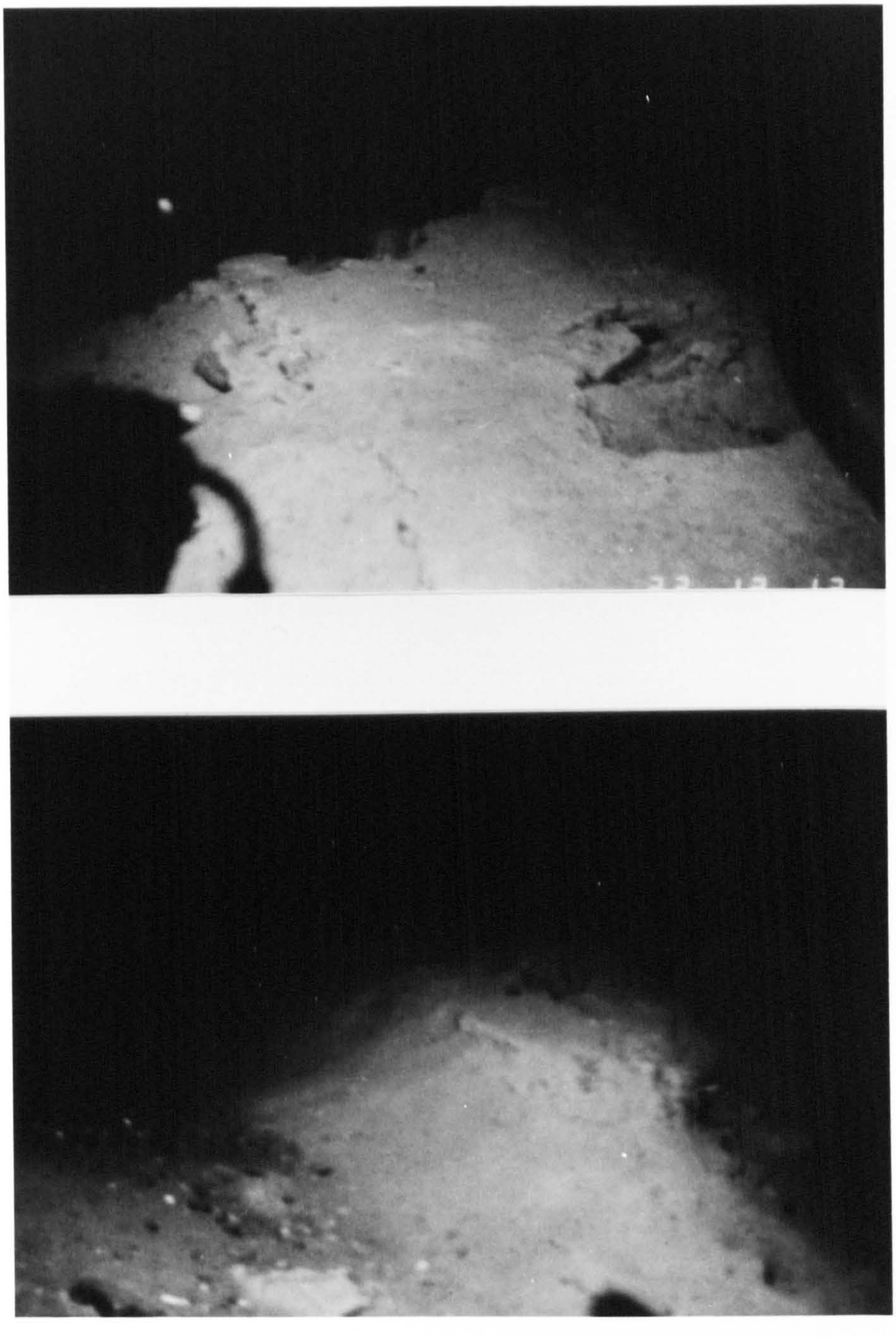


Figure 12a. Flat-topped mounds in the trough of "Big Makk" as they appear from *PISCES IV*, transition from scour mark trough (foreground) to topographically lower region of undisturbed seafloor beyond.
b. a typical isolated mound resting on undisturbed seabed. Lateral field of view about 3 m.

Inner berm flanks generally have low amplitude (less than 5 cm relief) ridge-and-groove microtopography developed on the concave slopes that rise up from the scour mark trough. In places the relatively smooth surface is disrupted by a network of open tension fractures (Figure 13a) ranging from <1 cm to about 20 cm wide. Normal, reverse or strike slip offset is not observed between the cracks. Where they are exposed the vertical crack surfaces display radial and columnar fracture patterns (Figure 13b). Micro-cracks may ramify the sediment in the inner berm region. Such a network was revealed during attempts to sample berm material in the new "Caroline" scour mark with the *PISCES IV* manipulator arm. Pushing small corers into the sediment caused sudden expulsion of fine material into the water column along the micro-cracks.

Approaching the berm crest the open fractures widen, separating discrete blocks of sediment. No longer constrained by adjacent material these blocks may collapse towards the outer berm slope creating spectacularly chaotic topography (Figure 14). In this region some vertical and horizontal offset is apparent. The tops of the blocks are usually faintly striated. The transition from berm crest to outer berm slope may be abrupt where large blocks are not present (Figure 15).

Outer berm slopes consist of small (5-50 cm wide) disaggregated angular blocks and rounded lumps of cohesive material, some of which are clearly derived from disintegration of the large fractured blocks along the berm crest. The small blocks rest on or are partially buried in loose, unconsolidated sediment that characterizes the outer slope. Isolated

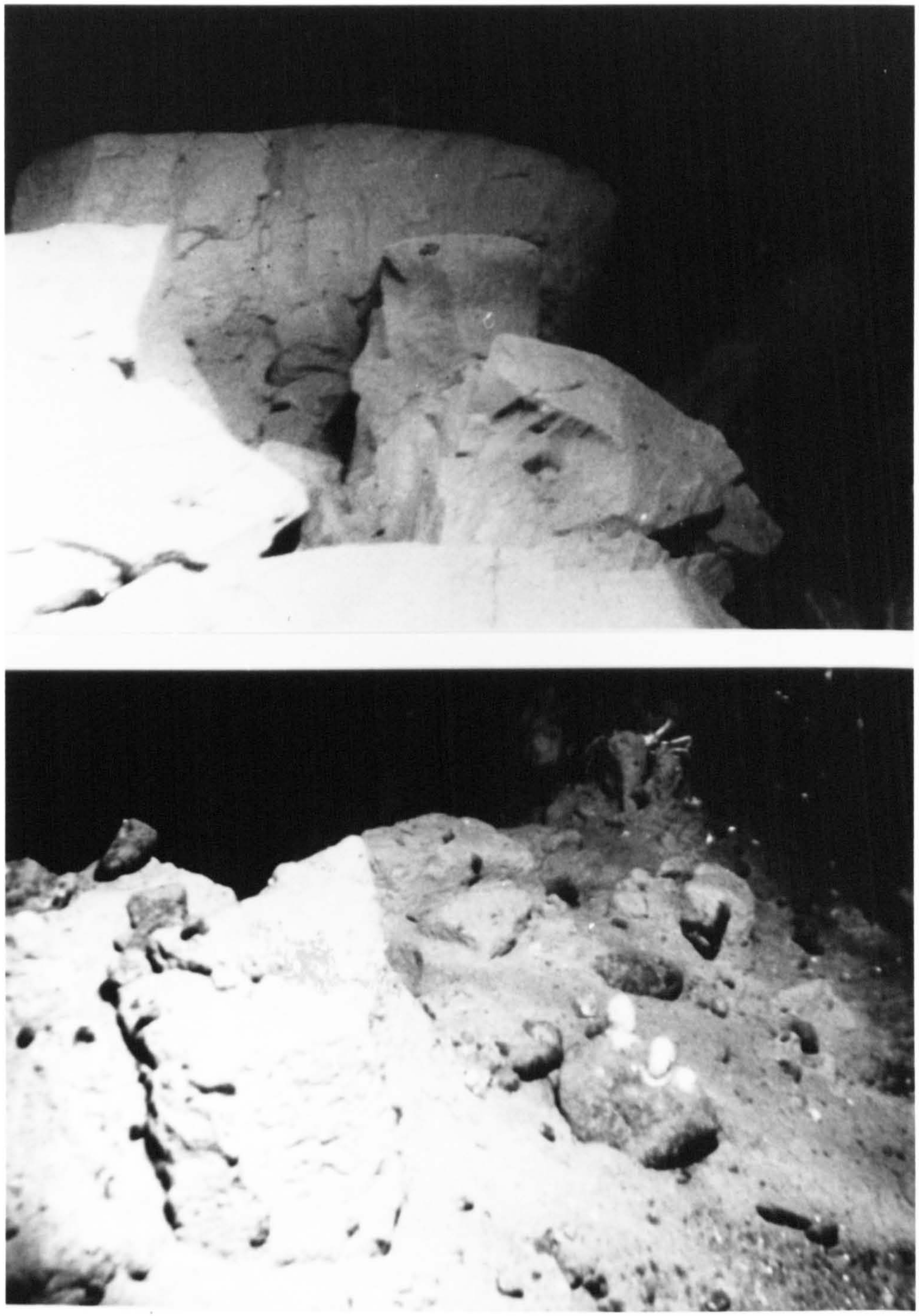


Figure 14a. View of fractured, consolidated blocks of sediment at the berm crest of the new "Caroline" scour mark, Saglek Bank. Individual blocks rise about 1 m above the general level of the berm. Lateral field of view about 3 m.
b. Partially degraded cohesive sediment blocks on the berm of "Big Makk", Makkovik Bank. Lateral field of view about 3 m.

Figure 15. Abrupt inner berm (right)/outer berm (left) transition. Large fractured blocks are not present in this region of the new "Caroline" scour mark berm. Small blocks resting on the loose outer berm slope material probably spalled from the cohesive inner berm at the transition. Lateral field of view about 3 m.

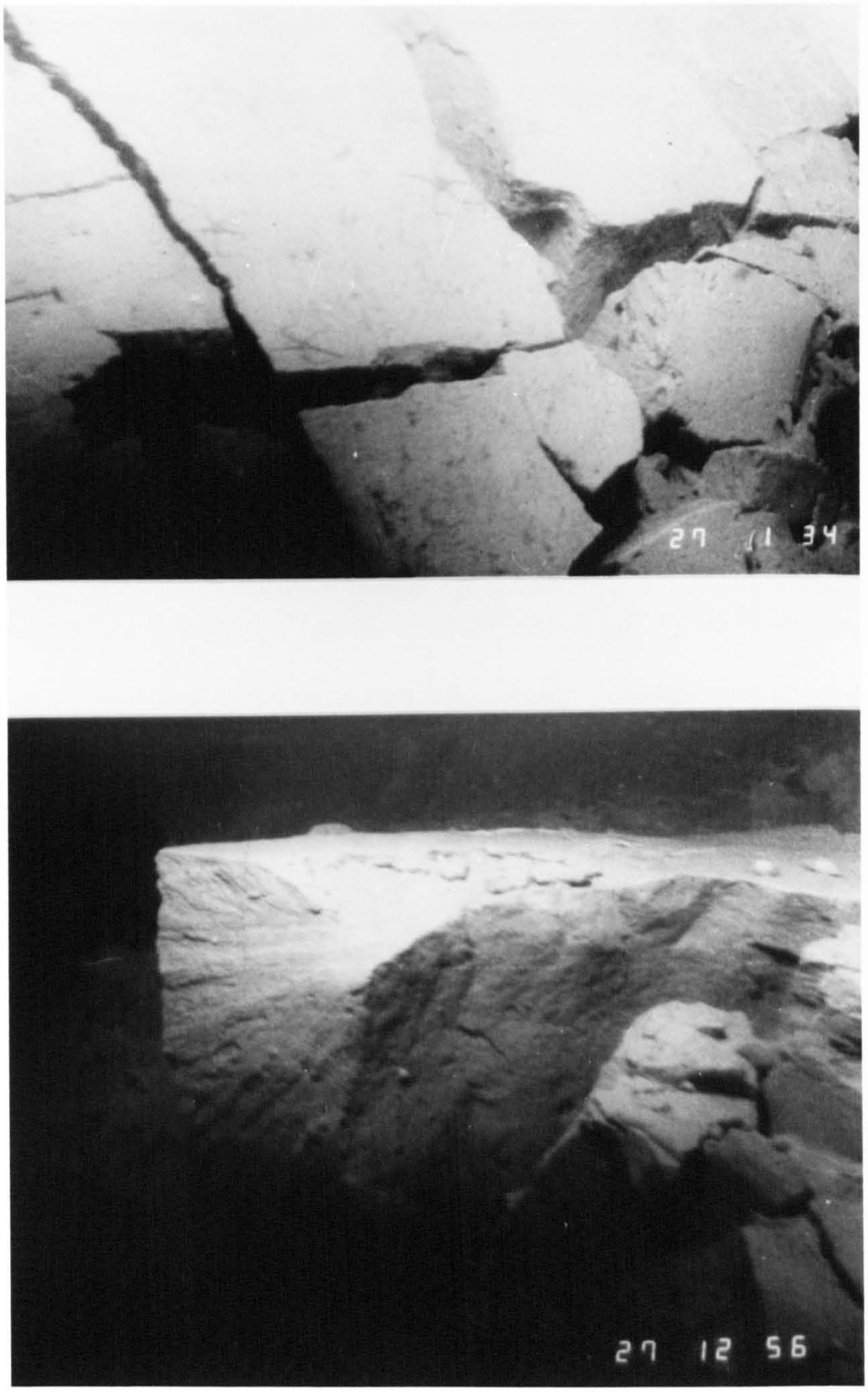


Figure 13a. Network of open fractures on the lower inner berm flank, new "Caroline" scour mark, Saglek Bank. Lateral field of view about 3 m.
b. Radial fracture pattern on a crack surface on the berm of the new "Caroline" scour mark, Saglek Bank. Lateral field of view about 3 m.

mounds or sub-angular blocks, 1-2 m^3 in volume, are occasionally found resting on undisturbed seafloor immediately beyond the lower berm slope. These appear to have originated from some point on the berm.

Surcharge

"Big Makk" was a complete, short scour mark (315 m long), that provided a rare opportunity to observe the intact surcharge of sediment piled up in front of the scouring keel. The surcharge pile, rising to 3.5 m above the seabed, was characterized by steep (30°) inner and outer slopes of lumpy, unconsolidated sediment. The top of the pile was rough and undulatory. Blocks of sediment, as seen in the berms, were nowhere evident.

Summary description

A typical new iceberg scour mark from the Labrador shelf consists of an essentially flat-bottomed trough incised up to 2 m into seafloor sediments. The trough between the two berms is characterized by scour mark-parallel ridge-and-groove microtopography. On inner berm flanks ridges and grooves may be at discordant angles to the scour mark trough. Irregular, small voids are found occasionally in the scour mark trough, and are the result of melting or dissolution of pieces of iceberg ice embedded in the seafloor. Coarse clastic

debris in the bottom of the voids was probably introduced with the ice. Flat-topped mounds may occur in areas of negative relief below the depth of keel penetration. Seabed between the mounds may be unaffected by scouring.

Cracks may be observed on the inner berm flanks. Cracks widen towards the berm crest separating free-standing, straight-sided vertical or tilted blocks of consolidated sediment that create irregular berm topography. Outer berm slopes consist of unconsolidated sediments containing small, angular blocks of cohesive material derived from partial collapse of larger blocks along the berm crest. Blocks or irregular mounds of sediment may occur resting on undisturbed seabed beyond the outer berm slopes.

Surcharge, developed in front of the scouring keel, consists of unconsolidated sediment with irregular hummocky topography. Cohesive sediment blocks are not associated with the surcharge.

Scouring processes

The descriptions given above are compiled from observations of five new scour marks studied during the DIGS experiment. Individual scour marks will not necessarily display all of the features, and some features are unique to specific scour marks. Bearing in mind that the amount of observational data are limited it is possible that elements described as unique

may occur in other new scour marks.

All of the elements are incorporated in a geological process model for the surface morphology of new scour marks. From the model inferences are made about the interactive processes of seabed and iceberg modification, and about iceberg stability during the scouring process.

Geological model of scouring

Likely mechanisms, affecting both iceberg and seabed, that create the features described from new iceberg scour marks are discussed. Prediction of the types of features that will be produced and the formative mechanisms that are to be expected during scour are implicit in the model.

Likely scouring mechanisms

Keel flattening

The scouring keel of an iceberg exerts both vertical and horizontal forces on the seabed (e.g. Lever, 1986). If seabed sediments are weaker than the scouring keel these

forces result in vertical penetration of the keel and horizontal and vertical components of displacement of seafloor sediments as the iceberg moves forward. In steady state scouring a characteristically curvilinear trough of relatively uniform depth is excavated on the seafloor.

The flatness of the scour mark troughs indicates that the scouring keel must also have been flat. Given the irregular three-dimensional geometries unique to each iceberg, and the random probability that any portion of the iceberg may, by unstable rolling, become a seabed-touching keel, it is unlikely that every keel will be fortuitously flat in the plane of the seafloor at the instant of contact. Instead it is likely that the processes of ice/seabed interaction modify the shape of the scouring keel until an equilibrium condition is reached, presumably when keel penetration stabilizes at a depth where keel modification ceases. The flat bottom of the asymmetric scour mark that conforms to the seabed slope on western Makkovik Bank suggests additionally that the attitude of the flattened keel may develop as a function of seabed slope.

Keel modification was demonstrated by observation of an overturned iceberg (see Figure 7). In this example of an iceberg keel interpreted to have been in seabed contact, the smooth ice slopes around the keel are truncated at the margin of the debris-laden surface, suggesting the former presence of ice in the region above the flat surface.

Further evidence of keel modification comes from the underwater calving event of

iceberg "Gladys" that released sediment-impregnated growlers interpreted to have originated from the edge of the grounded keel. In this instance the growlers are evidence that ice is removed from the keel by fracturing and break-off of blocks. Fracturing is clearly seen in the overturned iceberg (see Figure 7), and from this photograph it is easy to envisage blocks breaking off around the edge of the keel. Thin sections of ice from the "Gladys" keel reveal a two stage sequence of events (see Figure 8): 1) initial brittle fracturing and cracking and simultaneous injection of fine-grained sediment along the cracks as the iceberg strikes the seabed (this phase probably results in the generation of blocks of ice that may subsequently break out of the keel) followed by 2) dynamic recrystallization of the large glacial ice grains resulting in the development of domains of small, polygonal grains as a result of continued loading experienced by the grounded keel. Fine-grained sediment is incorporated between grain boundaries. Cracks are not formed during this phase.

Although the comparative morphology and dimensions of scour marks recorded on sidescan sonographs and high resolution seismic profiles may differ widely from each other, individually scour marks usually display relatively constant width, depth and morphology. The limited variance in shape and dimensions of individual scour marks reflects keel/seabed equilibrium suggesting that, in relative terms at least, the keel-flattening process is rapid and occurs near the start of the scour mark. Additional evidence for rapid keel flattening may be present at the "Big Makk" scour mark. The direction of iceberg movement is interpreted to have been towards the northeast from the existence of a surcharge mound at that end (Figure 5), and a smooth, sloping ramp at the southwest end of the 315 m long scour mark.

In order to generate a flat surface at the lead-in portion of the scour mark the keel must have either been coincidentally flat in the plane of the seafloor or, as the more likely postulate, the keel was flattened during the initial interaction. This being so, the flattening process must have occurred rapidly.

Based on analyses of iceberg drift tracks along the Labrador coast it is reasonable to assume that the average drift velocity of the iceberg that formed "Big Makk" may have been in the vicinity of 0.56 m/s (1.1 knots) (e.g Ball *et al.* 1981) and assuming that its keel was of similar length to its width (50 m as measured from the width of "Big Makk") then the amount of time taken for the longest part of the keel to pass over a single spot on the seabed would be about 90 s. If these conditions are valid then during this time the keel would have to have developed a flat base in order to create a flat lead-in ramp.

After initial rapid keel modification steady-state scouring occurs. Width and depth remain constant during this period and the keel undergoes only minor modification: this is exemplified by the sporadic occurrence of small dissolution pits that indicate breakout of relatively minor ice volumes (up to about 2 m^3).

Formation of ridge-and-groove microtopography

The ridges and grooves developed within the scour mark trough clearly result from

the sculpturing of sediment by irregularities in the scouring keel. Although the entire flattened surface of a scouring keel is probably in contact with the seabed, it is the relief of the trailing edge that generates the ridges and grooves. Relief of ridges and grooves directly mirrors the irregularities in the trailing edge of the keel. Irregularities of similar magnitude probably characterize the entire surface of the scouring keel (as exemplified in Figure 7) and, as it moves over the seabed, sediment adjacent to the keel is moulded and remoulded before it is finally shaped at the trailing edge.

During and after initial touchdown ice in the keel is fractured and crushed, and fine sediment is entrained (see above). If gravelly to bouldery clastic material is present on the seafloor it may be incorporated mechanically in the regelating ice and held at the surface of the scouring keel (see Figure 7). Clastic debris and fractured ice are thus the most likely factors creating keel topography, and which thus generate ridge-and-groove microtopography. Boulders are occasionally released onto the seabed at the trailing edge. When this happens a void is created in the keel at the site of the boulder, into which sediment may be forced from the underlying seabed. If the keel void remains stable and there is sufficient sediment supply to fill it as the iceberg moves forward, a ridge will be developed. Boulders at the beginnings of ridges thus mark the point of ridge initiation and indicate the direction of iceberg movement. If there is insufficient sediment supply to completely fill the voids and ice fissures the resultant ridges will be incomplete and may appear "ragged". New cracks may open and close in the keel and boulders, embedded in the ice, may rotate or break out because of continued fracturing, dynamic recrystallization,

and possibly pressure melting. These dynamic processes are reflected by gradual changes in the morphology and relief of ridges and grooves as they are traced along the scour mark.

Ridges and grooves within the main portion of the scour mark trough are nearly always parallel to the axis of the scour mark reflecting the rotational stability of the scouring iceberg about a vertical axis. This observation supports the inferred dynamic behaviour of a scouring iceberg which is that the iceberg yaws so that roll occurs about its weakest axis of rotation (Hodgson *et al.* 1988). Once this condition is achieved, vertical rotations cease (e.g. Woodworth-Lynas *et al.* 1985). This aspect of iceberg motion is discussed in Chapter 4.

Formation of voids

Blocks of ice may be formed by fracturing and, if at a free surface, such as at the margin of the keel (see Figure 7), may break off and float free (for example, the growlers calved from iceberg "Gladys"). The unusual ridges and grooves that were at 90° to the dominant movement-related set in one of the impact marks made by iceberg "Bertha" is possible evidence of the failure of a block of ice that was displaced outwards at a high angle from beneath the keel. Blocks that break out beneath the keel are prevented from floating and will be overridden and driven into the seabed by the iceberg. Because these blocks originate from the scouring surface of the keel they may contain boulders and cobbles

incorporated earlier; they may also contain original englacial clasts from the parent glacier. Subsequent melting or dissolution of the embedded ice blocks results in the formation of voids.

Formation of flat-topped mounds

As a scouring iceberg moves over an undulatory seabed (such as one affected by older scour marks) it is possible for the iceberg to pass over open depressions that are below the penetration depth of the keel. As the iceberg approaches, material from the leading edge surcharge is bulldozed into the depression ahead of the keel. The bulldozed material is subsequently overridden and reworked as the keel passes over it. In places where there has been incomplete filling of the depression, irregularly-shaped masses of sediment may be found resting on the old seabed that is exposed in the regions surrounding them. Sediment masses will have planar grooved surfaces, formed through direct contact with the flat keel, that will be at the same elevation as the rest of the scour mark trough (Figures 5 & 12).

Formation of berms and surcharge

There is little doubt that most of the material which forms the berms originates from the area below the seabed formerly occupied by the scouring keel. Horizontal translation of the keel through the seabed at velocities of about 0.5 m/s (see Keel flattening, this

chapter) causes most of the sediment to be displaced to the front and sides of the keel, as exemplified by the sediment surcharge piled up at the forward end of the "Big Makk" scour mark. Together with horizontal movement an upward component of displacement is implicit because the berms form positive relief. Depending on sediment type (in this case, generally muddy sands), cohesion, confining pressure and strain rate, sediment in front of the keel may behave initially as "rigid" slabs, decoupling from the seabed along failure planes, which are pushed radially away from the advancing keel. Slabs at the lateral margins of the keel may be displaced, intact, to the edge of the scour mark where their upper surfaces, having been in direct contact with the sediment-impregnated keel, form characteristically smooth, striated inner berm slopes (see Chapter 5 for discussion on sub-scour mechanisms and structures).

Cracks on the inner berm slopes perhaps develop as the result of stress release as sediment is expelled from beneath the edges of the keel. Alternatively shear between the moving keel and the sediment may cause cracking and tensional dilation. The deep-seated cracks are responsible for creating the often spectacular "blocky" berm topography.

Slabs in front of the keel are confined by surcharge material on either side and pushed further forward. As the keel continues forward new failure surfaces develop in seabed sediments in front of it. The older slabs are displaced upwards as new slabs, underneath, move forward and up, thereby generating a surcharge pile. As frontal slopes steepen the slabs begin to break up, possibly along tension cracks induced by components

of displacement to either side of the keel, and as the result of gravity-induced collapse, to form an apron of disaggregated material. Disaggregation processes may be so efficient as to cause almost complete comminution of previously consolidated sediment. This process may occur through a recycling mechanism where material at the top of the surcharge slope cascades down in front of the keel. Continued forward motion, that causes fresh sediment to be added beneath the surcharge pile, causes the passive movement of spalled material towards the top of the surcharge slope, where it will again cascade forwards and downwards. Such a "conveyor-belt" type of action may allow several episodes of recycling to occur before the material is eventually displaced to either side of the keel where it generates the outer berm slopes.

Sedimentological effects

Scouring icebergs probably lift sediment into suspension (see Chapter 5, King William Island where this is discussed in more detail). Fine-grained sediment may be winnowed away from the vicinity, aided by enhanced water velocity caused by current separation around the keel (e.g. Hodgson *et al.* 1988), and coarser material may settle within or adjacent to the trough. Also, scouring keels pick up seafloor sediments through mechanical embedding and freezing, and this material may be rafted beyond the immediate vicinity of scouring. The actual distance such scour-incorporated sediment is rafted may be less than for englacial material because it is held on the surface of the keel, and thus is more

susceptible to early meltout. Scouring-and-rafting may be the single most important factor affecting sediments on the Canadian eastern continental shelf. The seabed of this sediment-starved shelf (e.g. Piper, 1991) is annually exposed to iceberg-scour turbation and therefore to scouring-and-rafting, the latter process probably contributing to a net removal of sediment as material is rafted and redeposited seaward of the continental shelf edge. Scour mark troughs may serve as preferential depocentres (e.g. Barnes and Reimnitz, 1979) that enhances the preservation potential of scour marks, and may lead to the development of shoestring deposits.

Summary

From detailed analyses of five new iceberg scour marks a descriptive and mechanistic model of scour marks and the scouring process has been developed. The model is represented pictorially in Figure 15-1, and is summarized as follows:

1. As the keel of an iceberg contacts the seabed it penetrates seabed sediments. During this interaction the shape of the keel is modified resulting in flattening, in the plane fracturing and breaking off of blocks of ice and by dynamic recrystallization. Initial flattening may be rapid (possibly tens of seconds) involving the loss of significant volumes of ice. An equilibrium state is achieved when keel-modifying processes and the depth of seabed penetration are balanced. Equilibrium is reflected by maintenance of constant scour mark width and depth. Blocks of ice that break off at the margin of the keel may be

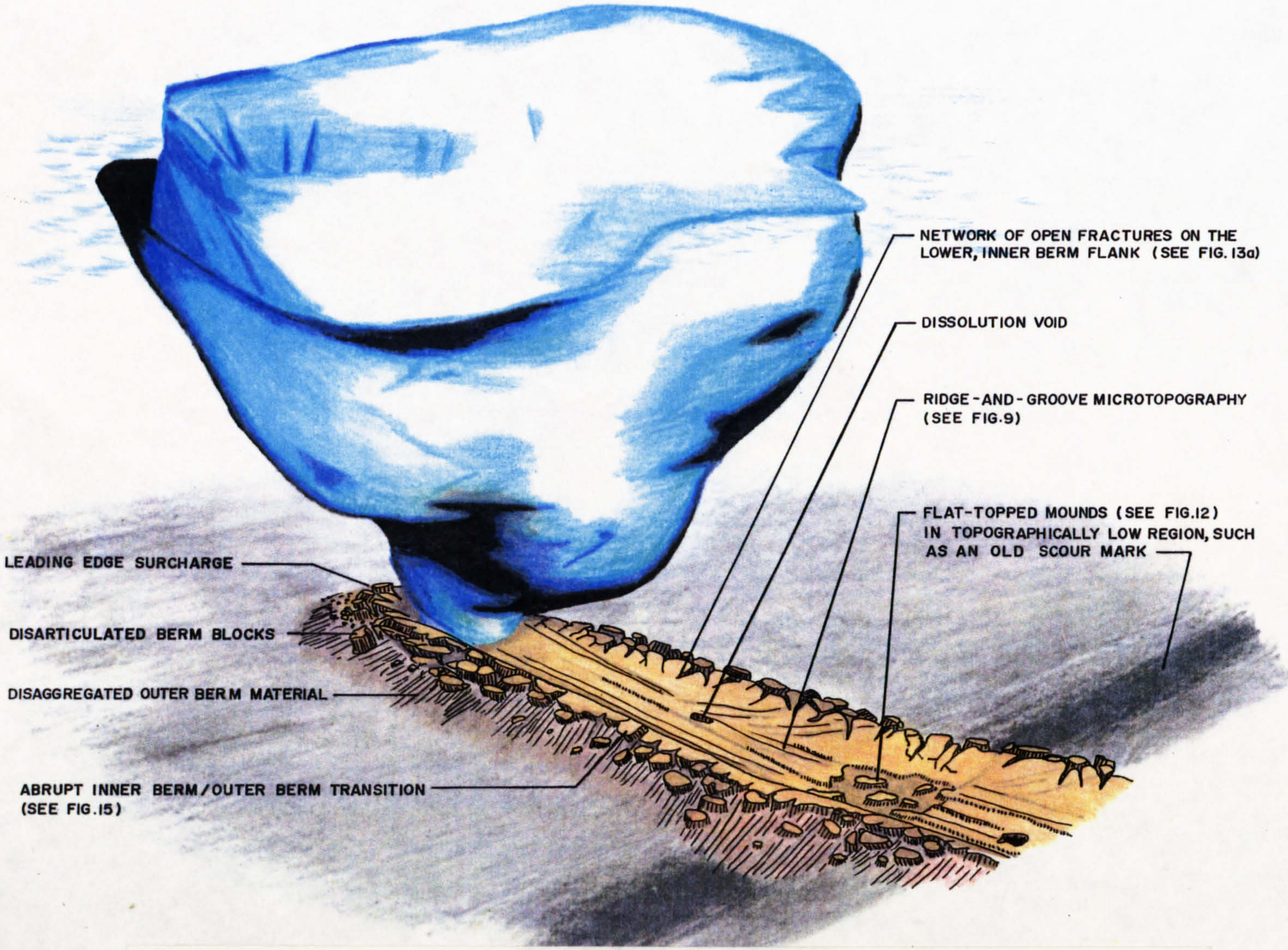


Figure 15-1. Summary diagram showing a typical scouring iceberg (actually based on a a 3-dimensional model of iceberg "Bertha") and features characteristic of a scour mark trough in fine-grained sediment. Typical water depth would be in the range 100-200 m, and the scour mark would be in the range 10-100 m wide and on the order of 1-2 m deep.

of the seabed, both by expelled and float to the surface. Blocks broken off beneath the keel may be driven into the seabed; after the scouring event melting or dissolution of these buried blocks of ice creates voids in the seabed sediments.

2. Ridge-and-groove microtopography in the scour mark trough is generated at the trailing edge of the keel by clastic material embedded in the ice and by direct contact with fractured ice. Following the breakout of boulders from the trailing edge of the keel, seabed sediment may be forced into the newly-created voids in the keel as the iceberg moves forward, initiating a ridge; boulders lodged at the start of ridges indicate the direction of iceberg movement. The area of the keel in contact with the seabed is impregnated with clastic material largely derived from interaction with the seabed. Some material may be englacial in origin. As the keel passes through the seabed subjacent sediment is moulded and remoulded before final shaping at the trailing edge. In linear scour marks ridges and grooves between the two berms are always parallel to the scour mark axis indicating rotational stability of the scouring iceberg about a vertical axis.

3. As the keel passes over minor depressions in the seabed that are lower than the depth of penetration, material derived from the surcharge pile may fill the sub-keel void. Incomplete filling results in topographically lower areas of undisturbed seabed within the scour mark trough that contain "lumps" of sediment, the upper surfaces of which are planed off through direct contact with the keel.

4. Cohesive sediment at the lateral margins of the keel is displaced to either side with both horizontal and vertical components of movement. As it emerges from beneath the keel, stress release in the sediment and shear stress between the keel and the sediment

may cause cracking and separation of the sediment into discrete blocks. Fractured sediment displaced to the berm crests may collapse under gravity generating a highly irregular "blocky" berm crestline. Sediment in front of the keel is recycled in a "conveyor-belt" type of action until the disaggregated material that results is displaced laterally to form the outer berm slopes and the substrate upon which sediment blocks, originating from the scour mark berms, are deposited.

CHAPTER 4

ICEBERG MOTION: A REVIEW

The aim of this chapter is to discuss the large and small scale general oceanic movement patterns of icebergs, and the motions associated with iceberg/seabed interactions. Icebergs are driven by oceanic currents, winds, waves and pack ice forces at velocities (for example in the Labrador Sea) generally between 0.25-1.0 m/s (e.g. Ball *et al.* 1981). Icebergs may move in any combination of six possible directions known as the six 'degrees-of-freedom'. These consist of the three translational motions of surge (forward and backward), heave (up and down), and sway (side to side), and the three rotational motions of pitch (forward and backward rotation), roll (from side to side), and yaw (swinging from left to right). All six motions are normally present in moving icebergs but usually only two or three dominate. In addition to these motions ocean waves may cause icebergs to bend. This flexural response is dependent on wave characteristics and iceberg size and shape, and can play an important role in the breakup of large tabular icebergs (Wadhams *et al.* 1983).

Patterns of free-floating movement

Most Arctic icebergs are produced from the calving margins of large outlet glaciers and ice fronts emerging at sea level around the coast of Greenland (Figure 16). In Baffin Bay icebergs are produced by smaller outlet glaciers on Baffin Island, Bylot Island, Devon

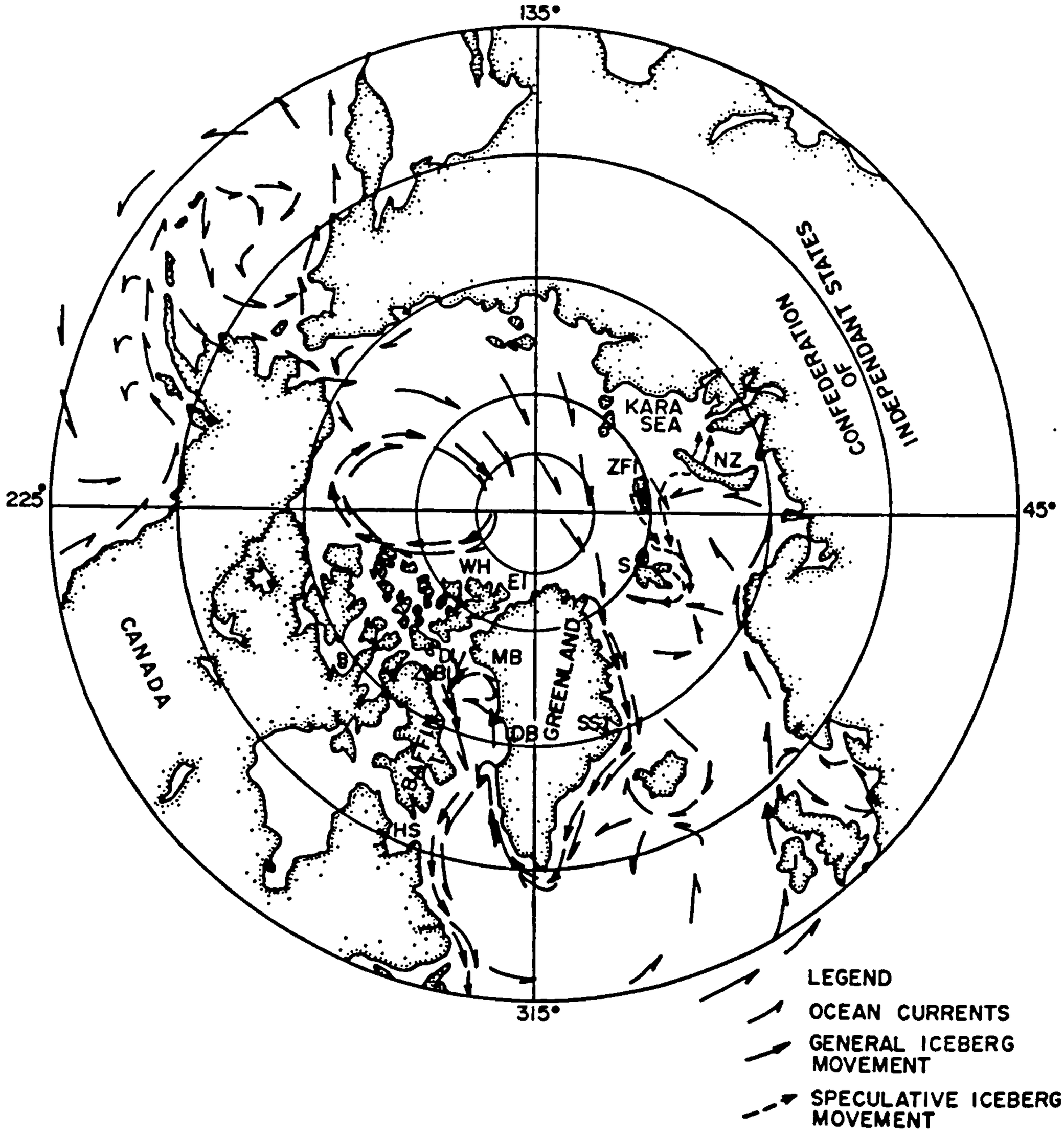


Figure 16. Map of the Arctic showing general iceberg circulation patterns and iceberg-calving areas. WH = Ward Hunt ice shelf; EI = Ellesmere Island; BI = Bylot Island; DI = Devon Island; MB = Melville Bay; DB = Disko Bay; SS = Scoresby Sund; S = Spitsbergen; ZFI = Zemlya Frantsa Iosifa (Franz Joseph Land); NZ = Novaya Zemlya.

Island and Ellesmere Island. Icebergs are also adrift in the Barents Sea where they calve from glaciers on the island groups of Zemlya Frantsa Iosifa (Franz Joseph Land), which is the most important source of icebergs in the Barents Sea (Zubov, 1945), Spitsbergen (Dowdeswell, 1989), and from the from the northern part of the island of Novaya Zemlya (Lepparanta, 1982). The largest icebergs (up to 700 ft. [220 m] thick) in the Russian Kara Sea originate from glaciers on Severnaya Zemlya (Kovacs, 1972). In the northwest Atlantic icebergs from Scoresby Sund on Greenland's east coast are carried southwest by the East Greenland Current, past Kap Farvel where they swing north, carried by the West Greenland Current. Most continue up into Baffin Bay picking up new icebergs from Disko Bay and Melville Bay before turning south and east in the Baffin Land Current. As they drift past southern Baffin Island some stragglers are added from the west Greenland Current that have been caught in a gyre and carried across Davis Strait to the Baffin Island coast. The icebergs pass Hudson Strait and continue southeast in the Labrador Current to the Grand Banks of Newfoundland where rapid melting destroys them as they enter warmer waters influenced by the Gulf Stream. Very occasionally an iceberg may penetrate into the north Atlantic and survive the warm, northeast-flowing Gulf Stream. Occasional sightings have been reported from as far away as Ireland (Figure 17).

Little is known about the movement patterns of icebergs in the Barents and Kara Seas. Those originating from Spitsbergen glaciers are smaller than the Greenland icebergs and if they survive the East Spitsbergen and Bear Island Currents that carry them south and west, they quickly disintegrate in the warmer north-flowing West Spitsbergen Current in the

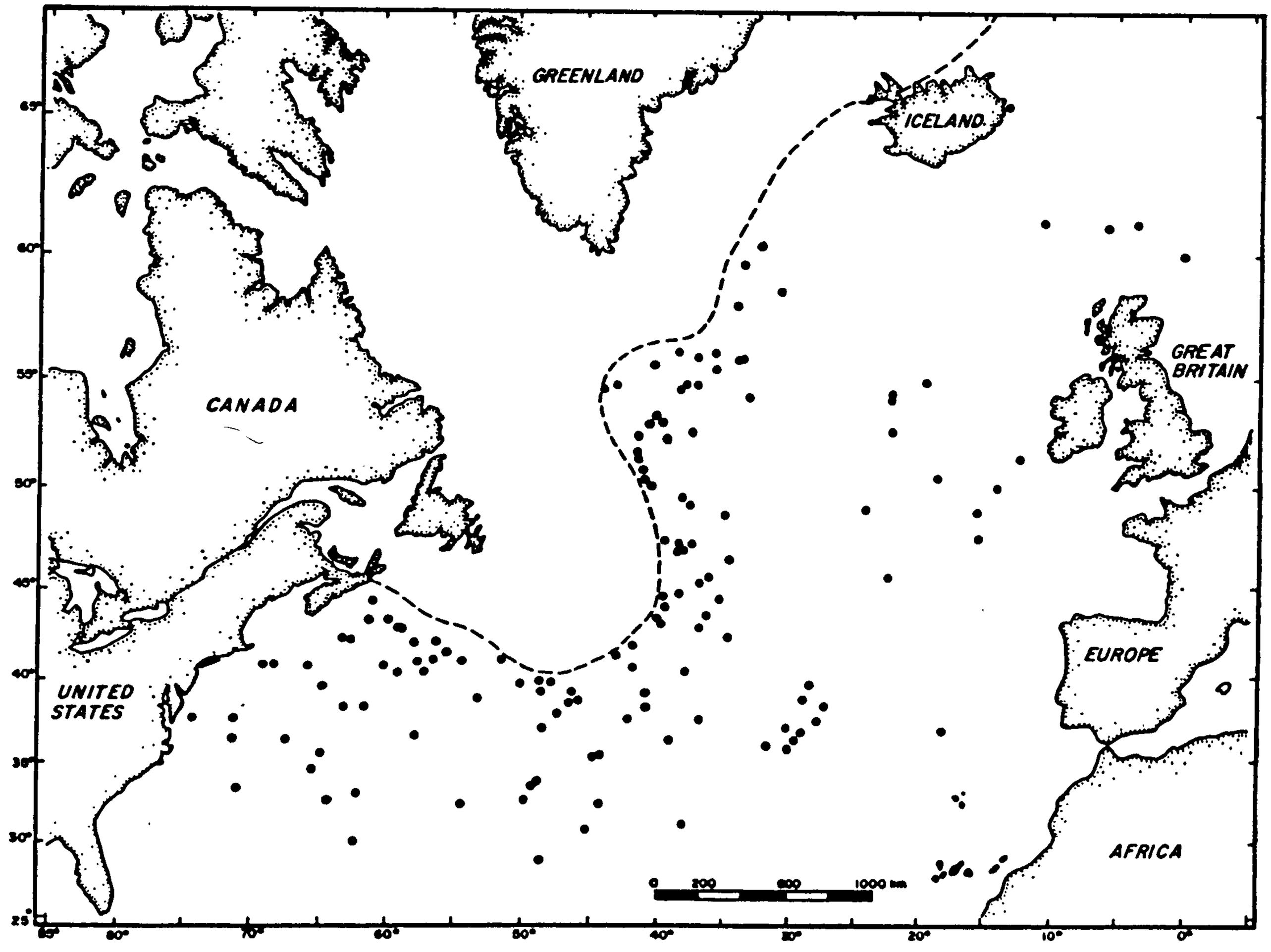


Figure 17. Map showing reports of unusual iceberg sightings in the North Atlantic. Dashed line is the maximum mean iceberg limit (adapted from Ketchen and Hildebrand, 1977).

Norwegian Sea (Figure 16). Less is known about the circulation adjacent to Zemlya Frantsa Iosifa and Severnaya Zemlya, although icebergs from both areas may be swept into Trans-Polar Drift in the Arctic basin: Zemlya Frantsa Iosifa is the largest producer of icebergs in the European/Russian Arctic, some exceeding 1 km in length (Dowdeswell, pers. comm., 1992, Scott Polar Research Institute).

Icebergs in the Antarctic generally have less convoluted drift patterns (Figure 18). Most icebergs calve from the enormous Ross, Ronne, Larsen and Amery ice shelves, and from a host of smaller ice shelves and tidewater glaciers that drain the Antarctic ice sheet. Once free from the grip of winter pack ice the majority of icebergs begin a slow easterly circumnavigation of the Antarctic continent, spiralling slowly northward and melting in the anticyclonic West Wind Drift of the Southern Ocean.

The tracks of individual icebergs are complex and often more convoluted than the general oceanic circulation pattern. Generally, icebergs that drift over relatively shallow continental shelf bank areas (< 300 m) are more strongly affected by diurnal and semi-diurnal tidal currents than by oceanic flow. In the northern hemisphere this results in often spectacular, regular clockwise spiral motions with radii of several kilometres (Figure 19). Icebergs in deeper water of the continental slope tend to have more linear motions, reflecting the trajectories of oceanic currents that drive them. Icebergs drifting immediately offshore of the continental shelf break of the Labrador Sea are often swept by contour currents into the north side of saddles; broad, deep (< 500 m) east-west-trending troughs

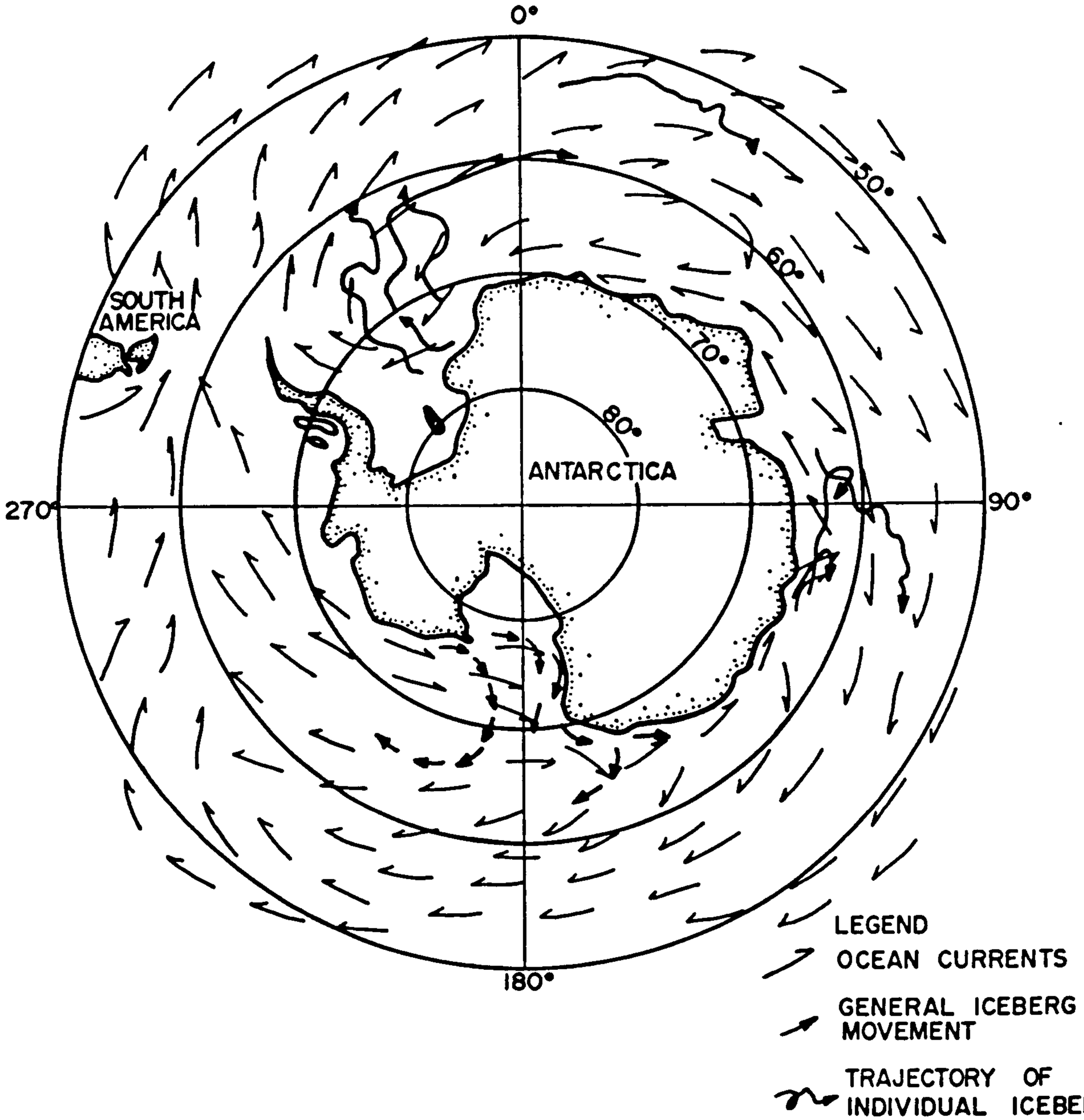


Figure 18. Map showing iceberg circulation patterns around Antarctica (base map courtesy of D. Benner, Navy/NOAA Joint Ice Center, 1992. Iceberg trajectories from Tchernia, 1977; Keys and Fowler, 1989; Vinje, 1980).

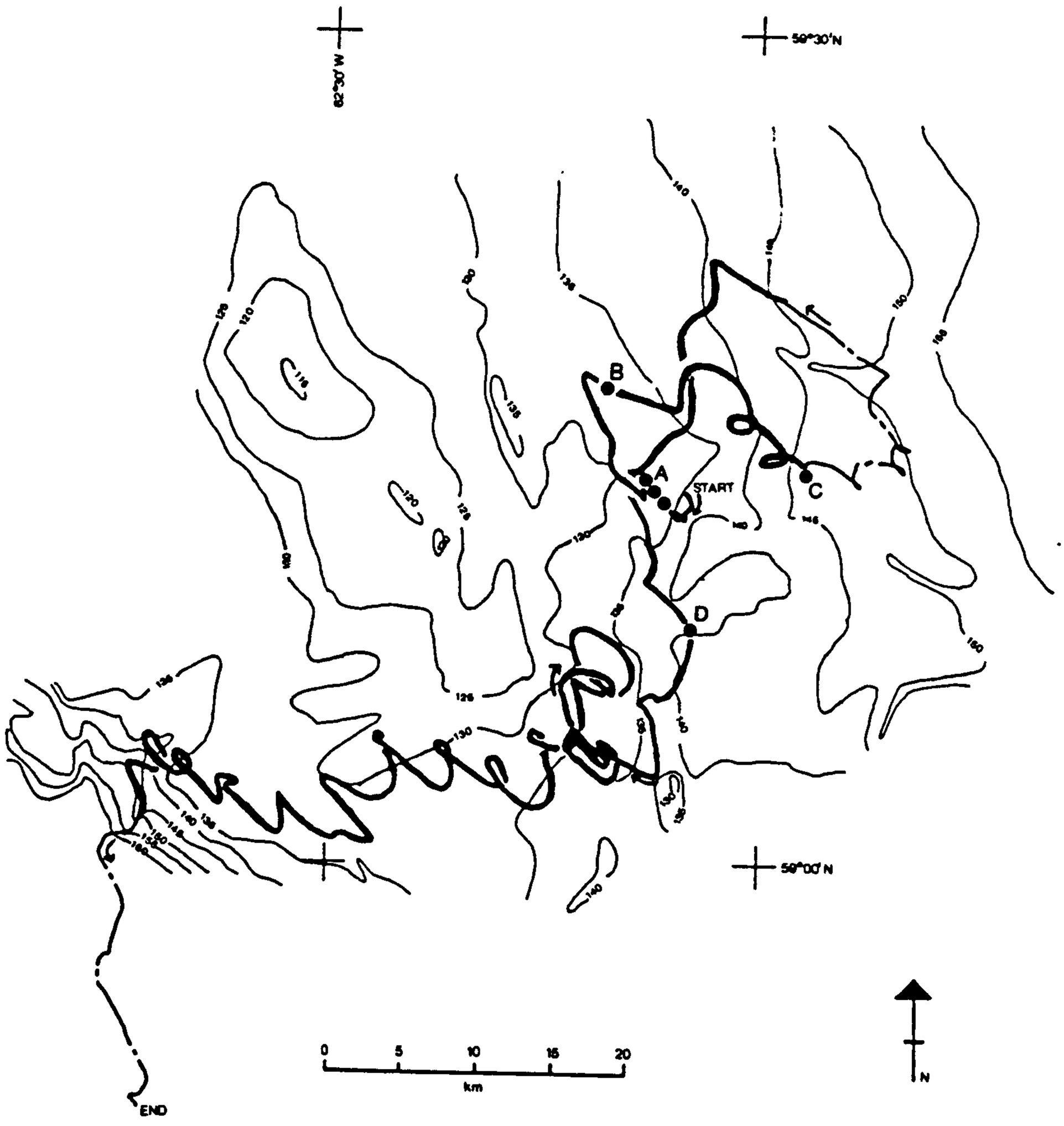


Figure 19. Clockwise spiral trajectory typical of icebergs affected by diurnal tidal motion, Labrador Sea.

that cut across the Labrador continental shelf separating bank areas. Once in a saddle, icebergs may move across it and be swept back out along the south side into the Labrador Current, or drift onto the shallow bank areas on either the north or south side. Dowdeswell *et al.* (1992) noted a similar counterclockwise circulation pattern at the mouth of Scoresby Sund where icebergs drift seaward preferentially on the southern side of the fjord. Cyclonic weather systems can significantly affect short term iceberg drift by causing wind-induced currents that disrupt the normal pattern (Dempster, 1974). Wind drag acting on the above water portion of large icebergs generally has little direct effect on the direction of movement. In the past, the ability of icebergs to move in directions opposite to prevailing winds has been used with advantage by the skippers of sailing ships who, when winds were unfavourable, would attempt to make fast to one moving in the right direction:

> *"..then with a good strong cable, and every bit of canvas tied up these icebergs would sometimes tow them at the rate of seven knots an hour dead to windward. It would be nothing strange to see as many as three vessels made fast to one.." Daily News (1912).*

In the Labrador Sea, most of the data from which short term movement patterns have been described were collected by ice observers using standard X-band marine radars on offshore drill ships since the early 1970's. Position data (range and bearing) were nominally collected once an hour from the radar screen and manually plotted on polar graphs. Above water dimensions and shape were recorded using a sextant and notebook sketches either from a standby rig-supply vessel, if the target was distant, or from the

deck of the drillship. These were supplemented by current meter and waverider buoy data and weather observations collected at the drillsite. Occasionally measurements of draft were made by rotating a vertically suspended modified sidescan towfish at increasing depths next to an iceberg until reflected signals ceased.

Position data have allowed the computation of iceberg velocity and acceleration, and when integrated with current, wave and wind information have provided sufficient information to allow hindcast prediction of iceberg trajectories (Ball *et al.* 1981; Banke and Smith, 1984). Accurate forecasting of iceberg trajectories is vital to the safe operation of offshore drilling rigs and their crews. With accurate foreknowledge, loss of drilling time can be minimized so that a rig costing tens of thousands of dollars per day to operate can remain on site rather than having to haul pipe and move off station "just in case". Significant progress has been made in forecasting, and a system that gives real time and forecast positions has been developed for eastern Canadian waters (El Tahan, 1991).

Movement during iceberg/seabed interaction

A drifting iceberg comes into contact with the seabed when draft exceeds water depth, and this may occur in one of three ways: (1) by drifting into progressively shallower water, (2) by weak rotational capsizing, caused by ablation and minor calving, to a deeper-draft orientation (e.g. Bass and Peters, 1984; Hodgson *et al.* 1988) or (3) by catastrophic

splitting that causes high-energy rotation of one or both fragments to a deeper-draft orientation (Hodgson *et al.* 1988; Lever *et al.* 1989). If the keel is strong enough to penetrate the seafloor an indentation will be made. This will normally be a curvilinear iceberg scour mark if the iceberg continues to move forward, or less commonly a pit if the iceberg ceases to move.

Scouring icebergs have forward velocities that are indistinguishable from free-floating velocities (Woodworth-Lynas *et al.* 1985) which makes the identification of both modes impossible in real time using radar. However, scouring icebergs can be identified from analysis of their radar trajectories by applying three simple interpretive criteria: (1) if an iceberg ceases to move for a period greater than a single tidal cycle (approximately 12 hours) it is grounded, (2) if a grounded iceberg resumes forward motion that carries it into shallower water or that carries it parallel to the isobath on which it grounded, it is scouring, and (3) if an iceberg whose draft is known moves into water depths shallower than its draft (without necessarily first grounding), it is scouring. These criteria were applied to iceberg radar trajectories obtained from the Labrador Sea (Figures 20, 21 & 22; Tables 2 & 3), and the movement patterns of icebergs interpreted to be scouring (Table 4) were, with one or two exceptions, indistinguishable from those of their free-floating companions (Woodworth-Lynas *et al.* 1985). Spiral scour mark tracks are rarely seen on sidescan sonographs because the area of coverage is generally too small to resolve more than a general curvature for single features. However Josenhans and Zevenhuizen (1990) described a large area of Hudson Bay characterized by arcuate relict scour marks that they tentatively interpreted as

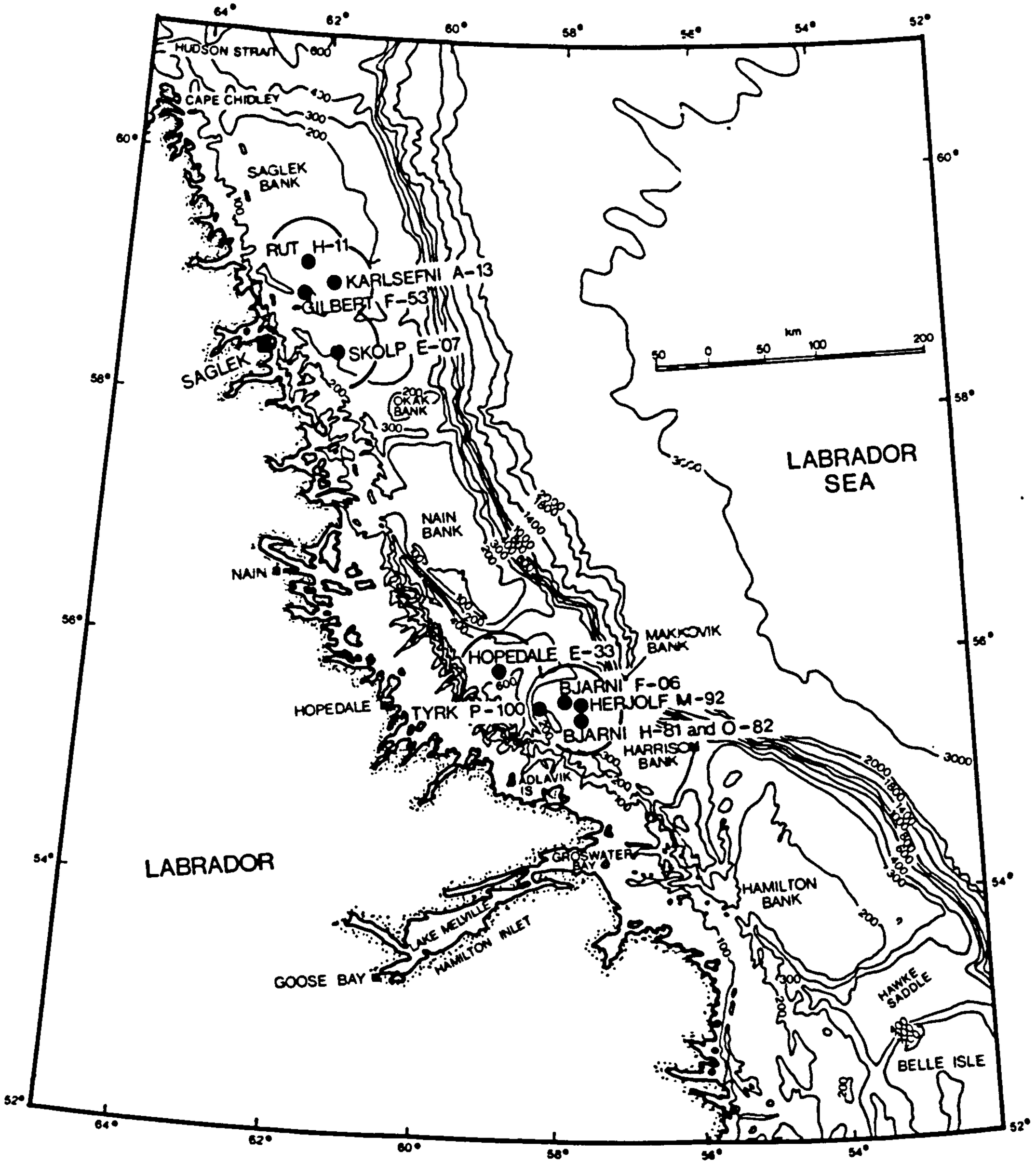


Figure 20. Map of Labrador Sea showing location of exploratory wellsites (dots) and range of radar coverage from each wellsite (circles) from which scouring iceberg trajectories were derived.

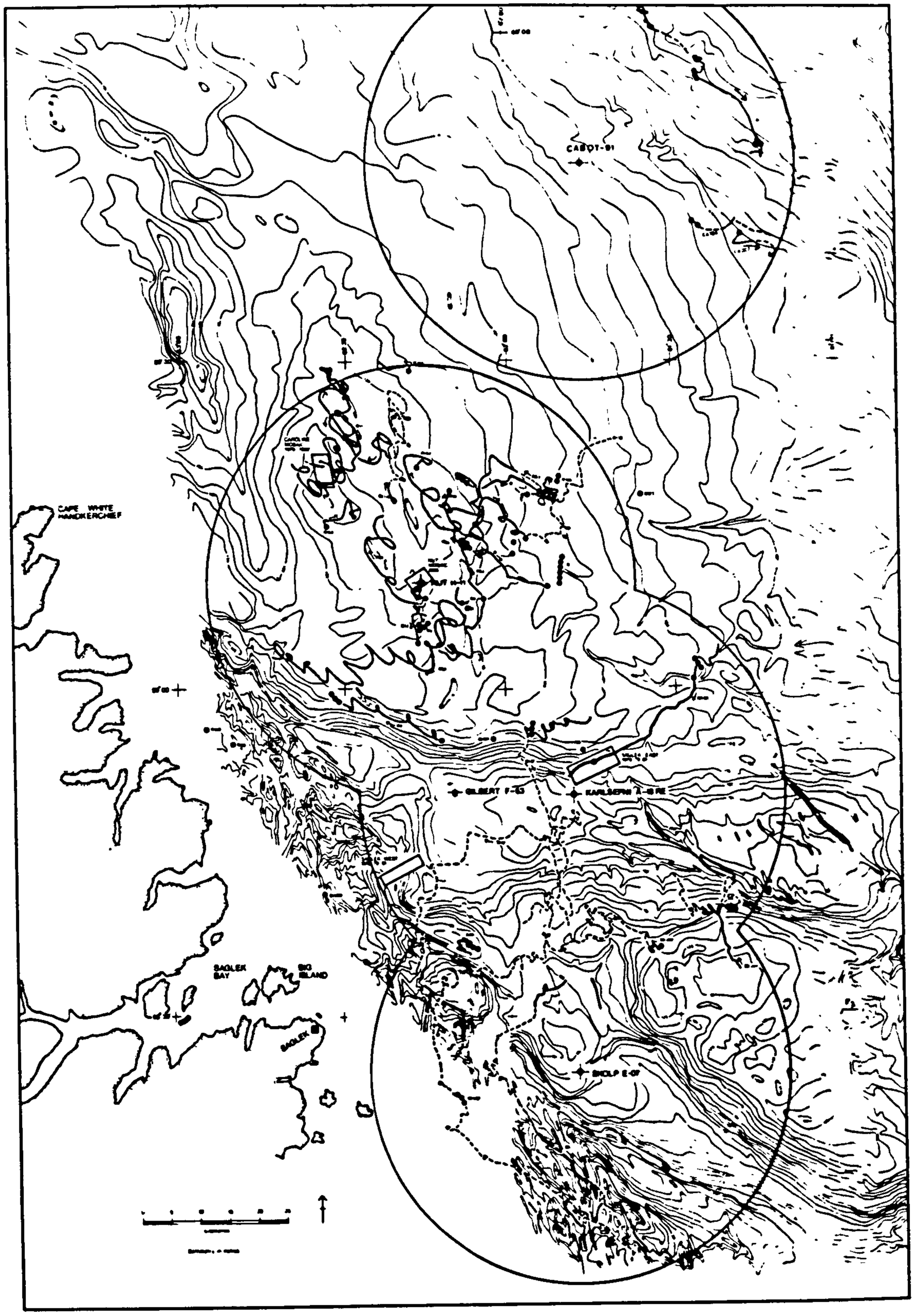


Figure 21. Bathymetric map of Saglek Bank, Labrador Sea, showing interpreted iceberg groundings (dots) and scour tracks (heavy black, meandering lines). Rectangular polygons show area of coverage of sidescan sonograph mosaics from which some of the scour mark width change data in Table 5 were measured.

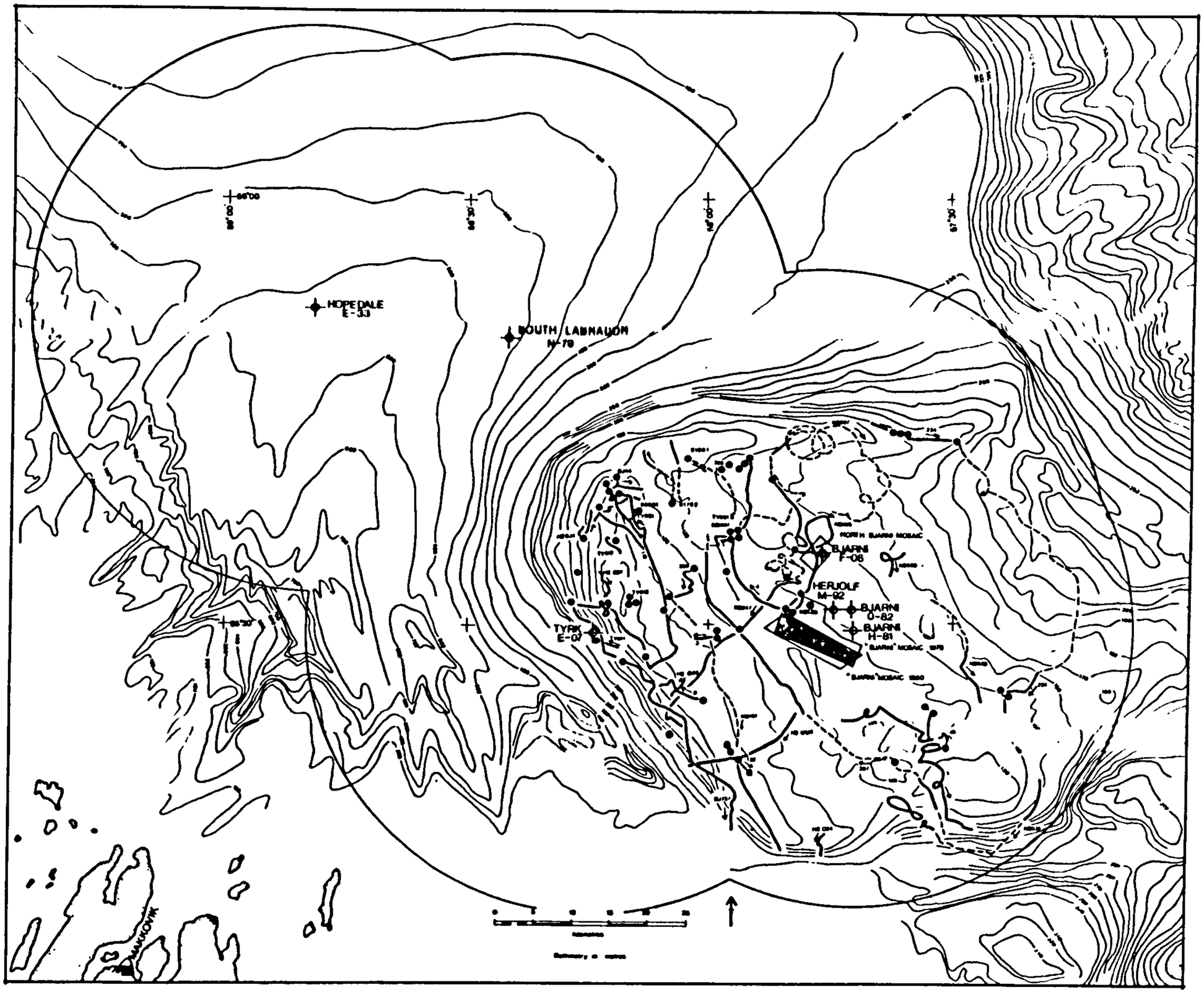


Figure 22. Bathymetric map of Makkovik Bank, Labrador Sea, showing interpreted iceberg groundings (dots) and scour tracks (heavy black, meandering lines). Rectangular polygons show area of coverage of sidescan sonograph mosaics from which some of the scour mark width change data in Table 5 were measured.

MAKKOVIK BANK OBSERVATION PERIODS

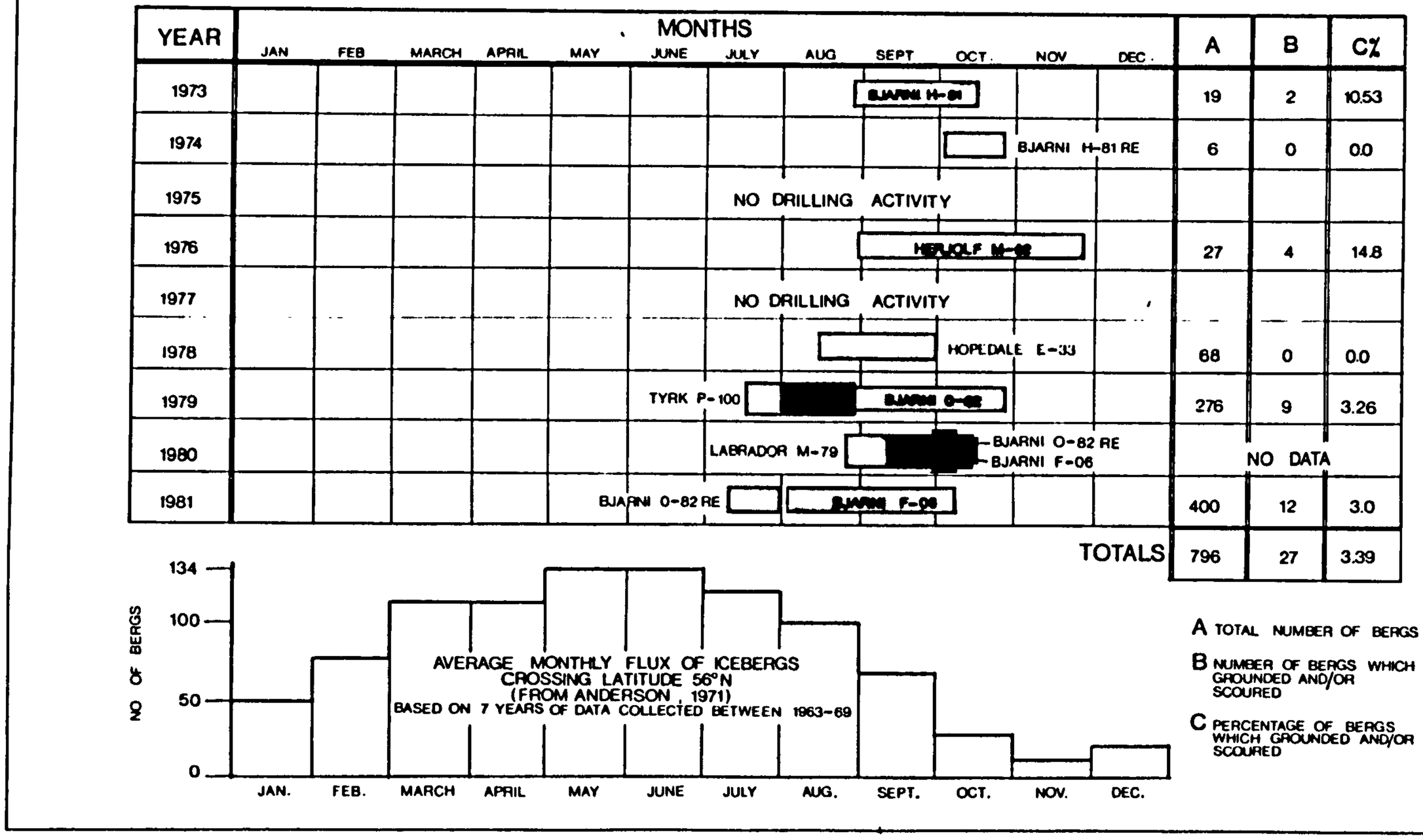


Table 2. Period of iceberg radar observations from wellsites on Makkovik Bank used in scour study.

SAGLEK BANK OBSERVATION PERIODS

YEAR	MONTHS	A	B	C%
1975	KARLSEFNI-A13	53	0	0.0
1976	CABOT G-91 / KARLSEFNI A-13 RE	30	1	3.3
1977	NO DRILLING ACTIVITY			
1978	SKOLP E-07	53	2	3.8
1979	GILBERT F-53	71	2	2.8
1980	GILBERT F-53 RE	50	2	4.0
1981	RUT H-11	193	16	8.3
	TOTALS	450	23	5.1

A TOTAL NUMBER OF BERGS

B NUMBER OF BERGS WHICH GROUNDED AND/OR SCOURED

C PERCENTAGE OF BERGS WHICH GROUNDED AND/OR SCOURED

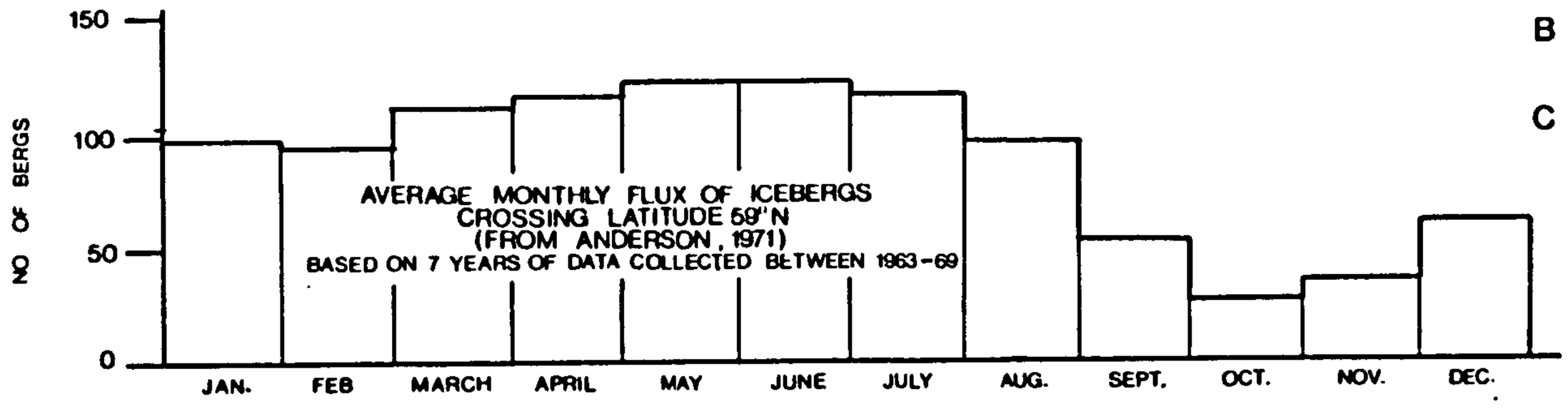


Table 3. Period of iceberg radar observations from wellsites on Saglek Bank used in scour study.

Table 4. Icebergs interpreted to have scoured upslope and downslope, from radar trajectory data

Saglek Bank

Number of scouring icebergs interpreted = 26
Number crossing isobaths = 20 (77%)

moved upslope	moved downslope	moved up/downslope	unknown (beyond bathymetric coverage)
2 (7.7%)	2 (7.7%)	16 (61.6%)	6 (23.1%)

Makkovik Bank

Number of scouring icebergs interpreted = 30
Number crossing isobaths = 23 (76.7%)

moved upslope	moved downslope	moved up/downslope	unknown (beyond bathymetric coverage)
5 (16.7%)	1 (3.3%)	17 (56.7%)	7 (23.3%)

the result of elliptical tidal circulation within the calving bay of a retreating ice margin. The width of the ellipses defined by individual scour marks ranges from about 750 m to 1.5 km (measured from Figure 8 of Josenhans and Zevenhuizen, *op. cit.*) that is considerably less than the diameter of the spiral radar trajectories of scouring icebergs on the Labrador continental shelf.

Rotations during upslope and downslope scour

Depending on the stability characteristics of a scouring iceberg as it moves upslope or downslope, it may accommodate changes in water depth and continue scouring by gradual, continuous rotation about a horizontal axis normal to the movement direction (pitching) (Woodworth-Lynas *et al.* 1985). Ridge-and-groove microtopography is always parallel to the scour mark berms, and is evidence that no rotation occurs about the vertical axis (yaw). If the iceberg is rotationally "stiff" (such as a tabular iceberg) and unable to reduce its draft as it scours upslope its keel will become more deeply incised until seabed resistance equalizes driving forces and the iceberg becomes grounded and ceases to move (e.g. Chari and Allen, 1972; Chari, 1979; Chari *et al.* 1980). These possible outcomes should be reflected by variations in scour mark morphology. Isobath-crossing scour marks made by rotationally "weak" icebergs might ideally maintain constant width and depth reflecting a stable balance between iceberg forces and seabed resistance. "Stiffer" scouring icebergs that move upslope may create scour marks which increase in depth. As incision depth

increases scour mark width should also increase because the keel (which is, up to a point, progressively thicker closer to the waterline) is pressed further into the seabed (Figure 23). The hypothesis of variation in scour mark morphology can be tested by an examination of scour mark width from slant range- and ship speed-corrected sidescan sonograph mosaics. Width is chosen over depth as the measured variable for several reasons: (1) depth measurements are obtained only at points where the survey vessel passes over the scour mark. Realistically only a few scour marks will be sampled for depth, and most scour marks will have only one depth measurement, (2) depth may vary along a scour mark trough as a function of the amount of post-scour sedimentation that masks the actual incision depth, (3) although it is possible to measure seabed relief from the acoustic shadows on sidescan sonographs, scour mark depth measurements are generally made from echograms or high resolution reflection seismic profiles. However, measurements from these types of record may underestimates scour mark depth because of "bowtie" acoustic artifacts caused by side echoes from the inner berm margins (e.g. Gilbert, 1990). The advantages of measuring scour mark width from slant range- and ship speed-corrected sidescan sonograph mosaics are: (1) it can be measured at several, regularly-spaced intervals along the entire visible length of a scour mark, (2) post-scour sedimentation or reworking generally will not affect width dimensions. For example, berm relief is generally propagated vertically as sediment accumulates over scour marks in the Beaufort Sea, although total relief continuously diminishes as post-scour sediments thicken. On the other hand, scour marks in the Labrador Sea generally are exposed to reworking by sediment-winnowing currents and bioturbation. The result of these these processes is the development of a coarse lag deposit,

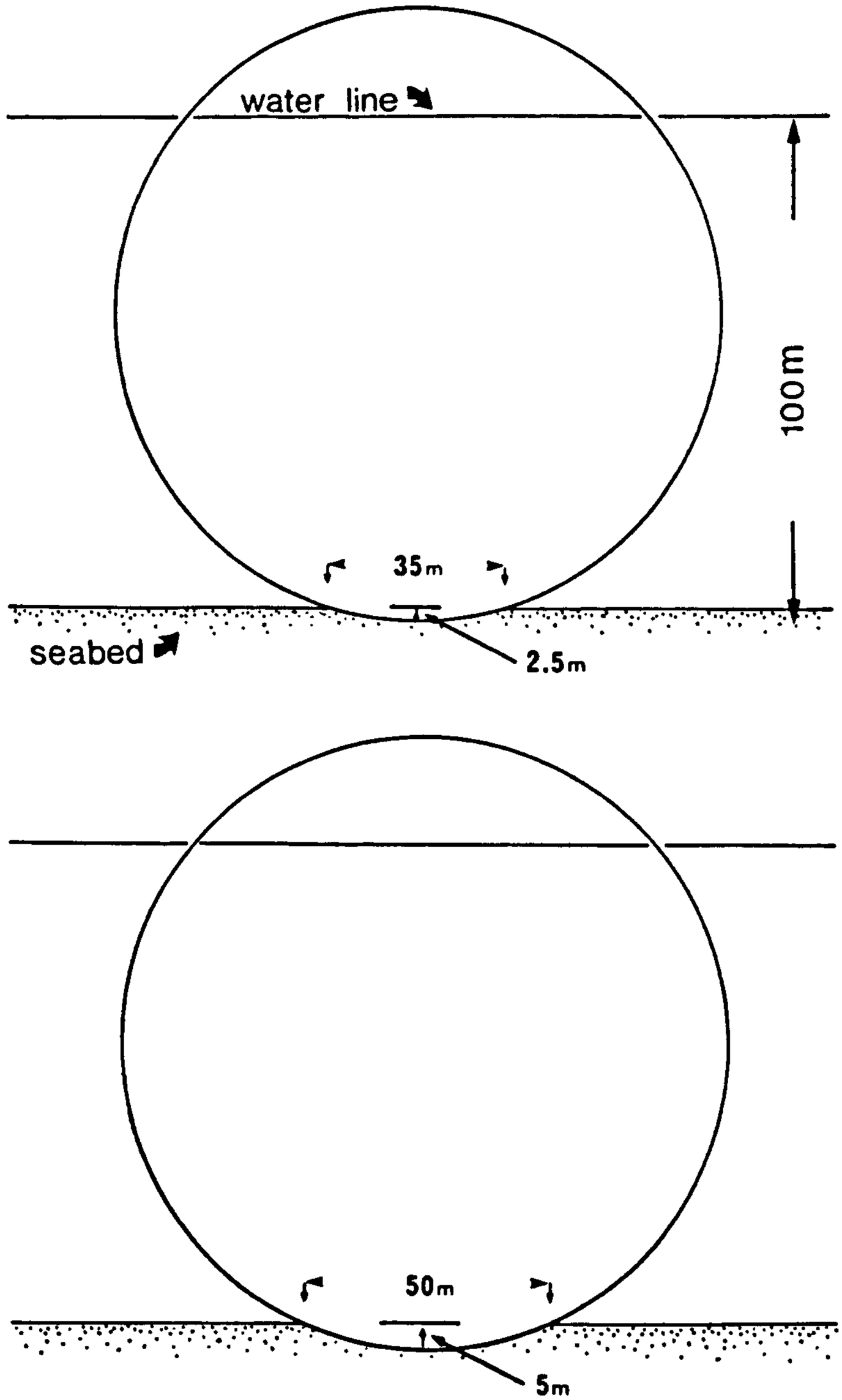


Figure 23. Cross-section through an "ideal" spherical iceberg to illustrate how a small increase in penetration depth of the keel into the seabed (from 2.5 to 5.0 m) will result in an associated, larger increase in scour mark width (from 35 to 50 m).

especially on the berms, that prevents modification of scour mark morphology and dimensions.

Change in observed width of scour marks that traverse upslope/downslope show four possible variations: (1) width increases upslope, (2) width increases downslope, (3) non-systematic variation in width, or (4) no observable change in width. A total of 3,293 scour marks were analyzed from 11 survey areas on 4 banks in the Labrador Sea (Figure 24). A total of 690 (21%) scour marks crossed isobath ranges of more than 2 m (Table 5). Of these 82.3% showed no change in width, 4.4% showed non-systematic variation, 6.5% had widths that increased upslope and 6.8% had widths that increased downslope. The great majority of scour marks showed no variation in width and (by association) depth, and is evidence that the majority of icebergs scouring across isobaths accommodate shoaling and increasing water depths by rotations which maintain the same keel/seabed forces.

Scour marks that increase in width upslope may be evidence of rotationally "stiff" icebergs moving into shallower water. Alternatively they could have been made by: (1) "stiff" icebergs drifting into deeper water, the keels of which gradually lifted off the seabed, (2) icebergs drifting into shallower water and rotating about a vertical axis so that the width of the attack face of the keel increased, (3) icebergs drifting

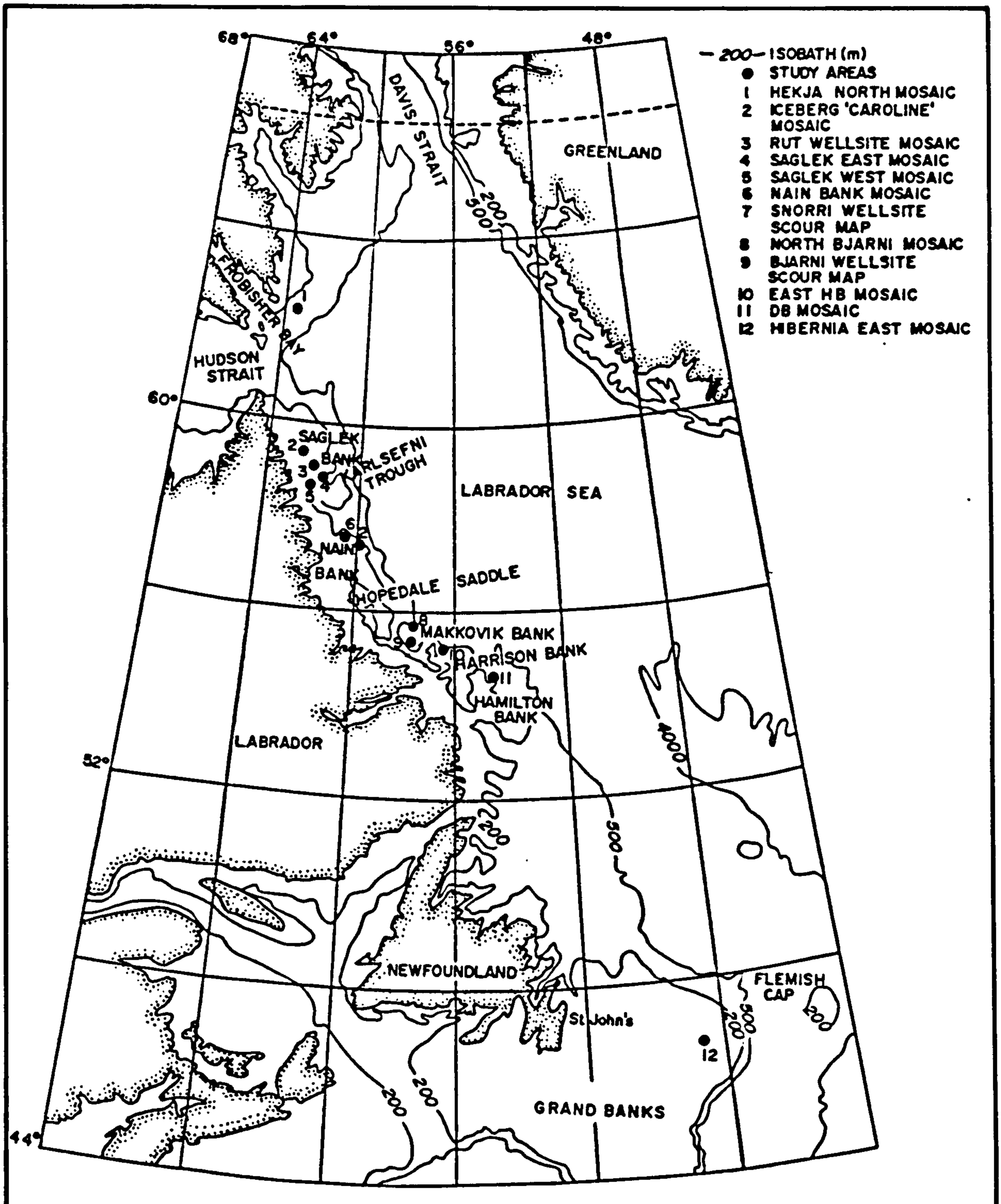


Figure 24. Map of Labrador Sea showing position of sidescan sonograph mosaics from which scour mark upslope/downslope and width data were measured. These data are summarized in Table 5.

Table 5. Variability in scour mark width with seabed slope Labrador Sea

Hekja North wellsite (South Baffin Island Shelf)

Number of scour marks identified = 775
Number of scour marks crossing isobaths = 48 (6.19%)

width increase upslope	width increase downslope	no change	variable
8 (16.6%)	6 (12.5)	28 (58.2%)	6 (12.5%)

Rut wellsite (Saglek Bank)

Number of scour marks identified = 327
Number of scour marks crossing isobaths = 48 (14.68%)

width increase upslope	width increase downslope	no change	variable
1 (2.1%)	2 (4.2%)	42 (87.4%)	3 (6.2%)

Saglek East survey area (Saglek Bank)

Number of scour marks identified = 532
Number of scour marks crossing isobaths = 101 (18.9%)

width increase upslope	width increase downslope	no change	variable
9 (8.9%)	8 (7.9%)	81 (80.2%)	3 (3.0%)

Saglek West survey area (Saglek Bank)

Number of scour marks identified = 265
Number of scour marks crossing isobaths = 71 (26.79%)

width increase upslope	width increase downslope	no change	variable
7 (9.9%)	2 (2.8%)	62 (87.4%)	0 (0.0%)

Caroline survey area (Saglek Bank)

Number of scour marks identified = 305
Number of scour marks crossing isobaths = 50 (16.39%)

width increase upslope	width increase downslope	no change	variable
1 (2%)	2 (4%)	47 (94%)	0 (0%)

Nain Bank

Number of scour marks identified = 22
Number of scour marks crossing isobaths = 18 (81.82%)

width increase upslope	width increase downslope	no change	variable
0 (0.0%)	3 (16.7%)	15 (83.4%)	0 (0.0%)

Table 5 (cont.)

Bjarni wellsite (Makkovik Bank)

Number of scour marks identified = 300
Number of scour marks crossing isobaths = 88 (29.04%)

Width information considered unreliable for use

North Bjarni wellsite (Makkovik Bank)

Number of scour marks identified = 219
Number of scour marks crossing isobaths = 22 (10.05%)

width increase upslope	width increase downslope	no change	variable
0 (0%)	0 (0%)	22 (100%)	0 (0%)

Snorri wellsite (Makkovik Bank)

Number of scour marks identified = 697
Number of scour marks crossing isobaths = 285 (40.89%)

width increase upslope	width increase downslope	no change	variable
17 (5.96%)	24 (8.4%)	233 (81.55%)	11 (3.85%)

DB wellsite (Makkovik Bank)

Number of scour marks identified = 43
Number of scour marks crossing isobaths = 24 (55%)

width increase upslope	width increase downslope	no change	variable
1 (4.2%)	0 (0.0%)	22 (91.7%)	1 (4.2%)

East HB wellsite (Makkovik Bank)

Number of scour marks identified = 108
Number of scour marks crossing isobaths = 23 (21.3%)

width increase upslope	width increase downslope	no change	variable
1 (4.35%)	0 (0.0%)	16 (69.6%)	6 (26.1%)

TOTAL NUMBER OF SCOUR MARKS IDENTIFIED = 3293
TOTAL NUMBER OF SCOUR MARKS CROSSING ISOBATHS = 690 (21%)

width increase upslope	width increase downslope	no change	variable
45 (6.5%)	47 (6.8%)	568 (82.3%)	30 (4.4%)

into deeper water and rotating about a vertical axis so that the width of the attack face of the keel decreased. Similar explanations can be applied to the almost equal number of scour marks that increase in width downslope: (1) that they were made by icebergs drifting into shallower water and rotating about a vertical axis so that the width of the attack face of the keel decreased, or (2) by icebergs drifting into deeper water and rotating about a vertical axis so that the width of the attack face of the keel increased. For any one of this type of scour mark, any one of these explanations may be valid depending on the characteristics of the scouring iceberg.

It can be shown that whereas most isobath-crossing scour marks reflect dynamic equilibrium of the scouring icebergs that made them, upslope- and downslope-widening scour marks can be interpreted in a number of ways, most of which imply changes in attack face width by vertical rotations rather than by stiffening resistance to rotation about a horizontal axis. Upslope- and downslope-widening scour marks represent only 13.3% of the upslope/downslope population and represent a minor component (2.7%) of the entire population. Thus, for the Labrador Sea at least, rotationally "stiff", upslope/downslope-scouring icebergs are uncommon.

Other types of iceberg behaviour are indicated by the presence of single pits or linear groups of pits on the seabed that are associated spatially with normal, curvilinear scour marks. Single pits are thought to be the product of grounding events (Barrie *et al.* 1986) following the split and high-energy roll of large icebergs. This phenomenon has been

verified from measurements obtained during the grounding of iceberg "Gladys", observed during the Dynamics of Iceberg Grounding and Scouring (DIGS) experiment (Hodgson *et al.* 1988; Lever *at al.* 1989). Other aspects of this grounding event are discussed in Chapter 3. Grounding pits are generally deeper than associated curvilinear scour marks and this overdeepening has been attributed to bearing capacity failure of the seabed beneath the keel after prolonged static or wave-induced cyclic iceberg loading (Clark *et al.* 1986). Pits that occur along the course of a normal curvilinear scour mark represent periods when the scouring iceberg ceased forward motion and grounded (Figure 25). These pits are always wider and deeper than the scour mark with which they are associated.

Linear groups of 3-5 pits, called crater chains, have been interpreted as the result of damped oscillations by capsizing icebergs (Bass and Woodworth-Lynas, 1988). This process has also been verified by observation and measurements obtained during the un-grounding and capsizing of iceberg "Bertha" during the DIGS experiment (Hodgson *et al.* 1988; Lever *at al.* 1989). This iceberg created 3 aligned pits during the un-grounding event, each slightly smaller than the preceding one. Results of the physical appearance of the pits are given in Chapter 3. The model put forward by Bass and Woodworth-Lynas (1988) does not satisfactorily explain the existence of crater chains with more than about 4 pits. It is possible that long trains of pits (Figure 26) are created by icebergs oscillating in resonant response to ocean swells. These long crater chain scour marks are very rare reflecting the improbability of such resonant behaviour during scour.

Figure 25. 100 kHz sidescan sonograph showing a grounding pit associated with a scour mark in Qeovik Silt Formation, water depth of 120 m, Saglek Bank. The pit is wider (and probably deeper) than the scour mark. The berm pile is intact all around the pit except on the left hand side where it has been removed as the iceberg continued scouring towards the top left.

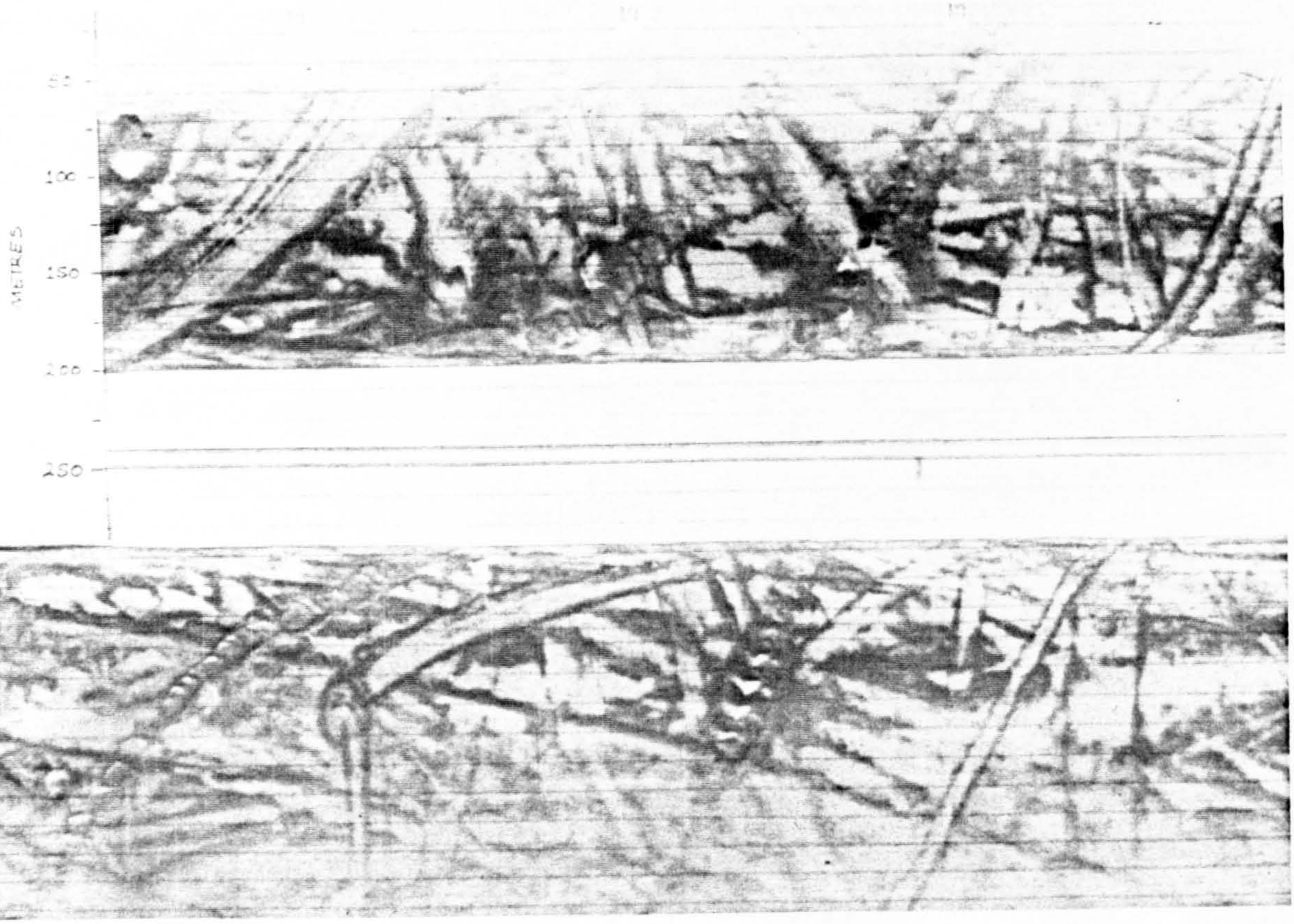


Figure 26. 100 kHz sidescan sonograph showing an iceberg crater chain (left hand side) and "tractor tire" scour mark developed on intensely scoured Qeovik Silt Formation, Saglek Bank in a water depth of 120 m. These features may have been created by icebergs oscillating in resonant response to ocean swells.

Scour marks with perpendicular cross-trough ridges have been identified from the Weddell Sea, Antarctica (Lien, 1981), from the United States Beaufort Sea (Reimnitz *et al.* 1973) and from the Northern Barents Sea (Solheim, 1991). These authors interpret the ridges to be the product of "wobbling" keels. In the Weddell Sea iceberg wobbling is interpreted to have been induced by resistance to forward motion by the build up of a large surcharge. The surcharge inhibits forward motion of the keel until driving forces overcome seabed resistance, and the keel swings forward to begin the process again (Lien, *op. cit.*). In the Beaufort Sea wobbling is thought to be induced by wave action on pressure ridge keels to produce similar seabed structures (Reimnitz, *op. cit.*).

CHAPTER 5

DEFORMATION BENEATH LARGE SCALE SCOUR MARKS

Introduction and summary

The mechanisms of scour mark formation have been derived largely from descriptions of scour marks as they appear on the seabed using sidescan sonar, high resolution sub-bottom reflection profile data, and direct observations from submersible on the Labrador shelf. Sediment deformation below, to the sides and in front of the keel are implied from the observations, but examination of sub-scour deformational effects and structures is impossible using submersibles. Gilbert (1990) has analyzed high-resolution reflection profile data from several pressure-ridge-generated ice scour marks in the Beaufort Sea. He described acoustic zones below the incision surfaces of the scour marks, and interpreted these zones to be the effect of consolidation of sediments by the scouring keel. He interpreted sediment in the scour mark berms to have undergone shearing and dilation, resulting in acoustic "pulldown" of strata below (Figure 26-1). Acoustically-defined scour-related deformation occurs to depths of 1 m below the scour mark troughs. The problem with this approach is that acoustic anomalies due to scour mark geometry are hard to distinguish from scour-related sediment deformation. Also, unless density contrasts within the sediment are sufficient, sub-scour deformation structures, such as slip surfaces, cannot be resolved and hence the mechanisms of sediment deformation cannot be defined.

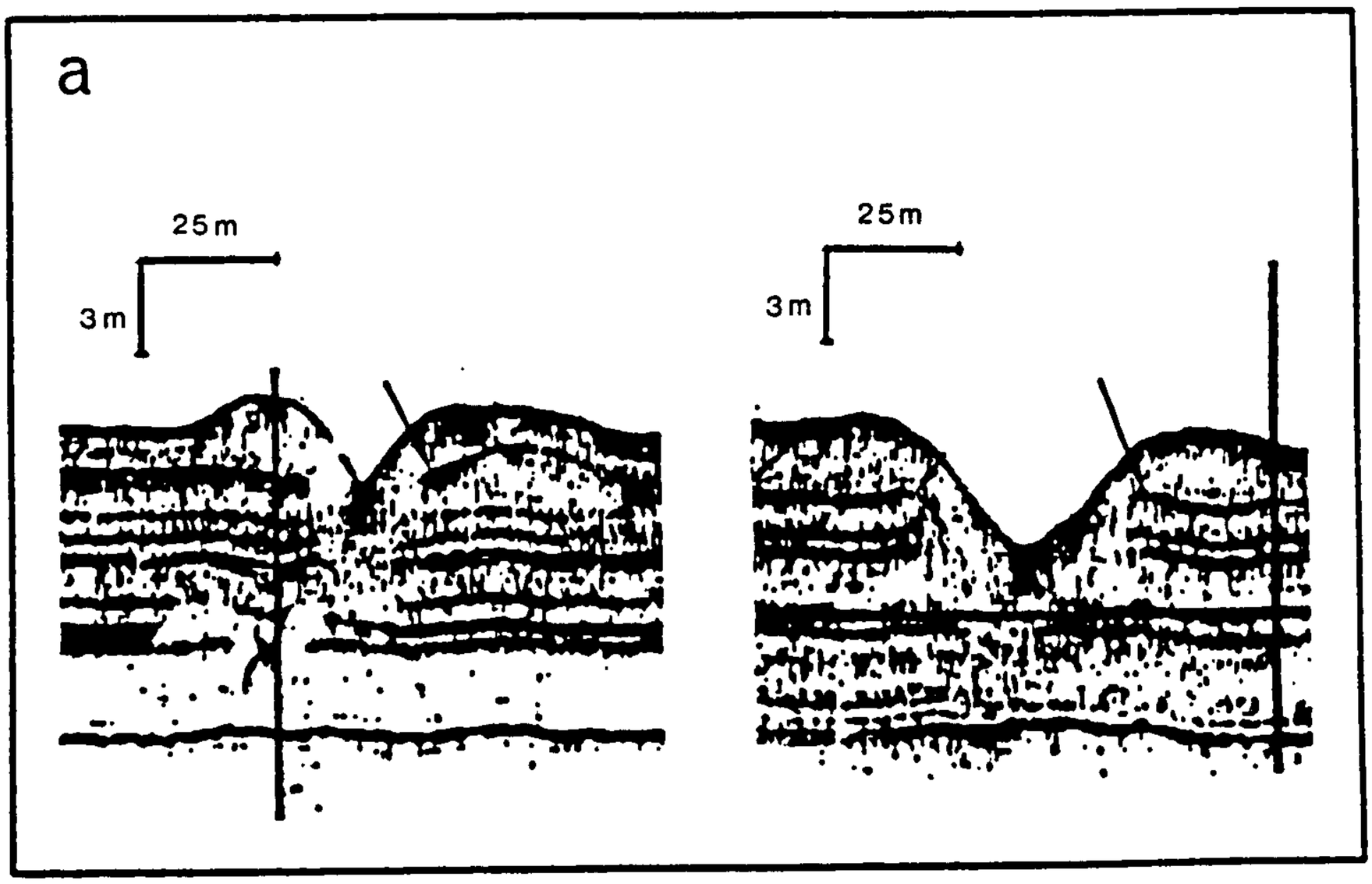


Figure 26-1. 3.5 kHz sub-bottom profiles of, a) two scour marks that show apparent down-folding (left) and upfolding (right) of strata beneath the trough and berms: b) a scour mark showing acoustic "pulldown" of strata below the berms (adapted from Gilbert, 1990).

The identification of scour-related deformation beneath submerged scour marks is limited to analysis of acoustic profile data, and can be problematic with respect to interpretation. A simpler approach is to examine and measure scour marks that are exposed on land. Careful excavation and documentation of structures can then be made without ambiguity, and the geometric association of structures with scour marks, and hence with the scouring action of ice keels, can be shown. An obvious advantage to this approach is that features such as slip surfaces and small scale folds can be resolved and mapped to accuracies of a few centimetres, whereas acoustic data are unlikely to resolve such details, and certainly not to such accuracy.

Scour marks are exposed on land in Canada in several areas. For example relict scour marks are preserved in lacustrine sediments of former glacial Lake Agassiz in southern Manitoba, and in glacimarine sediments of King William Island, Northwest Territories. Scour marks in these two regions generally have similar dimensions to their modern marine counterparts, and formed in similar water depths.

Partial burial of the Lake agassiz scour mark troughs have preserved most of the surface morphology, and sub-scour deformation structures are virtually in pristine condition. Prominent conjugate faults are developed below one scour mark trough, the former extending to at least 5.5 m beneath the deepest part of the scour mark incision surface. Stereo plots of structural data reveal that smaller, unconnected fault segments below all of the scour marks may also be conjugate sets. Conjugate faults are interpreted to have

formed in response to bearing capacity failure of soil beneath the scouring keel. A sub-horizontal thrust fault beneath one scour mark is interpreted to have developed immediately ahead of a scouring iceberg keel and indicates that horizontal shear forces propagated to depths as great as 6 m below the lakebed. Definition of deeply penetrating faults has significant engineering implications for the burial depths required to protect oil and gas production pipelines in areas of active scouring today.

This chapter describes the results of work carried out on the Lake Agassiz scour marks during three field seasons, and on the King William Island features from one field season. Two of the Lake Agassiz features (A and B) have been reported on by Woodworth-Lynas and Guigné (1990). Two additional scour marks (C and D) have also been investigated.

Previous work

Longva and Bakkejord (1990) studied two relict scour marks and a gravity crater (iceberg pit) cut into glacimarine clays in southern Norway. They show that beneath one 30 m wide feature (scour mark II) laterally continuous laminae are deflected in low amplitude (0.7 m), open folds that mimic the scour mark trough surface (Figure 2c). Faulting is restricted to very small movements (<100 mm) along a suite of near-vertical fractures in a narrow zone beneath the central part of the scour mark and which extend to

at least 2 m below the scour mark trough. Minor reverse faults in scour mark II and detached slabs of clay up to 2 m long in scour mark I (70 m wide), at or immediately below (<0.5 m) the scour mark surface, indicate thrusting of material ahead and to the side of the scouring keel. For one cross section (scour mark II) the authors attempted a palinspastic reconstruction of the sediments before the scour event, and concluded that 67% of the cross sectional area of clay was physically removed by the (bulldozing?) keel, and that 33% was displaced downwards beneath the keel (to a maximum of 0.75 m vertical displacement as measured from Figure 11c of Longva and Bakkejord [1990]). Unlike the results obtained by Woodworth-Lynas and Guigné (1990), faults with large displacements and deeply-penetrating low angle faults related to bearing capacity failure were not observed.

From sandy delta-front glacilacustrine storm deposits exposed along Scarborough Bluffs, Ontario, Eyles and Clark (1988) described a 9 m-wide, 2 m-deep V-shaped scour mark interpreted to have been made by a lake ice pressure ridge keel (Figure 2b). Normal and reverse high angle faults occur beneath the rising flanks of this feature with maximum dip slip offset of 0.5 m (measured from Figure 10A of Eyles and Clark, 1988). However, the deepest penetrating faults (max 2 m long) occur on the highest part of the scour mark flanks so that below about 0.25 m beneath the deepest part of the trough, sediments appear to be unaffected. Lateral compression seems to have been dominant where the trough is widest, as shown by the presence of asymmetric and recumbent folds in a prominent layer on either side of the trough, whereas downward displacement appears dominant beneath the deepest part of the scour mark. Again, there is no evidence of deeply penetrating, large

displacement faults related to bearing capacity failure.

Thomas and Connell (1985) describe a 3 m-wide, 2 m-deep iceberg grounding mark in laminated glacilacustrine silts, sands and gravelly sands from a quarry north of Aberdeen, Scotland. This feature was interpreted to represent a grounding event caused by falling lake level with little, if any, horizontal iceberg motion. Although this feature is not a true scour mark, where horizontal motion is dominant, it is illustrated for comparison (Figure 2a). The diagram shows that most of the deformation appears to have been accommodated by downfolding of sediments beneath the trough (deflections of at least 1.5 m), by reduction in bed thickness, and by displacement (up to 0.25 m) along near-vertical faults confined to the trough flanks.

Although faulting and downfolding of strata are common to all of the features reported by these authors, fault geometry in particular shows a wide variety in style. Woodworth-Lynas and Guigné (1990) did not report downfolding beneath the Lake Agassiz scour marks, possibly because original stratification is so heavily disturbed that continuous marker horizons do not exist.

Lake Agassiz iceberg scour marks

A region immediately southeast of Winnipeg was selected for the study where prolific, well-preserved exposed scour marks are preserved at the present surface in thick clays of glacial Lake Agassiz (Figure 27). The scour mark troughs are buried beneath a 2-3 m-thick layer of silty clay, thick enough to protect scoured sediments from the effects of farming activities and from deformation related to seasonal freeze/thaw of the ground. Neither bioturbation nor erosion of the sediments has occurred, and consequently most of the surface morphology of the scour marks is preserved, except for the berm crests that in places come close to the present ground surface. Sub-scour deformation structures are preserved virtually in pristine condition. Four scour marks (B - D) were chosen for study from analysis of aerial photographs of the area (Figure 28). In the regions chosen for excavation each scour mark is free from the influence of other, cross-cutting, scour marks.

General geology

At its maximum, Lake Agassiz was the largest lake in North America covering a total area of 950 000 km^2, although it never exceeded more than 350 000 km^2 at any one time (Teller and Clayton, 1983). It was as deep as 213 m in the Winnipeg area (Elson, 1967) and was supplied with most of its water from the melting of the Wisconsinan ice sheet via meltwater channels or directly from the glacier (Teller, 1976). Sediment-laden meltwater

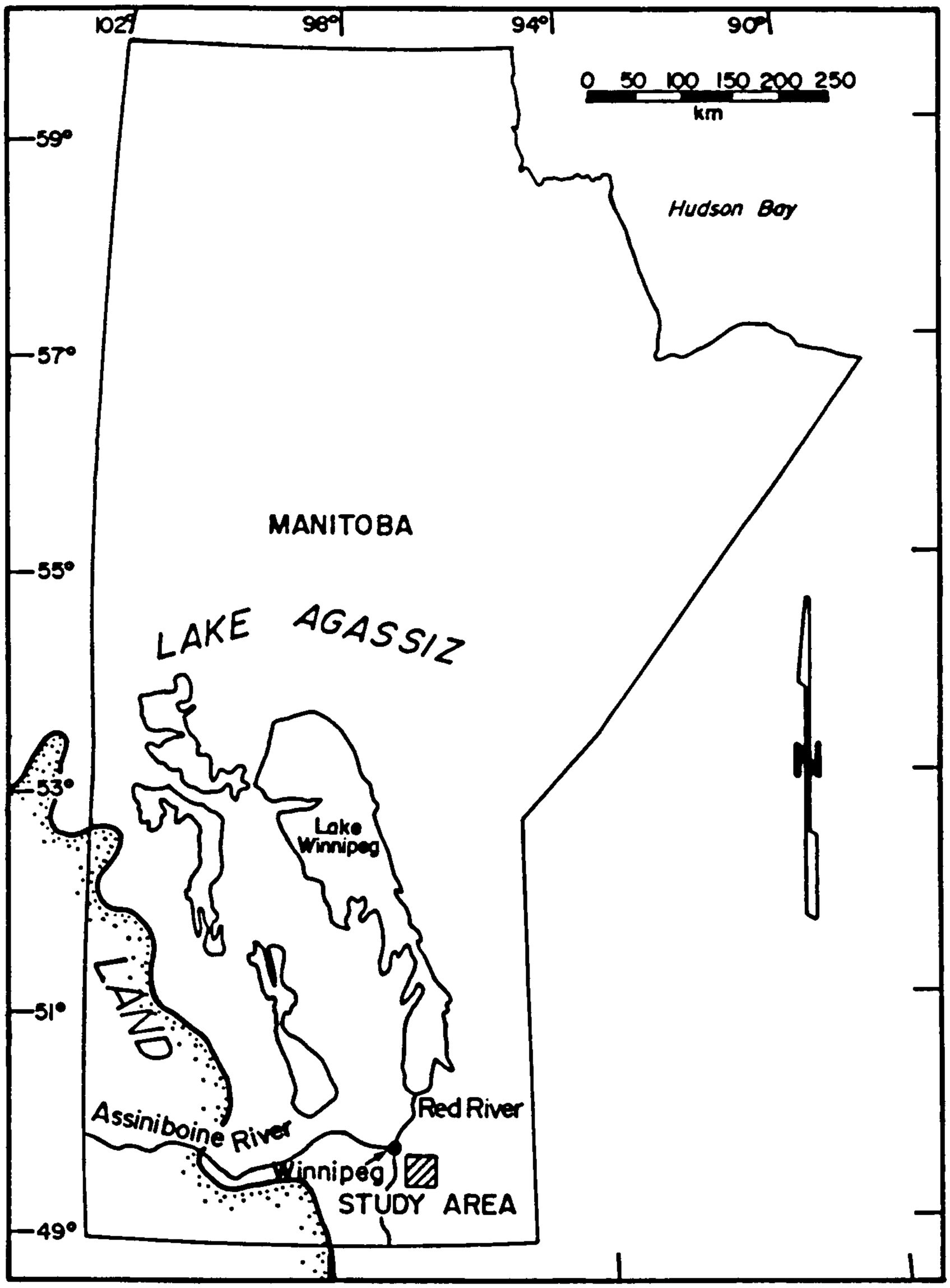


Figure 27. Location map of study area in southeastern Manitoba.

Figure 28. Aerial photograph of the study region southeast of Winnipeg. Iceberg scour marks show up as prominent white criss-crossing lines. The straight diagonal line in the upper right of the photograph is the Trans-Canada Highway. Cross-sections through scour marks B - D are discussed in the text.

probably travelled as slow-moving density currents that may have flowed the entire length of the Lake Agassiz Basin (Teller, 1976). The majority of sediments in the study region averages 79% clay, 20% silt and 1% sand (Last, 1974).

In southern Manitoba up to three stratigraphic clay-rich units overlie till (Teller, 1976). The lowermost unit (Unit 1) was correlated with the Brenna Formation in North Dakota and Minnesota by Teller (1976) and Fenton *et al.* (1983). The unit has an average thickness of about 15 m (Harris *et al.* 1974). It is characterized by a general absence of laminae, the presence of iceberg-rafted clasts of white calcareous silt, carbonate and crystalline rocks, and the presence of slickensided surfaces. Fenton *et al.* (1983) interpret deposition of this unit (in the study area) between about 11 200 and 10 000 years ago as glacial ice retreated north in the Red River Valley.

A final ice advance from the north caused lake levels to rise, allowing deposition of Unit 3 between about 10 000 and 9 000 years ago after several hundred years of low water levels (Fenton *et al.* 1983). Unit 2 of Teller (1976) may not be present in the study area, and Unit 3, that was correlated with the Sherack Formation, rests on the Brenna Formation. Unit 3 is characterized by the presence of laminae and absence of clasts (Teller, 1976).

Water depth and age of scour marks

Following a retreat of Laurentian ice to the north, and prior to scouring, a period of subaerial exposure existed between about 10 300 and 9 900 years ago. By using estimated lake levels in the Lake Manitoba basin (Teller and Last, 1981) and from outlets that allowed Lake Agassiz to drain into the Great Lakes system to the east (Teller and Thorleifson, 1983) it is likely that the study area was exposed at least 7 m above lake level during this period. The interpretation of exposure and possible desiccation is supported by the results of 1987 *in situ* geotechnical testing at scour marks A and B that indicates overconsolidation of the clays down to a consistent depth of 8 m below the present ground surface (Woodworth-Lynas and Landva, 1988).

About 9 900 years ago the eastern outlets were dammed by glacial ice, and lake depth increased to about 110 m (Teller and Thorleifson, 1983) and deposition of Unit 3 began. As water depth increased beyond 60 m scouring by lake ice pressure ridge keels would not have occurred (e.g. Reimnitz *et al.* 1984). Woodworth-Lynas and Matile (1988) presented evidence that the rise in lake levels at this time triggered a southeast-directed movement of ice from north of the Winnipeg area terminating east of the study area against a significant (unnamed) north-south oriented moraine. After the surge the ice sheet would have begun to disintegrate producing numerous icebergs that scoured the previously exposed lake bed sediments, beginning shortly after 9 900 years ago when water depths rose to the 110 m level. This was the last advance-retreat phase of Lake Agassiz, that ended as recently

as 8 700 years ago. In the study area deposition of a tan-coloured unit that fills the scour mark troughs was under way during the period of scouring because reworked sediments of the lowermost part of the unit are incorporated within deformed sediments of the underlying dark brown and grey clay unit at scour marks B and D (see below).

Morphology and sediments of the scour marks

Scour mark A is about 50 m wide and can be traced for at least 6 km, both ends probably disappearing beneath thickening sediments of the tan-coloured unit (Figure 28). Scour mark B is about 55 m wide as measured between berm crests exposed in the excavations and about 2 m deep. It can be traced for at least 8.5 km before dying out beneath overburden deposits at both ends. Scour mark C is about 65 m wide and 2.5 m deep, and can be traced for at least 6.5 km. Scour mark D, which is about 60 m wide and 2 m deep, can be traced for only 0.5 km, both ends being obscured by other cross-cutting scour marks. It is stressed that scour mark width should be taken as an approximate measurement because well-defined scour mark berms are not readily apparent in the excavations. This is probably because the berms may have originally stood proud from the lakebed, and as lake levels fell to zero depth they may have experienced preferential wave-induced and later subaerial erosion. Also, where the scour mark berms are very close to the ground surface, there has probably been additional reworking by seasonal freeze/thaw

and agricultural tilling.

The scour marks are incised into brown and grey mottled clays (Figure 29), and sub-scour sediments at scours B and D also contain zones of reworked tan-coloured silty clay. The brown and grey clay is characterized by the presence of plate-like clasts of white calcareous silt. The clasts are commonly concentrated along the scour incision surface, which is a contact between the brown and grey clay and tan-coloured units. Matrix-supported clasts of carbonate and friable crystalline rock are also present, generally ranging in diameter from 1-5 cm, and exceptionally to sub-rounded cobbles 20-40 cm in diameter. The brown and grey clay is generally plastic, cohesive and easily sampled. Except where it has been affected by scouring, the tan-coloured unit occurs as a well laminated deposit of silty clay filling the scour mark troughs. At scour mark B discrete layers, generally less than 10 cm thick, of yellow/white finely cross-bedded silty clay typify this overlying unit.

Grain size analyses were performed on borehole samples retrieved from scour marks A and B. The results are considered representative of the study area because all the scour marks are in close proximity to one another. The brown and grey clay has a mean clay content of 73% and 27% silt (scour mark A) and 71.1% clay and 38.9% silt (scour mark B). The tan-coloured unit has a mean clay content of 45% and silt content of 55% (scour mark A) and 41.1% clay and 58.9% silt (scour mark B) (Table 6).

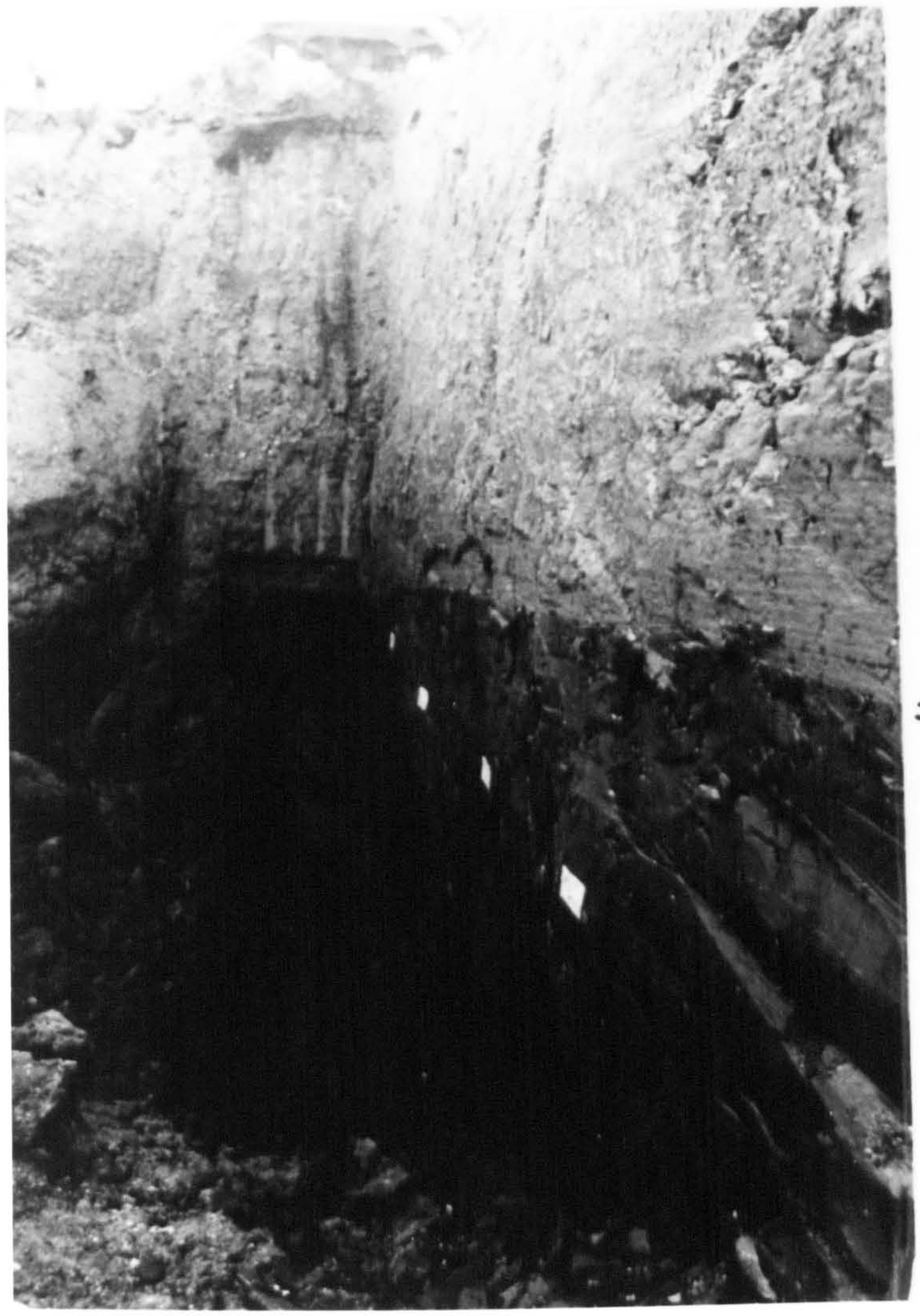


Figure 29. View from the northeast berm looking towards the centre of the trough at scour mark B, trench 1, showing the incision surface (abrupt contact) separating dark, scoured massive sediments of the brown and grey clay, from overlying, well laminated silty clays of the tan-coloured unit. The incision surface dips away from the camera (white cards on the trench wall are spaced 1 m apart and define a horizontal line).

Table 6. Silt (grain size > 0.002 mm) and clay contents of scour-affected sediments, Lake Agassiz scour marks.

SCOUR MARK A

BOREHOLE #	GREY/BROWN CLAY	TAN UNIT
8	68% clay	62% clay
8a	49% clay	
	34% clay	
	93% clay	
	92% clay	
	95% clay	
9	52% clay	60% clay
	57% clay	
	91% clay	
10	94% clay	58% clay
	80% clay	34% clay
		11% clay
mean clay content	73.2%	mean clay content 45%

SCOUR MARK B

BOREHOLE #	GREY/BROWN CLAY	TAN UNIT
3	90% clay	48% clay
	86% clay	50% clay
		47% clay
		90% clay
4	83% clay	35% clay
		40% clay
		41% clay
		29% clay
		17% clay
5	87% clay	38% clay
		27% clay
		32% clay
		24% clay
15	60% clay	58% clay
	89% clay	34% clay
	89% clay	
	80% clay	
	68% clay	
16	55% clay	42% clay
	92% clay	46% clay
	46% clay	
	40% clay	
	41% clay	
	46% clay	
	85% clay	
mean clay content	71.1%	mean clay content 41.1%

Sub-scour deformation structures

Scour marks A and B were excavated and fully described by Woodworth-Lynas and Guigné (1990). The following discussion includes results presented by these authors with additional data from a third excavation of scour mark B, 35 m northwest of the first two trenches (Figure 30).

Scour mark A

A single trench was excavated across this feature. Small scale chevron folds occur immediately below the incision surface on the southwest edge of the scour mark. The folds are sharp-crested and symmetric with flat limbs and vertical axial surfaces, and have amplitudes and wavelengths no greater than 5 cm. The scour mark incision surface is not affected by the folds. Faults were not seen in any part of the section. This may in part be the result of the general absence of bedding, truncation and offset of which is an important criterion for identifying faults.

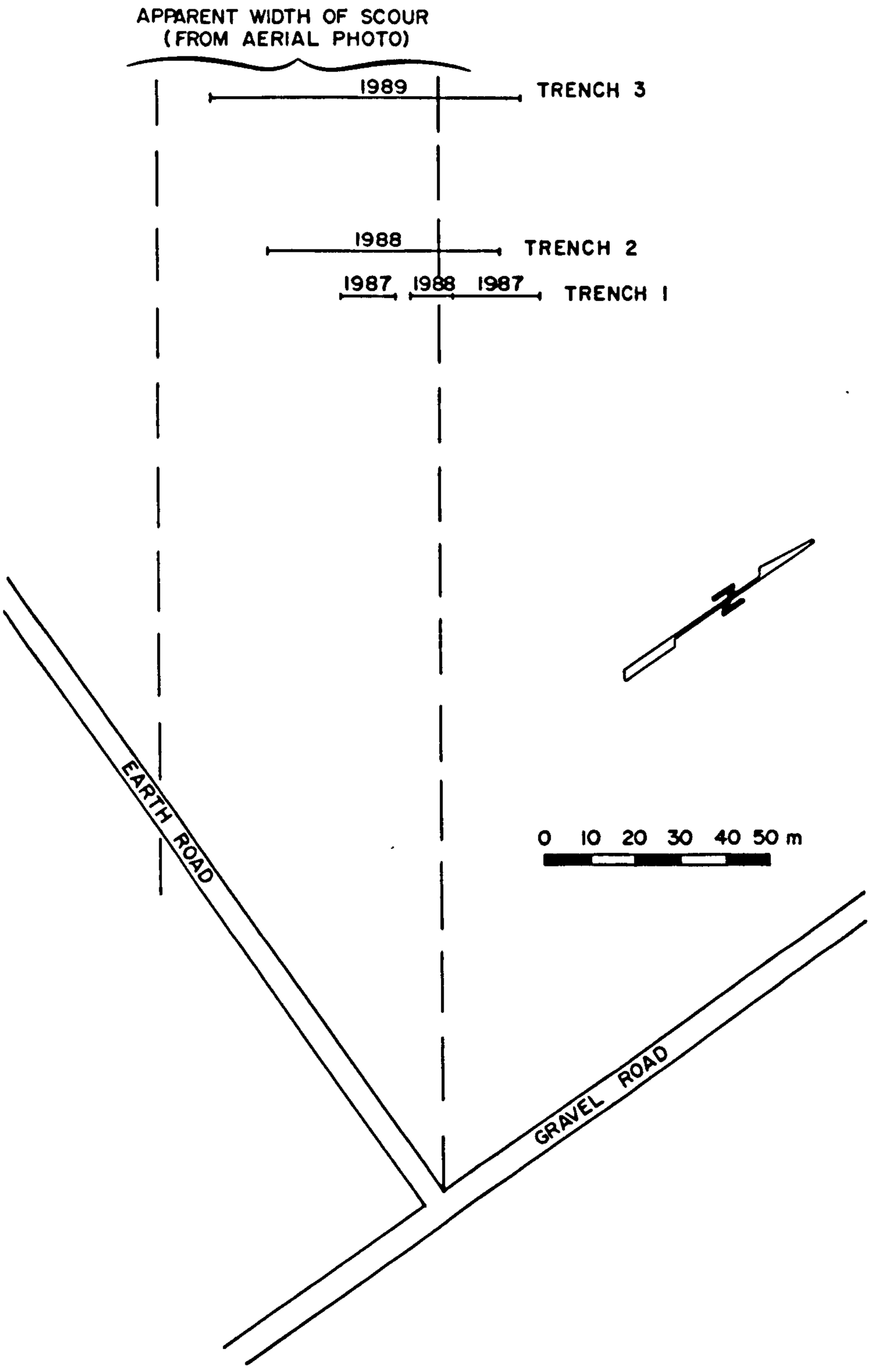


Figure 30. Map showing relative positions of the excavations carried out on scour mark B by Woodworth-Lynas and Guigné (1990) in 1987 and 1988, and of the 1989 excavation reported in this study.

Scour mark B

Faults

Two continuous trenches (trench 2 and trench 3) were excavated across this scour mark (Figure 30). In both excavations a suite of symmetrically arranged faults affect the sub-scour clays (Figures 31 & 32). Faults are sometimes defined by offset bedding, but where bedding is absent they are hard to discern. After excavating the trenches minor settling sometimes caused small displacements (1-2 mm) of the trench walls along fault surfaces. These displacements threw shadows on the trench wall, thereby assisting recognition of faults in areas of structureless clay. Three types of fault were distinguished, each associated with different parts of the scour mark. Fault types included I) low angle faults beneath the central part of the scour mark trough, II) low angle faults located below and beyond the berm regions, and III) sub-horizontal faults beneath the scour mark berms and, in trench 3 only, beneath the central portion of the trough.

I. Low angle faults - trough. On each side of the scour mark between the inner berm flanks and the centre of the trough, faults with apparent dips ranging from about 25-55°, extend from the scour mark incision surface to at least 5.5 m below the deepest part of the scour mark trough (trench 3). In both trenches the left-dipping fault propagates from the right side of the scour mark, and the right-dipping fault from the left side, plunging towards an extrapolated intersection point about 6 m below the

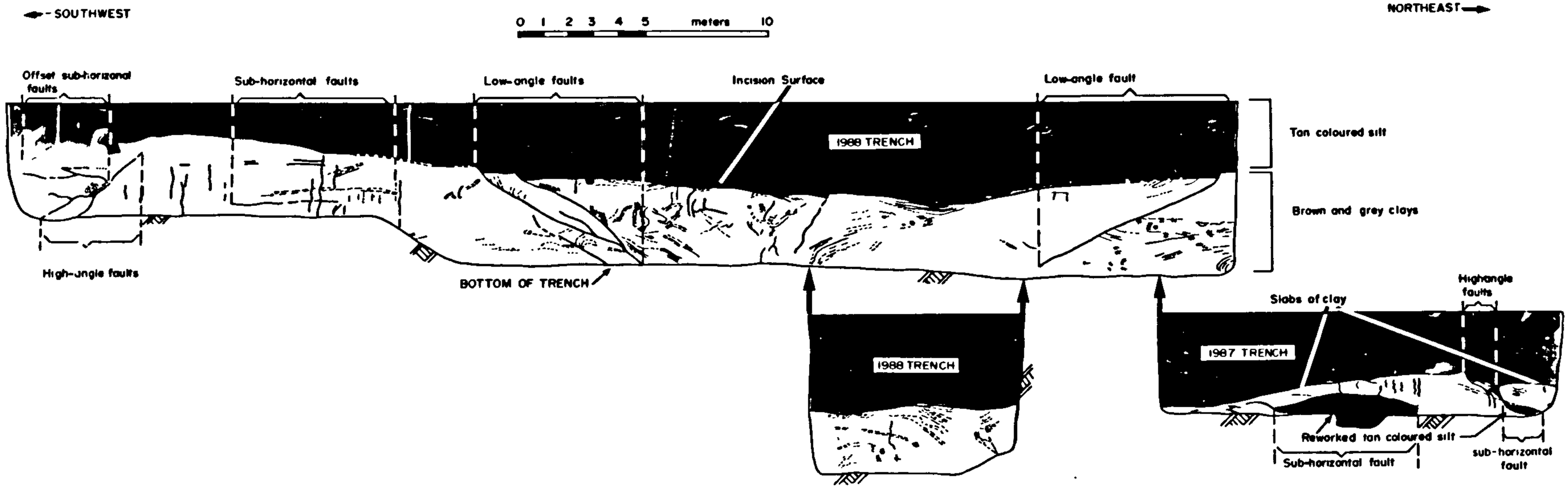


Figure 31. Cross-section through scour mark B, trench 2, showing the scour mark incision surface (sub-horizontal line), sub-scour faults (heavy solid lines) and deformed bedding (curved lines). No vertical exaggeration.

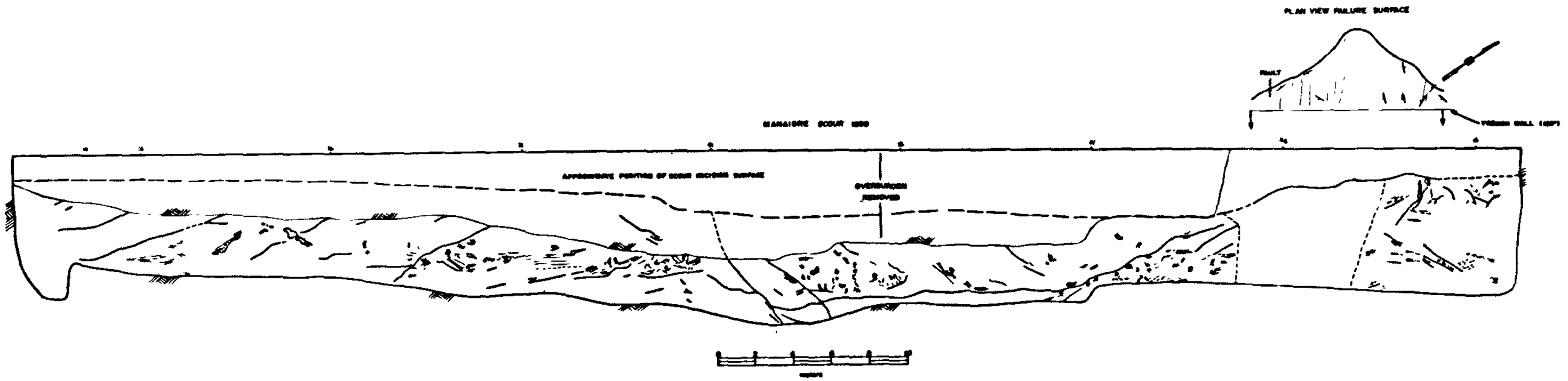


Figure 32. Cross-section through scour mark B, trench 3 showing the scour mark incision surface (heavy dashed line), sub-scour faults (heavy solid lines) and deformed bedding (curved lines). No vertical exaggeration.

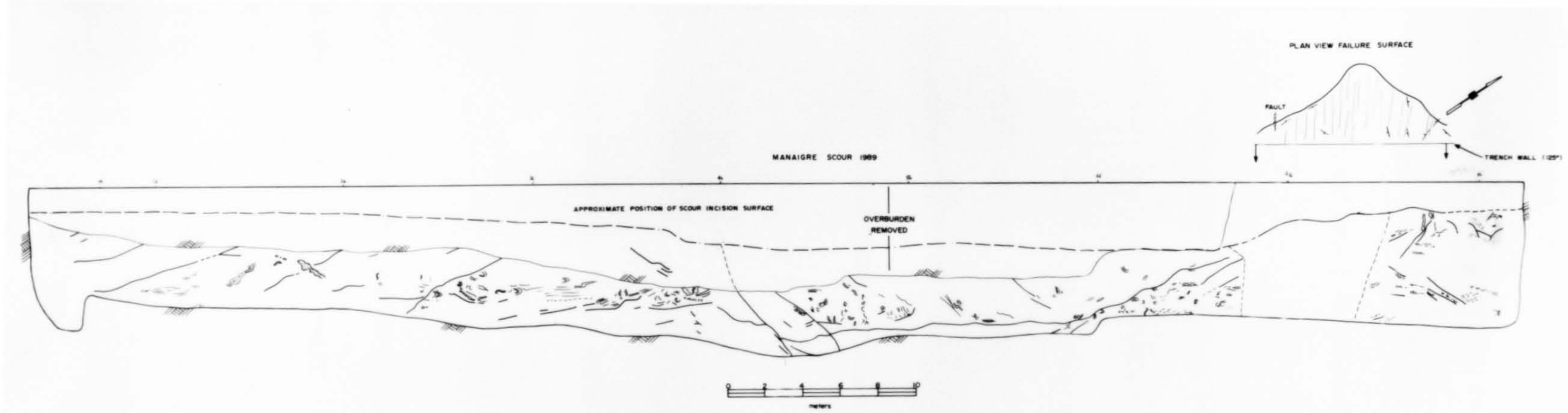


Figure 32. Cross-section through scour mark B, trench 3 showing the scour mark incision surface (heavy dashed line), sub-scour faults (heavy solid lines) and deformed bedding (curved lines). No vertical exaggeration.

deepest part of the scour mark trough in trench 2 and to 9 m below the trough in trench 3. Although it may exist, there is no supporting evidence to show that the faults are physically connected between trenches 2 and 3 which are 35 m apart. Excavation of the faults reveal well developed highly polished slickensided slip surfaces (Figure 33).

Along the single fault on the northeast side of the scour mark in trench 2 (Figure 31) a band of severely distorted clay laminae is truncated at the hanging wall (Figure 34). Continuity of this band is not seen on the hanging wall side and thus a dip slip displacement of at least 3.5 m along the fault can be inferred. There is no distinct marker horizon associated with the anastomosing shallow angle faults on the southwest side of the scour mark so that relative amounts of displacement cannot be inferred.

Trench 3 reaches to a depth of 5.5 m below the deepest part of the scour mark incision surface (depth below ground of 9 m). The fault on the northeast side of the scour mark extends to at least 4.5 m below the scour mark trough, and a double fault on the southwest side extends to at least 5.5 m below the trough.

Occasionally during the excavation process the trench walls collapsed, usually along fault surfaces, exposing the slickensided foot walls. Where foot walls were exposed a general preferred orientation of dip was readily apparent. However, small scale (5-10 cm amplitude) hummocky relief of fault surfaces often caused considerable local variation in fault orientation.

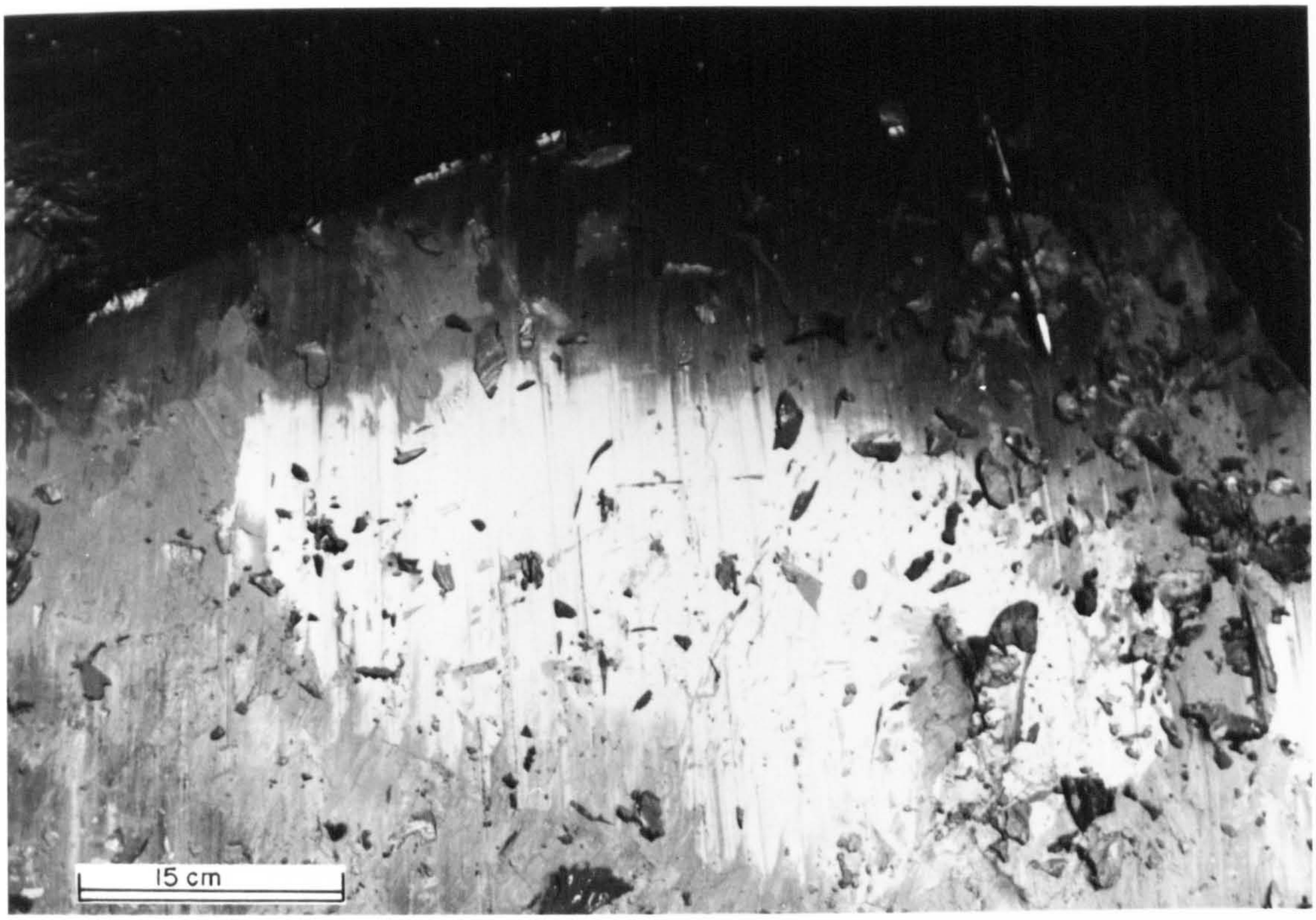


Figure 33. Slickensides on a fault surface, scour mark B, trench 2.

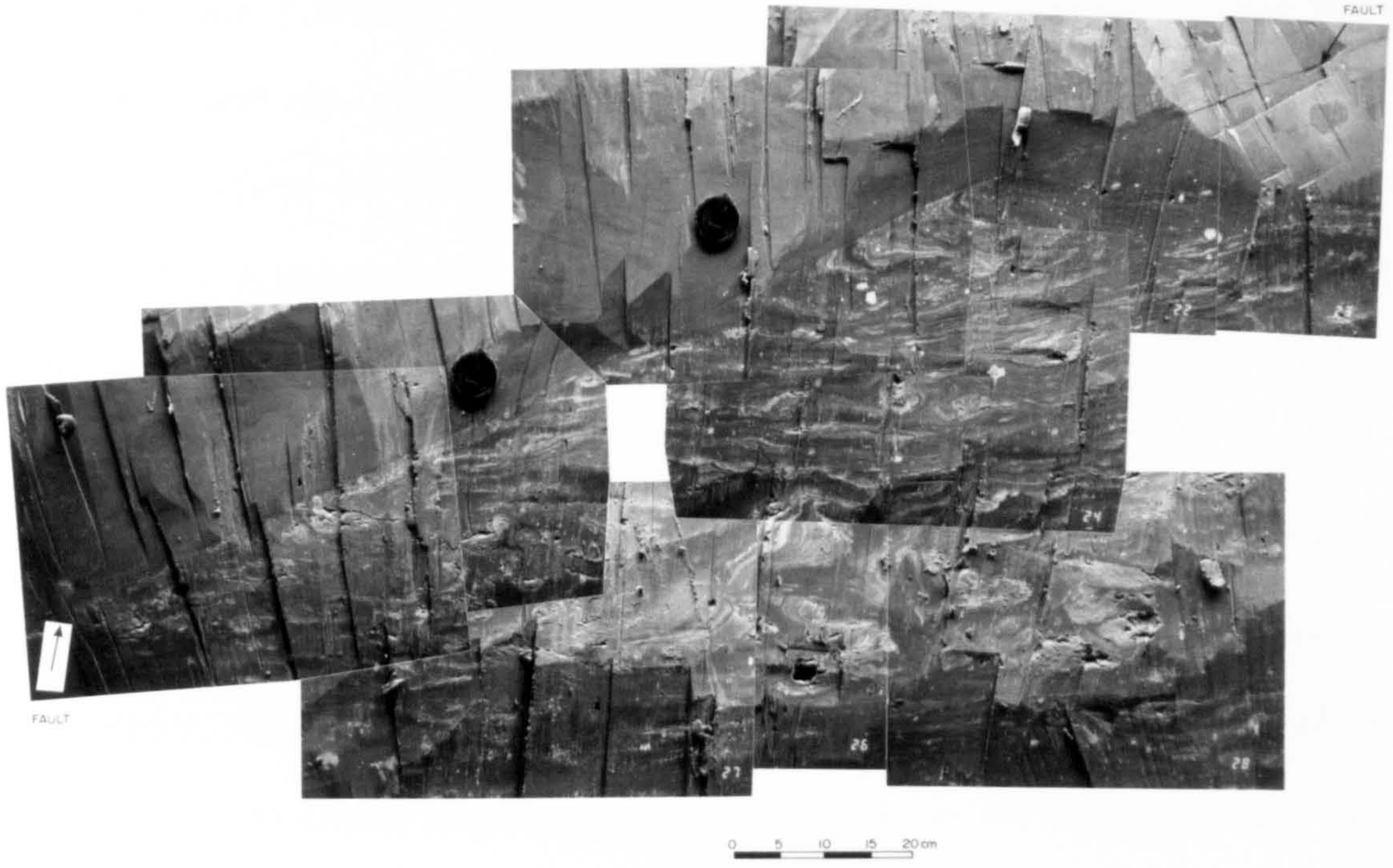


Figure 34. Low angle fault on the northeast side of scour mark B, trench 2, showing truncation of deformed bedding. Dip slip offset along this fault of at least 3.5 m is inferred. Note typical fold geometries (defined by silt laminae) in the brown and grey clay.

In trench 2 the low angle faults offset the scour mark incision surface by about 20 cm of normal displacement (Figure 35). As they are traced up into the tan-coloured unit the offset diminishes to zero in less than 75 cm. Because they extend into and offset both the incision surface and laminated sediments of the overlying tan-coloured unit by the same amount the movement is clearly a fault reactivation phenomenon of post-scour and post-early tan-coloured unit age. Scanning electron micrographs of freeze-dried samples of slickensided fault surfaces from the brown and grey clay show a dominant set of micro-grooves (Figure 36). A less well developed subordinate set of micro-grooves cross-cuts the dominant set at a slight angle.

II. Low angle faults - berms. Sediments beneath both outer berms contain low angle faults that generally dip away from the scour mark trough. Slickensides are developed on some fault surfaces. On the northeast margin of the scour mark in trench 2, offsets of the top surface of the berm clearly indicate normal faulting. Here the horizontal base of a down-faulted block of brown and grey clay rests above distorted tan-coloured unit sediments on the outer berm (Figure 37). Although faults affect the upper berm surface they do not continue into the overlying tan-coloured unit.. Bedding clearly drapes or onlaps local berm topography indicating the development of berm relief at the time of scouring and prior to burial by continued deposition of the tan-coloured unit. Low angle faults with sub-horizontal offshoots are found below the outer berm on the southwest scour mark margin.

Figure 35. View of the trough surface, scour mark B, trench 2, showing post-scour offset of the surface along two low angle faults (arrows).

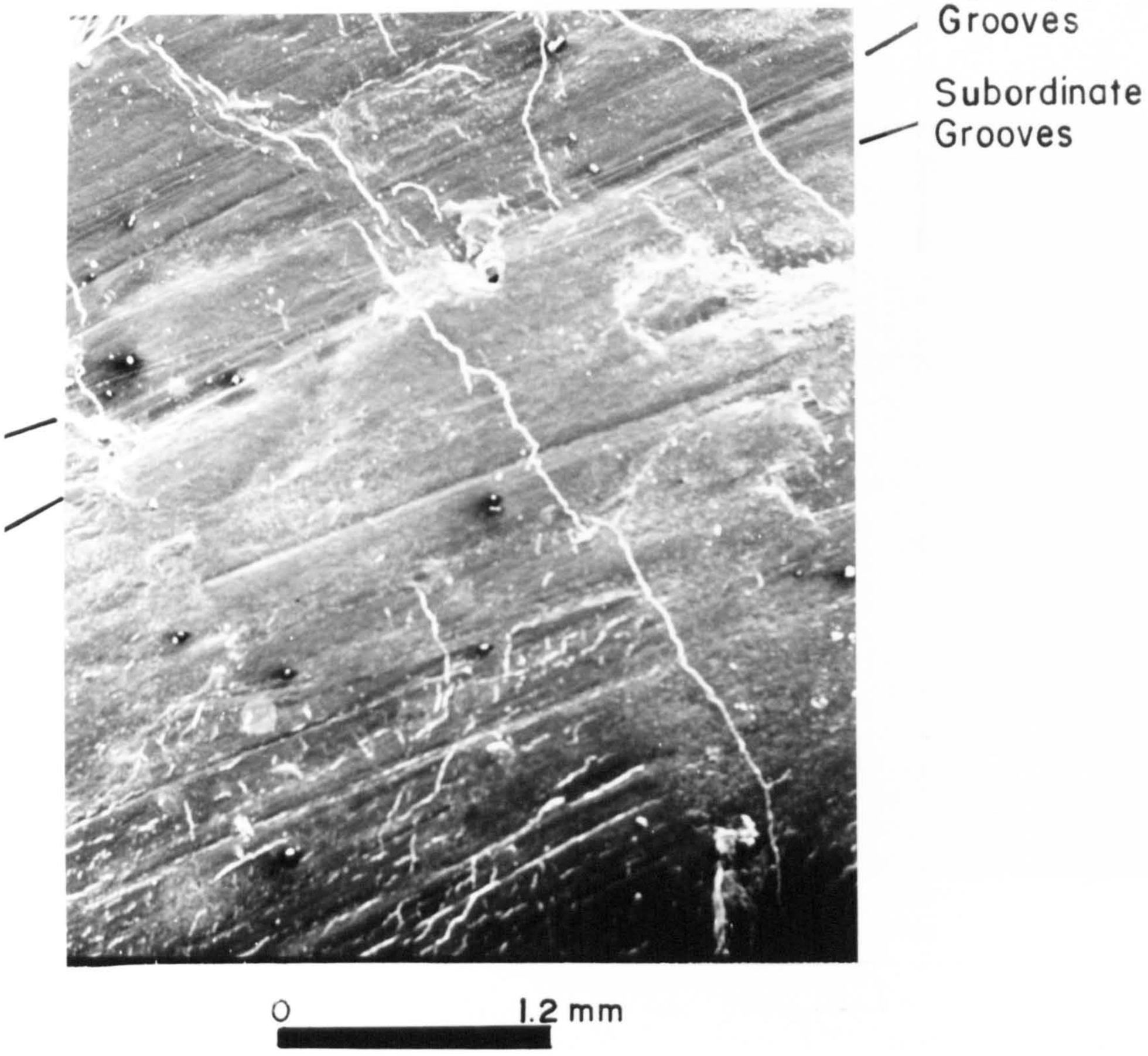


Figure 36. Photomicrograph of a slickenside surface. The dominant grooves are interpreted to have formed during the scouring event. The subordinate grooves are interpreted to have formed during post-scour reactivation of faults that affect sediments filling the scour mark trough.

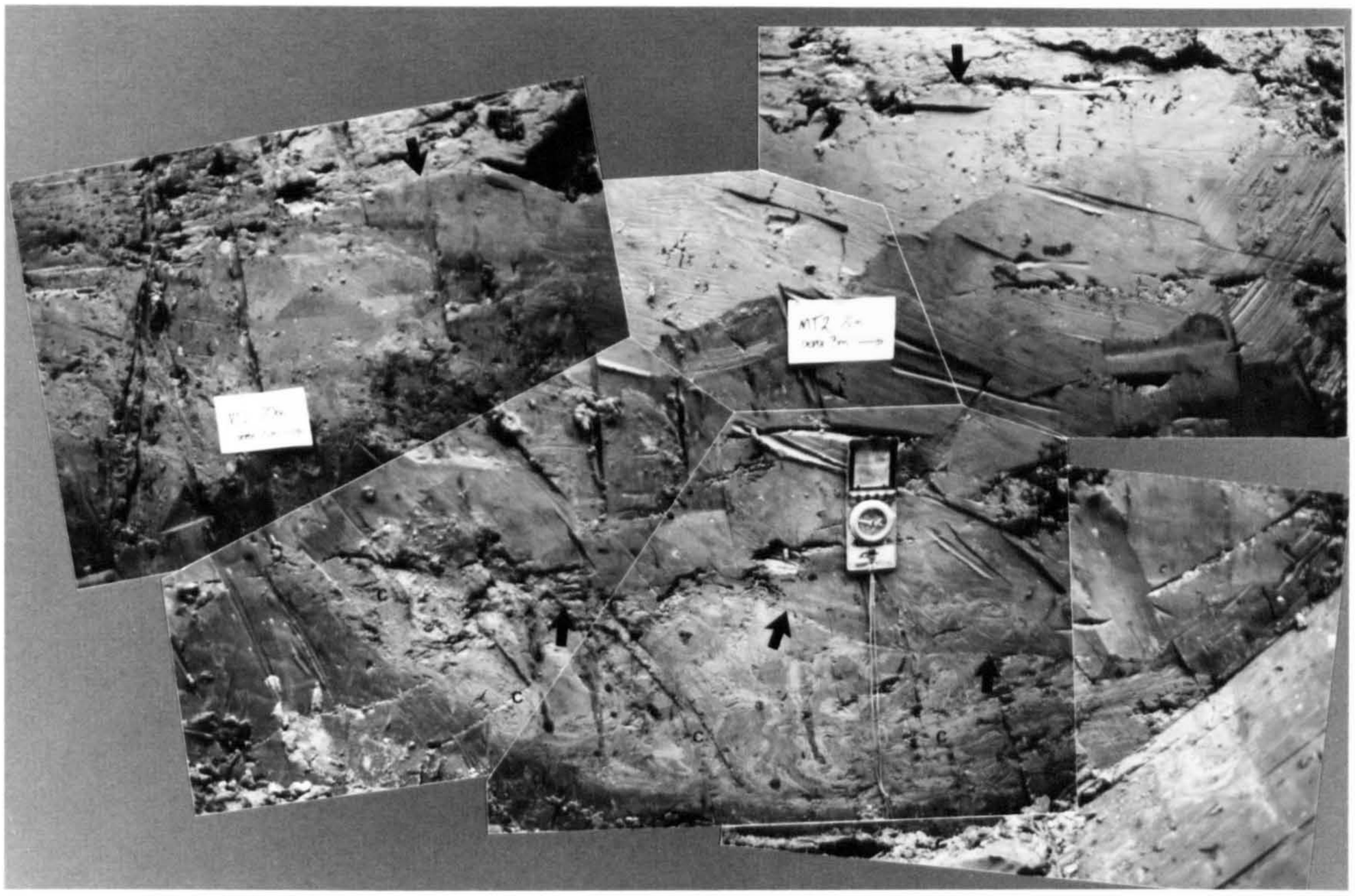


Figure 37. Block of brown and grey clay resting on deformed tan-coloured silty clay on the outer northwest berm of scour mark B, trench 2.

On the southwest side of the scour mark in trench 3 (beyond the original scour mark berms?) four low angle faults dip away from the scour mark trough. The angle of apparent dip (as measured on the trench wall) of each of these faults decreases progressively further away from the scour mark at 30°, 25°, 18° and 14° respectively. A similar low angle fault on the northeast side dips away from the scour mark at 34°.

III. Sub-horizontal faults. The low angle faults are connected by a sub-horizontal fault at a depth of about 4 m below the scour mark trough in trench 3. The sub-horizontal fault propagates from, and is continuous with, the low angle fault on the northeast side. Below the inflection point where the low angle fault becomes horizontal, two low angle offshoots continue downwards to the bottom of the trench. On the southwest side where they intersect, the horizontal fault is offset by one of the two low angle faults. The sense of displacement is normal with a dip-slip component of 70 cm.

In trench 2 sub-horizontal faults are developed at depths between 1 - 3 m below the scour mark berms (Figure 31). There are no physical links between these faults and the low angle faults, and slickensides were not seen on most of the excavated fault surfaces. Below the northeast berm rests a slab of brown and grey clay bounded on the top by the scour mark incision surface and on the bottom by a sub-horizontal fault (Figure 38). The slab rests on severely contorted laminated silty clays of the tan-coloured unit. Discontinuous faults occur beyond the low angle faults on the southwest side of trench 3. The faults have small apparent dips of

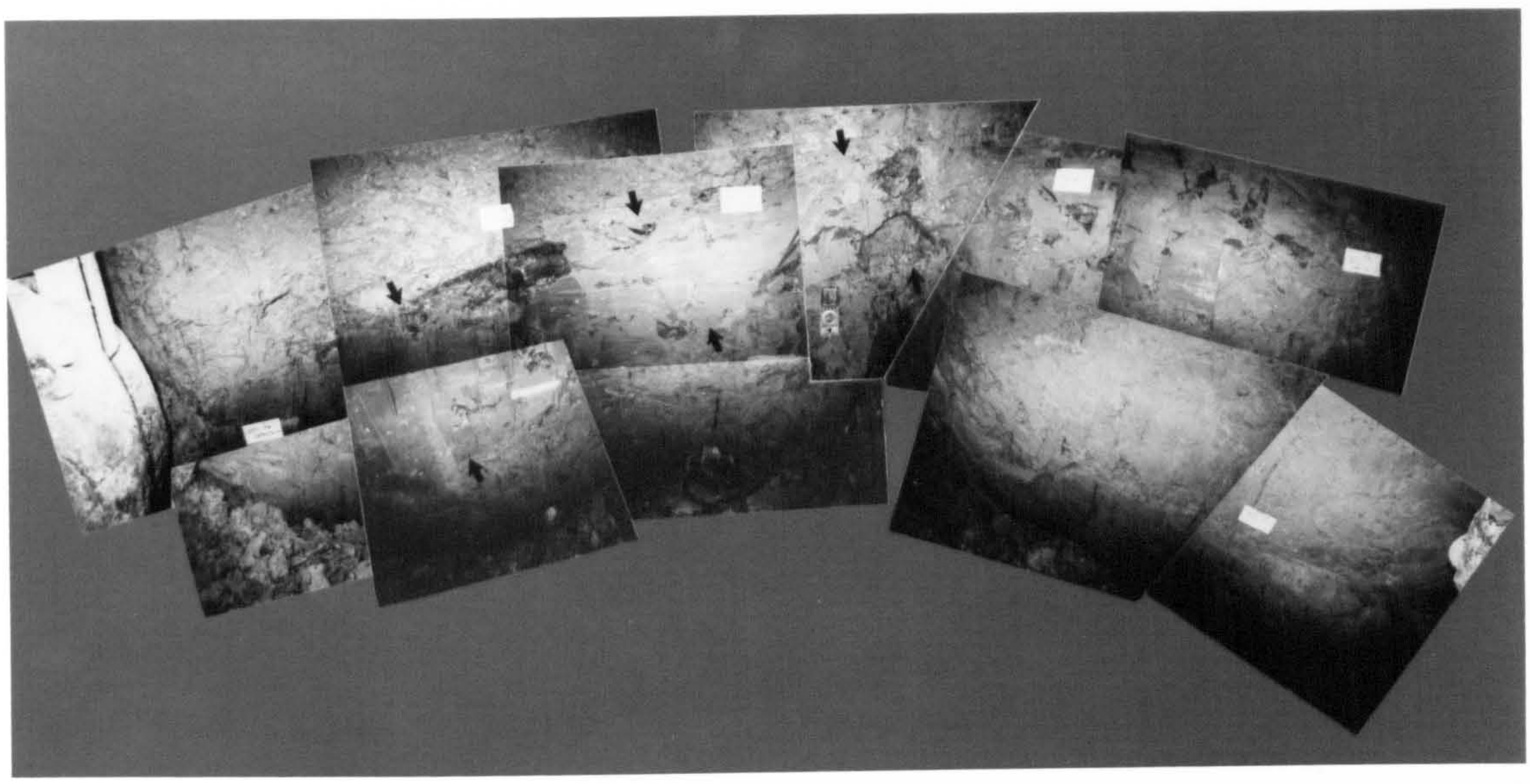


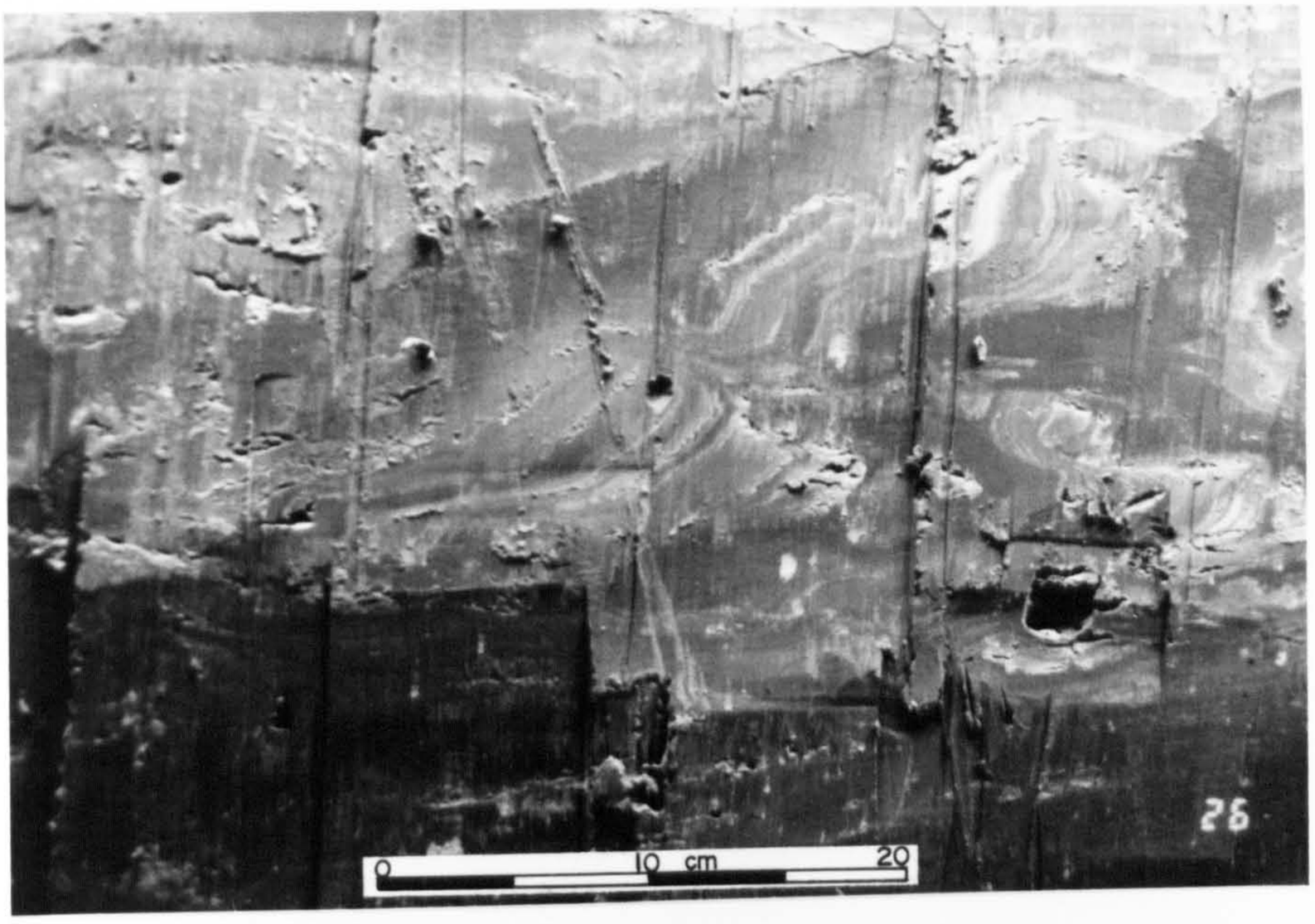
Figure 38. Thin slab of brown and grey clay resting on deformed tan-coloured silty clay, and bounded on the upper surface by post-scour, undeformed laminated silts.

between 5-10° to the southwest.

Folds and cleavage

Pre-scour primary bedding below scour mark B has been largely obliterated. However, discontinuous laminations can be traced over small distances but are generally confined to fold structures. Dislocated small scale (5 -20 cm), disharmonic, non-cylindrical folds typify the brown and grey clay and incorporated tan-coloured unit sediments. Folds range from open, tight to isoclinal and there is no consistency in fold symmetry even between adjacent structures (Figure 39).

Some folds are characterized by the presence of a well developed, non-fissile fracture cleavage. Cleavage planes are spaced about 1 mm apart with average displacements of 1 mm along the planes (Figure 40). Because they are associated with disharmonic folds there is no consistency in apparent cleavage orientation although it may be axial planar to specific folds. There is evidence that the cleavage is also folded (Figure 40b). The cleavage is seen only in association with the folds and cannot be traced into the structureless groundmass. In places where cleavage is not developed, micro-faulting may affect the silt/clay laminae.



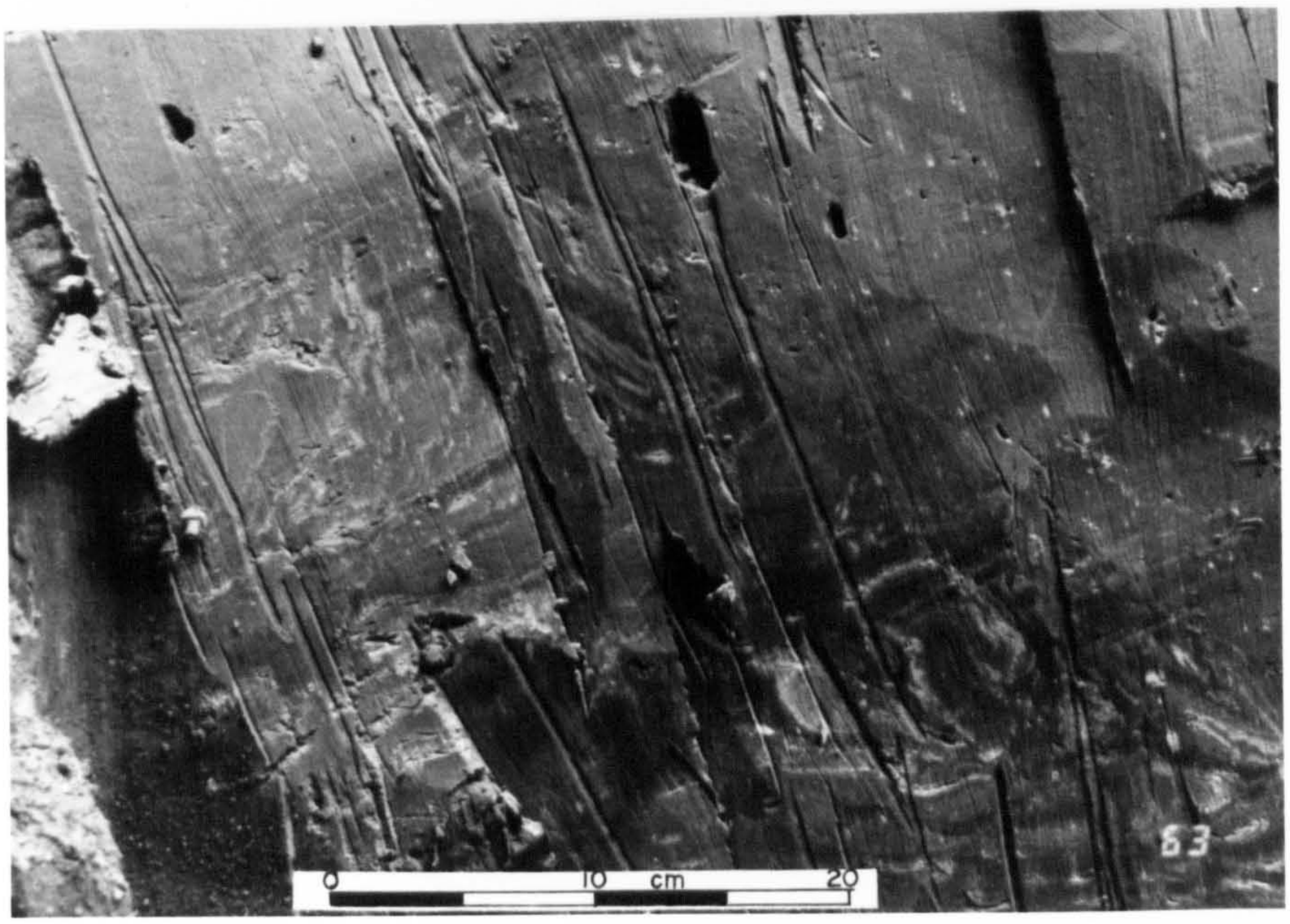
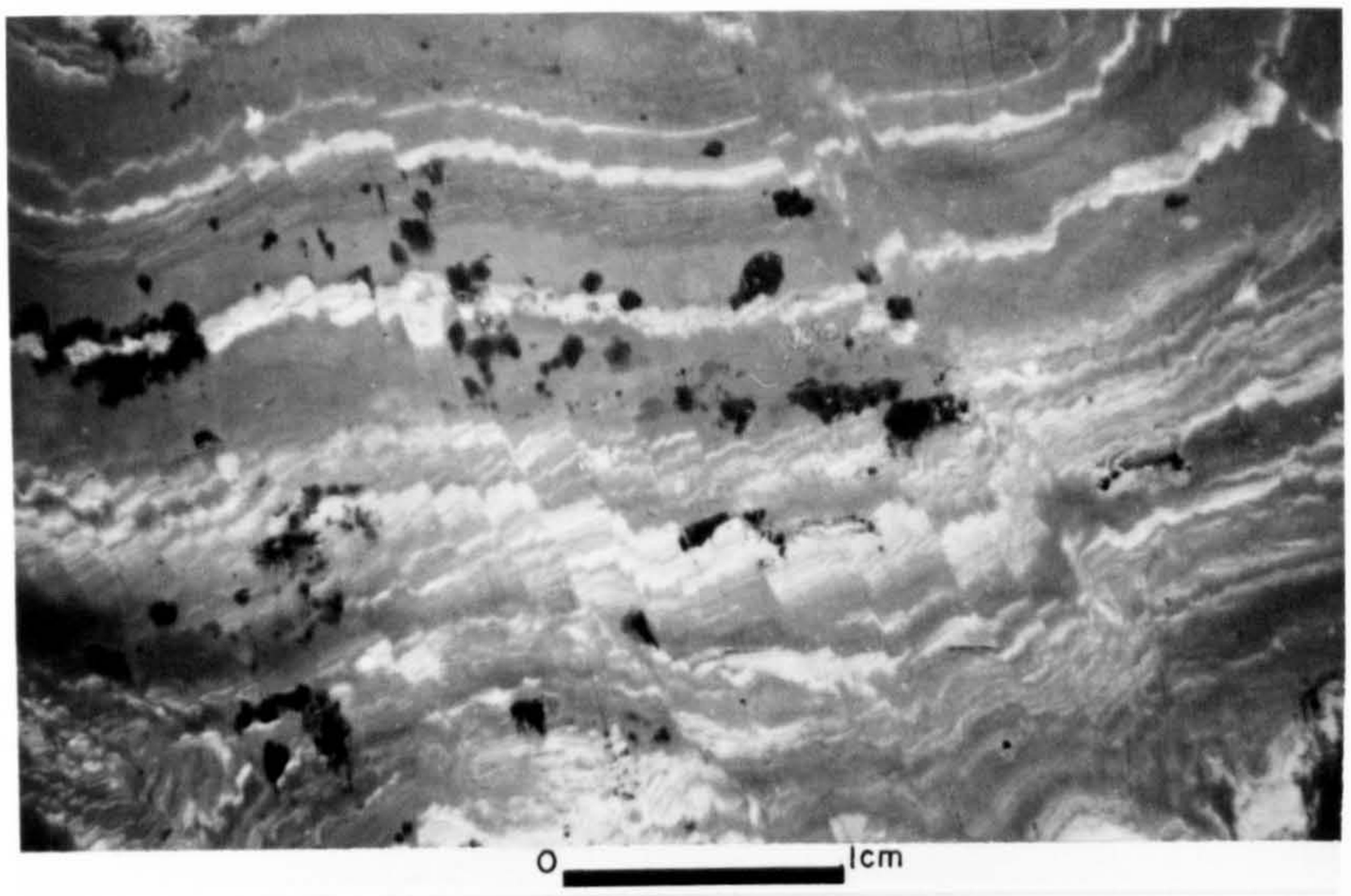


Figure 39. Typical fold structures in brown and grey clay beneath scour mark B. There is no consistency in fold symmetry.



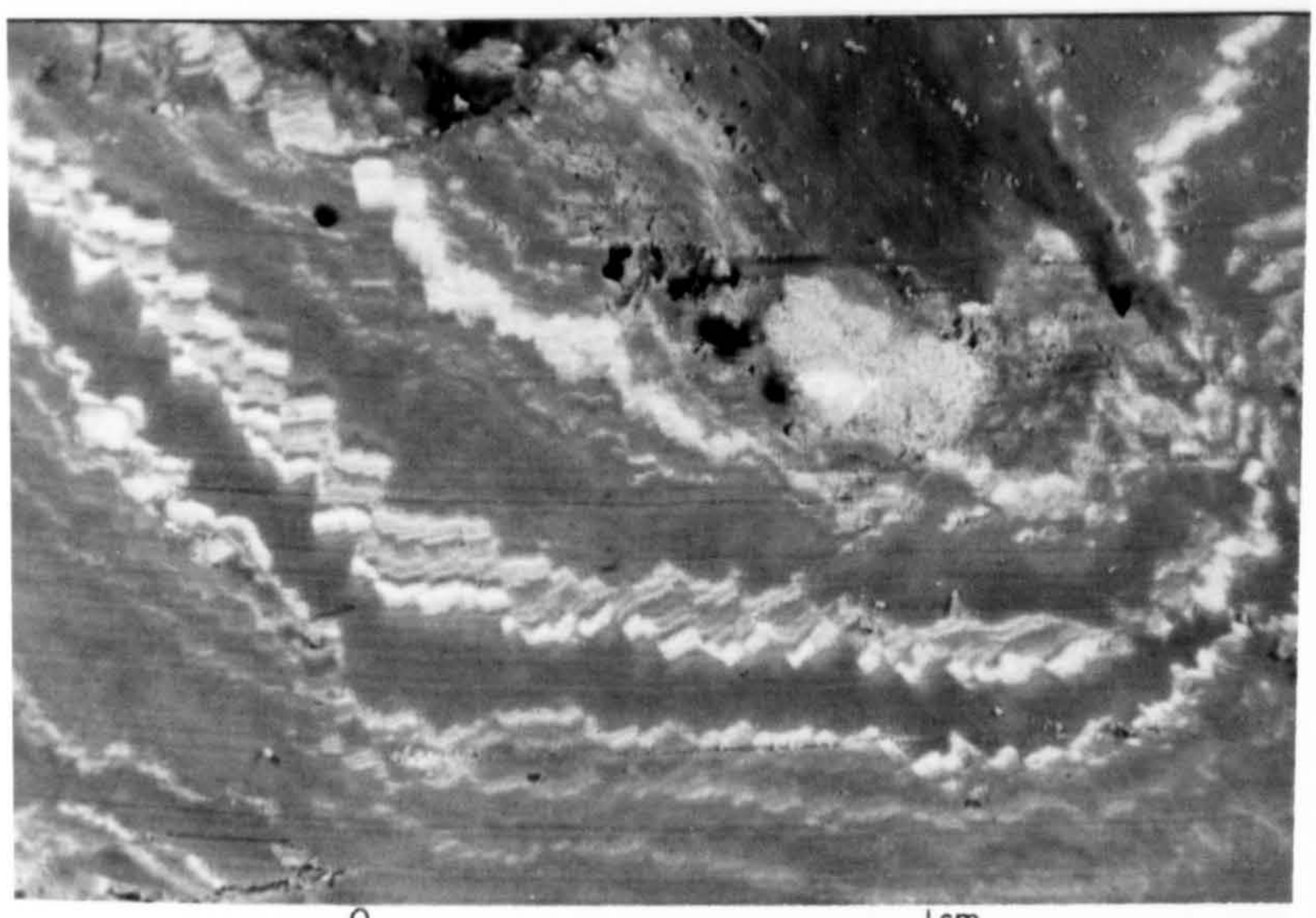


Figure 40a. Fracture cleavage developed in part of a small scale open fold from the brown and grey clay below scour mark B. Note the larger displacements associated with a band in the centre of the photograph where several cleavage planes are bounded by regularly spaced (approx. 4 mm) slip planes defined by larger offsets (approx. 2 mm).

b. Folded fracture cleavage in the limb of an earlier fold. Note the change in cleavage orientation from nearly vertical (left) to nearly horizontal (right).

Scour mark C

Sediments below scour mark C are typified by the occurrence of numerous unconnected fault segments often no greater than 0.5 m long (Figure 41). A low angle fault on the southwest side dips away from the scour mark trough at an apparent angle of 40°, becoming less steep near the bottom of the trench. Beyond this fault are two semi-circular faults with apparent dips of about 55° towards the scour mark trough. One of these two faults recurves to dip away from the trough at a similar angle.

A possible set of low angle faults, similar to the set exposed below scour mark B, occurs on either side of the deepest part of the scour mark trough. These dip towards the scour mark centre line at apparent angles of 35° and 70° on the southwest side, and at 40° on the northeast side. However, the interpretation of the faults as part of a low angle set cannot be verified because the trench was only excavated to 1.5 m below the deepest part of the scour mark trough. The faults extend below this depth.

Scour mark D

Below scour mark D undeformed horizontal layering is preserved between 1 and 1.5 m below the scour mark incision surface (Figure 42). The undeformed layering occurs in two zones, each approximately 8 m long on either side of the centre of the scour mark

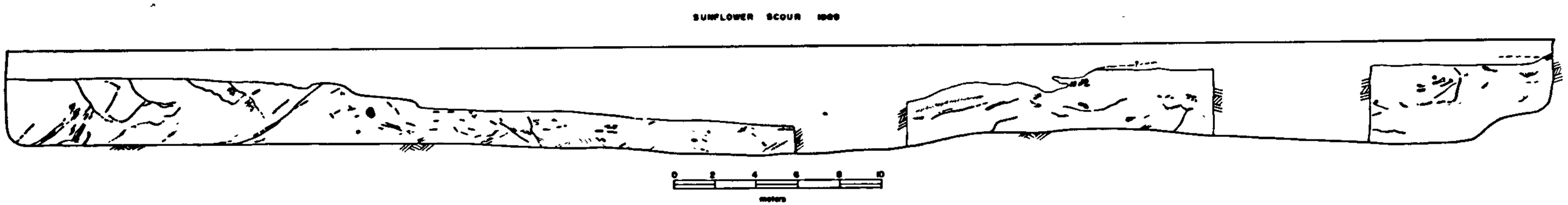


Figure 41. Cross-section through scour mark C showing incision surface (heavy, sub-horizontal line), numerous short, unconnected sub-scour faults (heavy, short lines) and deformed bedding (dots). The two gaps, at centre and on the right hand side, are where the trench collapsed, obscuring the section.

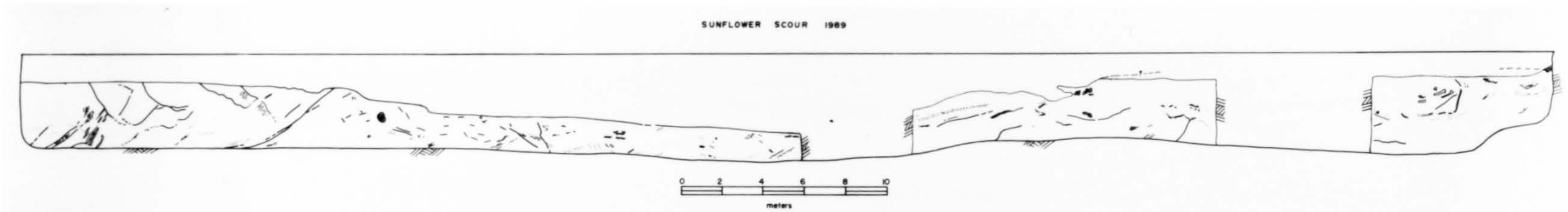


Figure 41. Cross-section through scour mark C showing incision surface (heavy, sub-horizontal line), numerous short, unconnected sub-scour faults (heavy, short lines) and deformed bedding (dots). The two gaps, at centre and on the right hand side, are where the trench collapsed, obscuring the section.

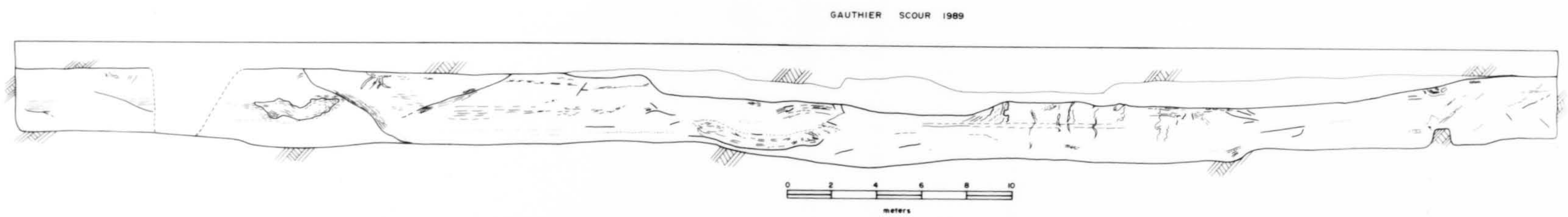


Figure 42. Cross-section through scour mark D showing incision surface (heavy, sub-horizontal line), sub-scour faults (heavy lines), and largely undeformed, horizontal bedding (dots, dashed and continuous light lines). The gap in data on the extreme left side is where the trench collapsed, obscuring the section.

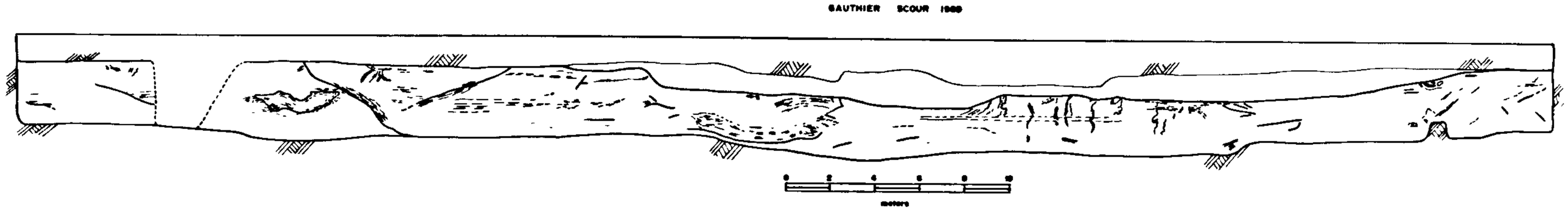


Figure 42. Cross-section through scour mark D showing incision surface (heavy, sub-horizontal line), sub-scour faults (heavy lines), and largely undeformed, horizontal bedding (dots, dashed and continuous light lines). The gap in data on the extreme left side is where the trench collapsed, obscuring the section.

trough, and at about 1.5 m depth below the incision surface. Between the undeformed zones a large sub-horizontal lens of reworked tan-coloured silt 5 m long and 0.75 m thick, has been structurally emplaced along a sub-horizontal fault that is at a depth of 3 m below the scour mark trough. A similar 3 m long lens of reworked tan-coloured silt occurs in the vicinity below the southwest berm. The upper surfaces of the two silt lenses are at approximately the same depth (1.5 m) below the incision surface as the undeformed layering.

Few continuous faults occur below the scour mark incision surface, and these do not conform to the well defined pattern observed at scour mark B. Notably two low angle faults are developed on the southwest side between the two lenses of tan-coloured silt. The faults propagate from the incision surface dipping towards each other, and almost intersecting, with apparent dips of 20° and 35°. Other faults do occur in segments up to 2 m long, and most of these have low apparent dip angles. The scour mark was excavated to a maximum depth of 2.5 m below the deepest part of the trough, and the deepest fault is 2 m below the deepest part.

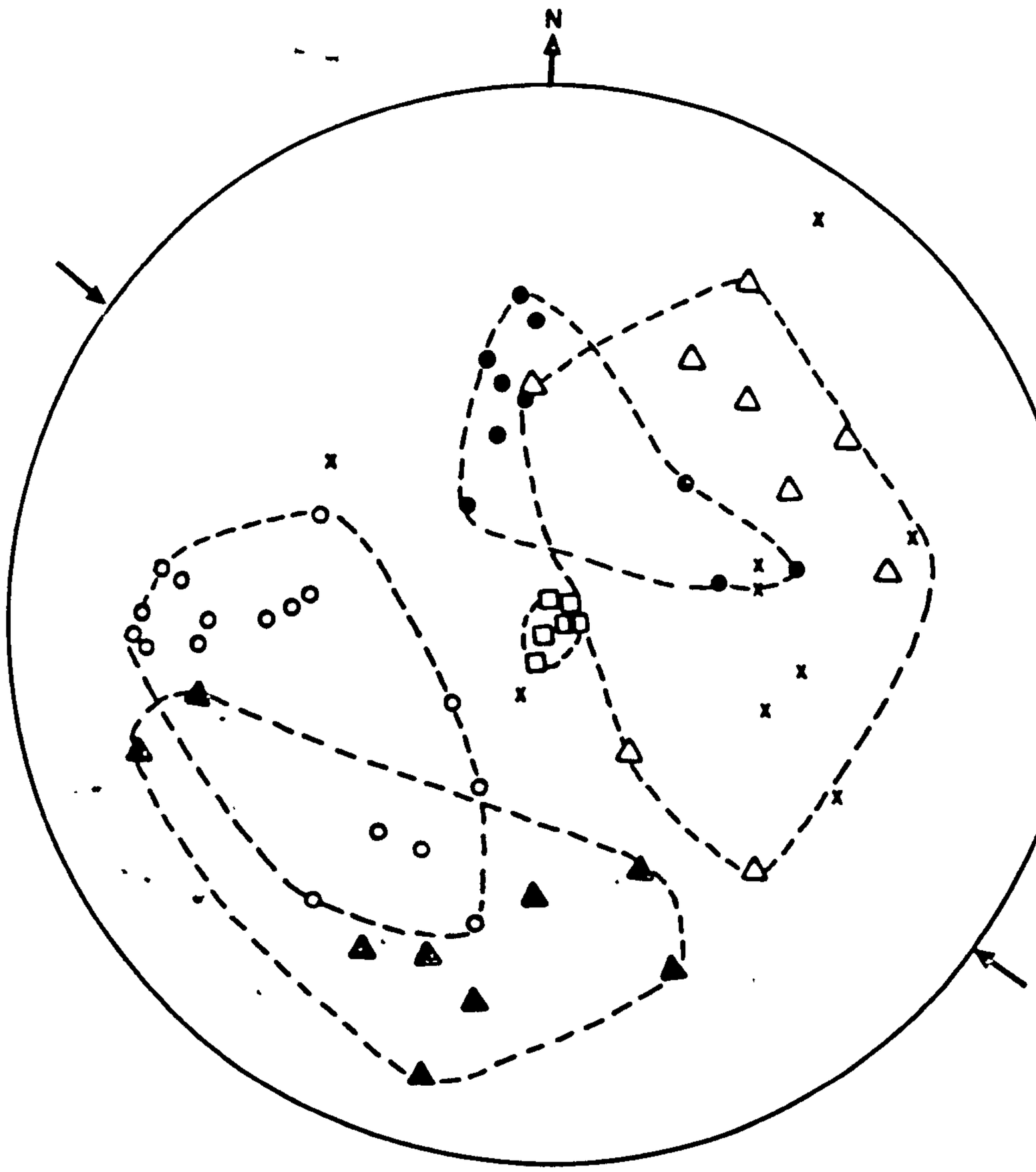
Structural data

Several methods for presenting stereographic data were attempted. For each scour mark these included: (1) plotting all fault surface measurements from one scour mark as

poles to planes on one diagram, (2) dividing faults into four groups based on apparent dips (as they appeared on the trench walls) to the left or right hand side, and plotting according to whether they occurred on the right or left hand side of the cross-section, (3) plotting each group on a separate diagram as great circles, (4) plotting all left-dipping and right-dipping faults as great circles on separate diagrams. Except for scour mark B, trenches 1 and 2 and scour mark C the latter option was adopted because, although resulting in rather cluttered diagrams it assumes no previous interpretation to the significance of apparent fault dip. Structural data for scour mark B, trenches 1 and 2 were plotted as poles to planes on a single diagram. This method best shows the structural symmetry of faults. Structural data for scour mark C were plotted on two separate diagrams because the clutter from a single diagram made analysis impossible. In this case the left- and right-dipping faults were plotted on separate diagrams. The stereoplots are presented in Figures 43 - 45. There are no structural data for scour mark A.

Scour mark B

Data obtained from the two dominant low angle trough faults in trenches 1 and 2 are symmetrically disposed about the scour mark axis within two distinct domains (Figure 43). The spread of points parallel to the scour mark axis suggests an overall cusp - shaped fault geometry, the general attitude being slightly oblique to the axis. Slickenside data from the two faults also fall into two domains on either side of the scour mark axis (Figure 43), and



- Low angle fault (NE side of scour)
- Low angle fault Slickensides(NE side of scour)
- Low angle fault (SW side of scour)
- Low angle fault Slickensides (SW side of scour)
- Horizontal faults
- High angle faults

Figure 43. Stereo plot of fault and slickenside data from scour mark B, trenches 1 and 2, plotted as poles to planes. Arrows indicate orientation of scour mark axis. Taken from Woodworth-Lynas and Guigné (1990), Figure 7.

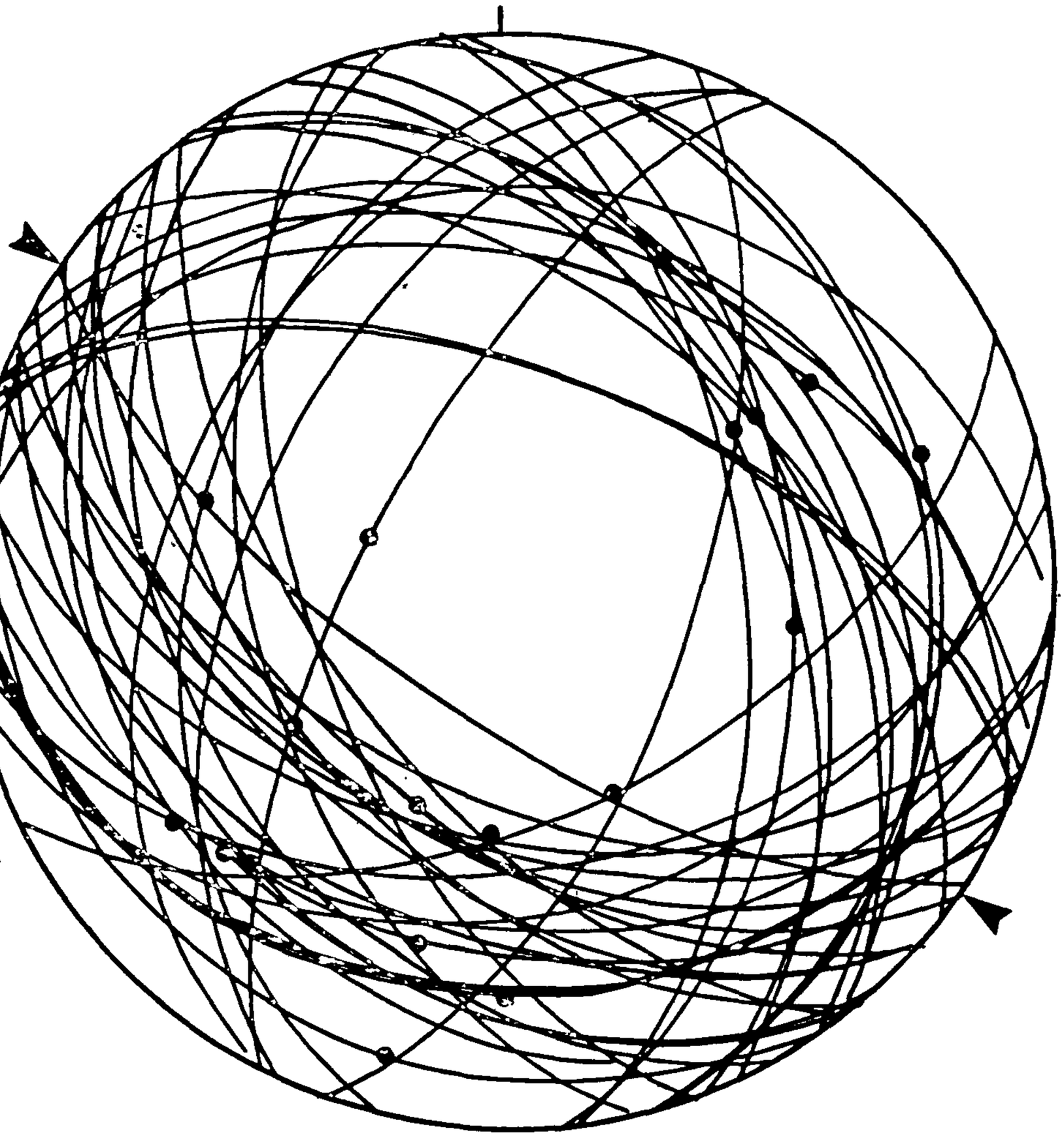


Figure 44. Stereo plot of fault and slickenside data from scour mark B, trench 3. 47 fault plane readings (great circles); 17 slickenside readings (black dots). Tick mark is north; arrows indicate orientation of scour mark axis.

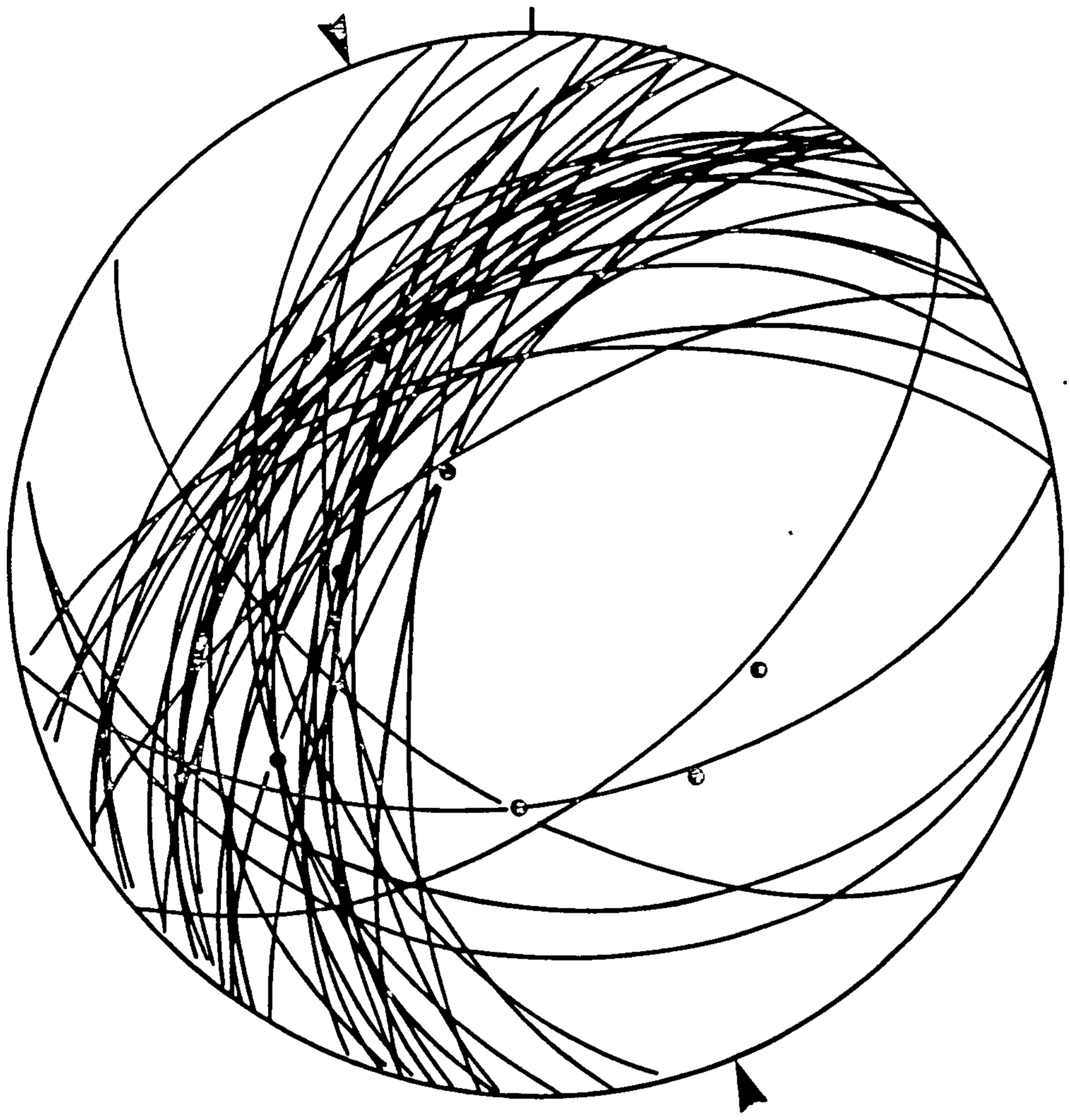


Figure 45a. Stereo plot of fault and slickenside data from scour mark C showing *left-dipping* faults. 68 fault plane readings (great circles); 12 slickenside readings (black dots). Tick mark is north; arrows indicate orientation of scour mark axis.

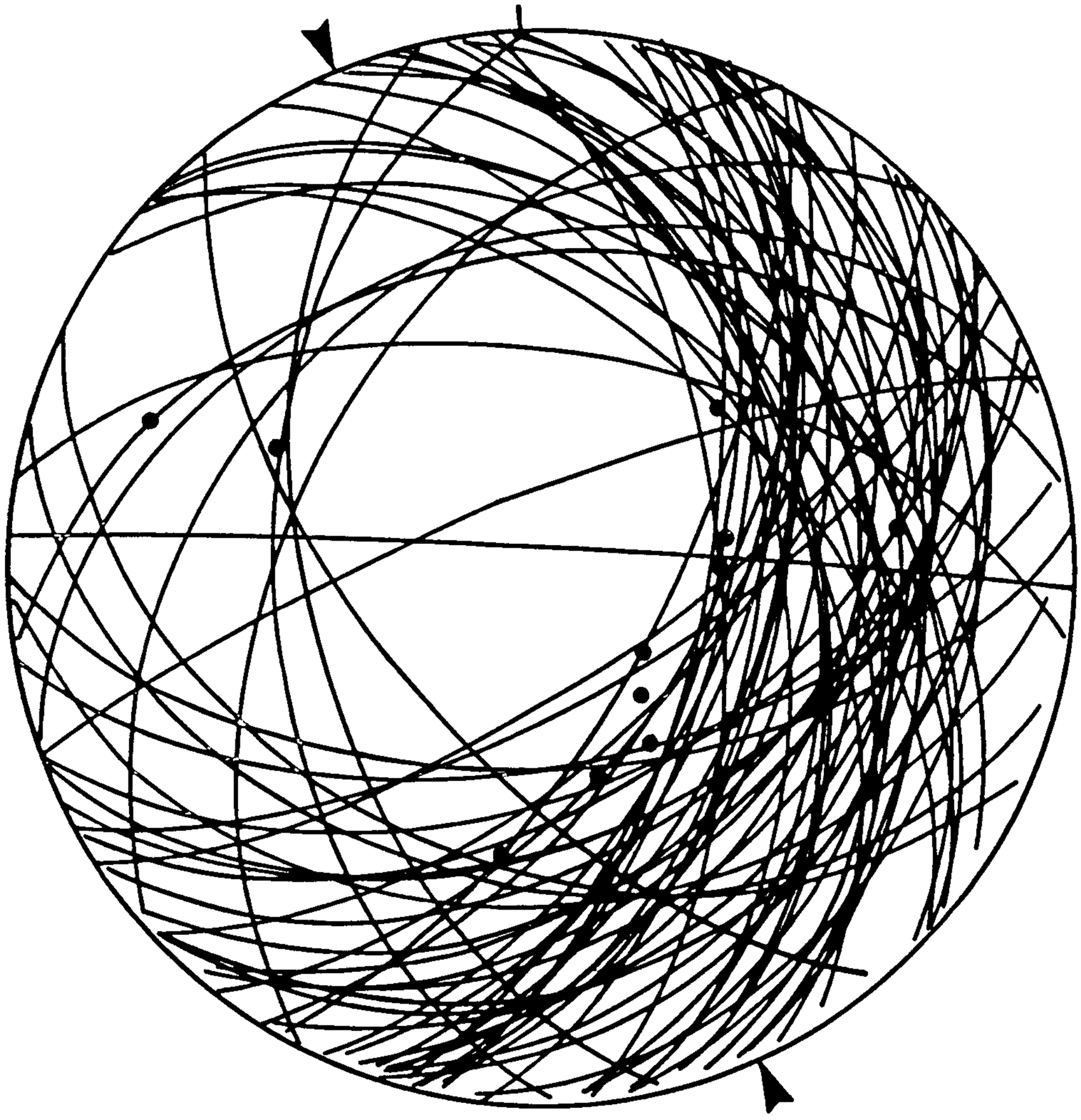


Figure 45b. Stereo plot of fault and slickenside data from scour mark C showing *right-dipping* faults. 37 fault plane readings (great circles); 7 slickenside readings (black dots). Tick mark is north; arrows indicate orientation of scour mark axis.

are consistent with a sense of displacement symmetrically oblique to the scour mark axis.

Figure 44 shows data from all low angle faults in trench 3 with apparent dips to the left and right of the scour mark trough, and also data from the horizontal fault below the central region. Although there is considerable spread in fault surface attitude, general clustering in a southwest-dipping and northeast-dipping group occurs symmetrically about a vertical plane approximately parallel to the scour mark axis (126°), with dips averaging about 40° and a separation angle between the groups of about 100°. A minor west-northwest and an east-southeast-dipping group disposed about a vertical plane, oriented about 020-030°, is also apparent with a separation angle of between 60-70° and dips of between 50-60°. Slickenside data have a wide range of plunges between 10-70°, but are nearly all restricted in orientation to the southeastern hemisphere of the diagram. No slickenside data were retrieved from the horizontal fault which connects the low angle faults.

High angle faults from both margins also fall into two nearly orthogonal sets symmetrically arranged about vertical planes, one parallel to the scour mark axis and the other between 0-25° (Figure 44). The separation angle between both groups is about 70-80°. The few slickenside measurements suggest a sense of motion along the 0-25° fault set orthogonal to the fault plane intersection.

Scour mark C

Faults with apparent dips to the left and right hand side of the scour mark are shown in Figure 45. Both sets generally dip between 35-70° to the northwest and southeast respectively, and are symmetrical about a vertical plane oriented at about 030-040°. This orientation is 50-60° east of the scour mark axis orientation (160°). The fault sets have a separation angle of between about 100-120°, similar to scour mark B. Slickensides plunge in a range between 20-70°, with most data retrieved from the right-(southeast) dipping set.

Scour mark D

Faults below this scour mark show a wide spread in orientation but with dips concentrated between about 15-45° (Figure 46). Clustering of faults into groups can not be distinguished.

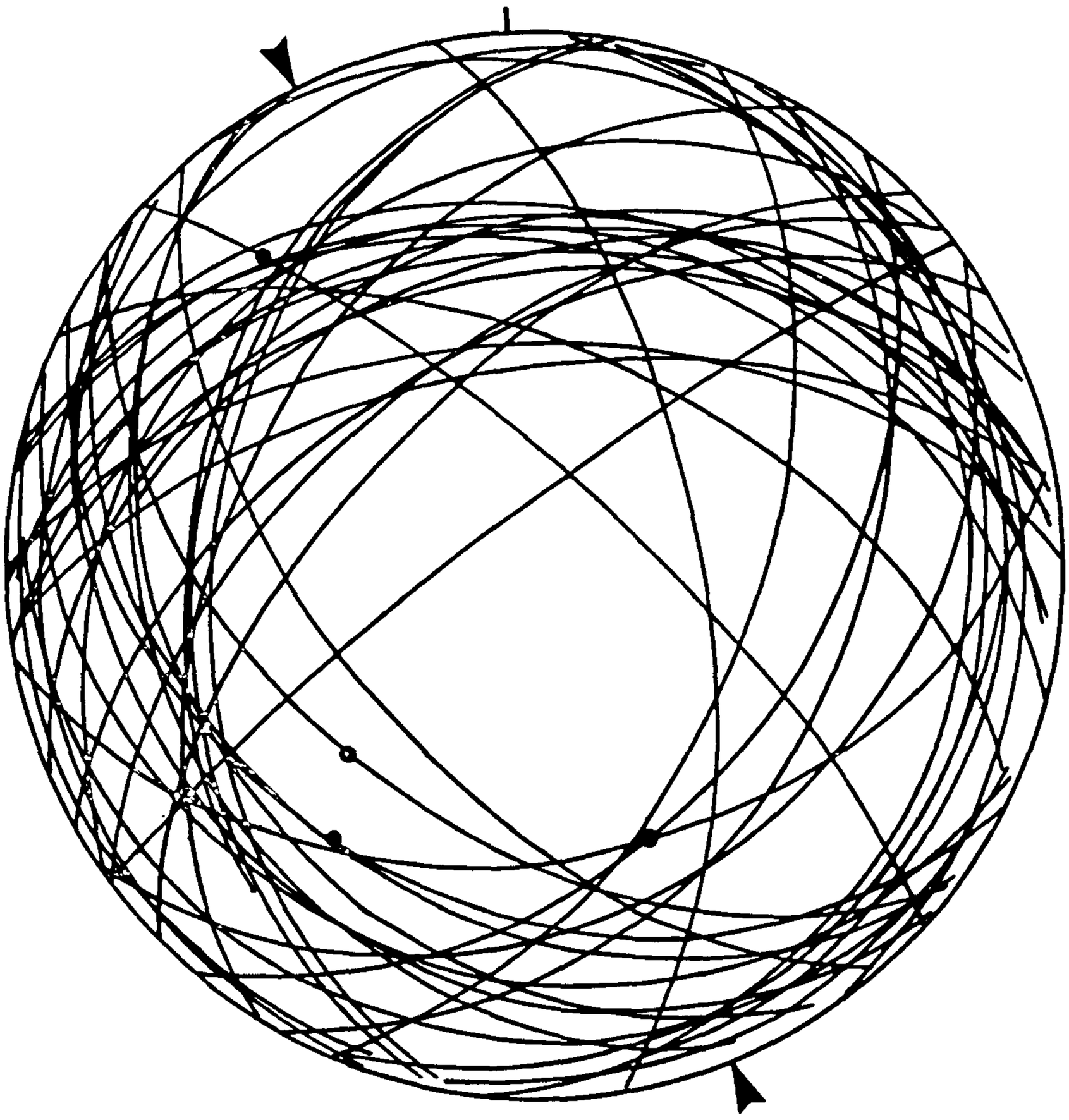


Figure 46. Stereo plot of fault and slickenside data from scour mark D. 45 fault plane readings (great circles); 4 slickenside readings (black dots). Tick mark is north; arrows indicate orientation of scour mark axis.

Interpretation

Regional geological correlations

In general, numerous faults often with well developed slickensided slip surfaces occur in, and are restricted to, the brown and grey clay beneath the scour marks. The unit is heavily reworked resulting in the general absence of laminae, except in isolated pockets (below scour mark D) and in small scale, dislocated fold hinges. Deformed, discontinuous bedding laminations and dislocated fold hinges associated with cleavage are features commonly associated with highly deformed tectonic rocks. These features occur in the brown and grey clay, most notably beneath scour marks B-D, and are an indication that the material has experienced intense deformation. There are no tectonic mechanisms operating in this region of the earth's surface that could generate forces sufficient to create these structures, and there is no evidence of tectonism elsewhere in the Lake Agassiz basin. Scouring icebergs can impose large forces and strains in sediments (e.g. Poorooshasb *et al.* 1989), and because these deformation structures are associated with iceberg scour marks it is interpreted that they were created during the scouring process. The brown clay unit is also characterized by the presence of matrix-supported calcareous and crystalline rock clasts. In the absence of regional slopes that might have allowed debris flows to introduce coarse material into this part of the Lake Agassiz basin, it is probable that these clasts, which include occasional cobbles, were imported by the process of iceberg-rafting. The characteristic association of these features in the brown and grey clay with similar features

described by Teller (1976) means that the clay can be reasonably interpreted as belonging to Unit 1. If this is the case, it is possible that all or much of Unit 1, which occurs in large areas of southern Manitoba, northern North Dakota and northern Minnesota, has been affected by scouring ice keels and is, therefore, an ice keel turbate.

Folds and cleavage

Fracture cleavage is seen only in dislocated fold hinges because of offset bedding laminations in Unit 1. Cleavage surfaces are actually micro-faults with offsets of about 1 mm. A cleavage fabric cannot be defined in the largely structureless groundmass that constitutes the bulk of the Unit 1 clay. Where it is axial planar to fold hinges the fracture cleavage is probably associated with fold development. It is interpreted that the cleavage formed in response to scouring forces. Observations of scour-induced fracture cleavage may support the experimental results of Maltman (1987), who showed that bulk strain in unlithified fine-grained sediments is accommodated not by pervasive homogeneous flow but along discrete shear zones.

In some places the fracture cleavage imprints earlier folds and is not axial planar, and in others it has been folded. These two pieces of corroborative evidence suggest that some fold structures and cleavage may be reworked relics from an earlier scour event, or that they are the products of progressive deformation from a single event during which changes

occurred in the orientation of principle stress and in deformation mechanisms. Evidence to support both suggestions is good. The evidence for inheritance of structures from older scour marks is circumstantial. Aerial photographs of the study area show high concentrations of intersecting scour marks visible on the ground surface, multiple scouring obviously having occurred at the cross over points. Even though the position of trenches for this study were carefully chosen so as to avoid scour mark intersections it is possible that earlier features are buried just below the ground surface.

Small scale chevron folds beneath scour mark A have vertical axial surfaces and are restricted in their occurrence to just below the scour mark trough. They are thus probably a near-surface phenomenon and are interpreted to have formed in response to horizontal forces generated by the lateral displacement of sediment as the scouring keel passed this region. It is not clear whether the foliation that defines the fold limbs is sedimentary or tectonic (scour-induced) in origin.

Chevron folds commonly form through the progressive development of coalescing kink bands (e.g. Park, 1983), but there is no evidence to support such a mechanism in this case. The scour mark incision surface has not been affected by the folds and it is interpreted that they were truncated by the passing keel either during fold generation or immediately after they were formed.

Structural analysis of faults

Before reading further it must be pointed out that the following analysis of structural data is possibly complicated by two factors. One is that scouring is a dynamic process, and sediments affected by it are likely to experience progressive deformation resulting in the development of fault structures whose initial, intermediate and final orientations are probably quite different. This factor is discussed further below. The second factor, that may be cumulative with the first, is that some faults may have been formed during a previous scour event and were incorporated, and possibly reactivated, with new structures formed during the later events which created the scour marks being studied here. Differentiating relic and reactivated faults is probably impossible and is not attempted.

However, the analysis is approached with some confidence on two grounds. The first is an assumption that long, continuous faults are probably the product of a single scour event. Short faults may also form during a single scour event, but alternatively they may be the segmented remnants of long faults formed during a previous event(s). Thus more significance is attached to the presence of long faults and to the structural data obtained from them. The second is that long faults that display a conspicuous symmetry in orientation and position with respect to the scour mark trough are probably related to one event; this situation is particularly apparent beneath scour mark B.

The initial interpretation of the origin of low angle trough faults below scour mark

B by Poorooshasb *et al.* (1989) and Woodworth-Lynas and Guigné (1990) was that of classic bearing capacity failure, induced by the downward-directed load of the scouring keel (Figure 47). This interpretation is developed further in the following discussion.

Horizontal faults

The horizontal fault that connects the two low angle trough sets at between 4-5 m below the trough of scour mark B in trench 3 is a feature not observed in either of trenches 1 or 2, which did not reach this depth. The horizontal fault is a physical extension of the low angle fault on the right hand side of the scour mark, but is offset by the low angle faults on the left side indicating the contemporaneous origin of both. Because the horizontal fault is genetically linked to the low angle trough set, horizontal motions associated with it must also have occurred at the same time. Woodworth-Lynas and Guigné (1990) showed that horizontal displacement of clay slabs, at a higher elevation, was responsible in part for construction of the scour mark berms. The horizontal fault is the first indication of deep-seated horizontal shear in sediment below a scour mark trough. There is some evidence that the fault began forming ahead of the keel on the left hand side because it is offset by low angle faults which are shown to have developed beneath the keel (Woodworth-Lynas and Guigné, 1990).

Below scour marks B and D, slabs of brown clay, their lower surface defined by a

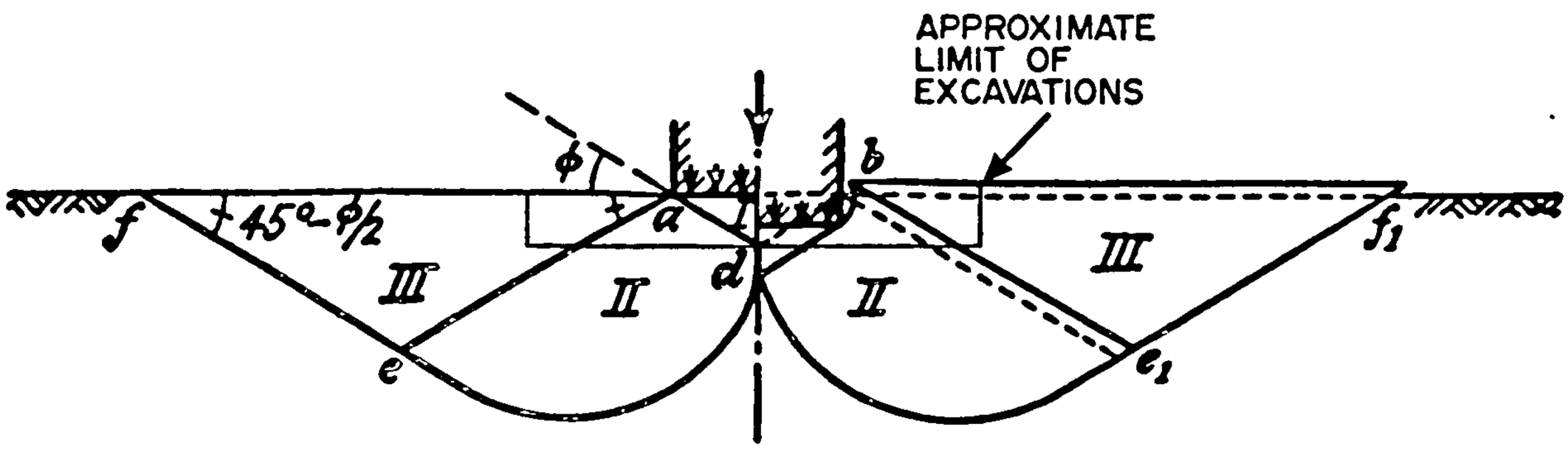


Figure 47. The kinematic model for two-dimensional shallow bearing capacity failure beneath a scouring keel (adapted from Terzaghi, 1959) as advanced by Poorooshasb *et al.* (1989). The triangular-shaped area (*I*) beneath the keel is the zone bounded by the low angle faults and the scour mark incision surface. A normal sense of fault motion is implied. Two zones (*II*) of radial shear, *ade* and bde^1 occur on either side of zone *I* and two passive Rankine zones (*III*) beyond. The approximate area represented by the excavations of scour mark B is shown. This interpretation implies the continuation of low angle faults to at least 9 m below the deepest part of the scour mark trough.

sub-horizontal fault, rest on top of deformed silty clays of the younger tan-coloured unit. Such structural stacking of older sediments above younger implies upward vertical, and horizontal components of movement of the brown clay slabs, and downward vertical displacement of tan-coloured silts to a position below the base of their stratigraphic occurrence.

Unit 1 clay rests on reworked silt at two locations beneath each of these two scour marks. One location is from scour mark B (trench 1) where a downfaulted clay block (see Figure 37) rests on deformed silt below the outer berm. Another is below the inner northeast berm of scour mark B (trench 2). Here a clay slab has been overridden by the scouring ice keel because its upper surface is continuous with the scour mark incision surface on either side (see Figure 38). Below the trough of scour mark D the presence of two sub-horizontal lenses of tan-coloured silt at 1.5 m depth suggests that the silt has been similarly structurally incorporated in the matrix of the brown and grey mottled clay.

It is interpreted that the clay slabs originated from a structurally lower region near the centre of the scour mark. Horizontal loads in the sediment ahead of the encroaching iceberg keel caused decoupling of the slabs along décollements within the brown and grey clay. Forward, upward and outward translation of the "rigid" slabs occurred as the keel approached. The thrust surfaces penetrated through an overlying thin deposit of tan-coloured silt to the lakebed surface. As the clay slabs overrode the silt, thrust movement possibly accounted in part for reworking of the younger material. The scouring keel

overrode thrust slabs trapped in the central part of the scour mark trough, as at scour mark D and below the inner northeast berm of scour mark B, possibly causing additional reworking of the silt. Thrust slabs closer to the berms were pushed aside as the keel passed and may have collapsed, under self-weight, on the outer berm margins, as at scour mark B (trench 1).

Three sub-horizontal faults, arranged one above the other, occur on the southwest margin of scour mark B (trench 1), but there are no tan-coloured unit sediments beneath them. Although there is no direct evidence, the development of these faults beneath the scour mark margin suggests the sequential structural stacking of horizontal blocks of brown and grey clay displaced, as in the other scour mark margin, from the central part of the scour mark by the scouring keel. Such stacking is envisaged as being responsible for generating positive relief of the scour mark berms.

Low angle faults

Direct physical evidence for the presence of low angle trough fault sets below scour marks A, C and D is scant. However when structural data from *all* faults from scour marks B and C are examined on stereo plots, similar geometries can be seen. Specifically, a dominant fault set with a wide separation angle (about 100-120°) can be distinguished, as well as a secondary set below scour mark B. With the exception of the existence of the

horizontal fault below scour mark B (for which no structural data exist), the consistencies in fault dip and separation angle about vertical planes are evidence that these are conjugate fault sets. Normally the acute angle of a conjugate fault set is bisected by the maximum principal stress, $\sigma 1$, and the intermediate principal stress, $\sigma 2$, is parallel to the line of intersection of the two fault sets (e.g. Park, 1983). During a scouring event $\sigma 1$ will be nominally a vertical stress imparted by the scouring ice keel.

The orientation of conjugate fault sets with respect to the scour mark axes from scour marks B and C is not consistent, and from scour mark B two sets can be identified, whereas from C only one set is present. These variations in orientation should not be seen as inconsistencies because there is no reason to expect that conjugate faults developing beneath an instantaneous vertical load should assume a preferred orientation if the soil has no previous structural fabric that will inhibit fault growth in some orientations and promote it in another. Similarly there is no requirement that only one conjugate set should develop, although once initiated, stress is more likely to be accommodated by movement along an existing fault set than it is by creating another set until, as discussed below, changes in the stress regime cause an initially favourably-oriented set to lock up.

Except for scour mark B, slickenside data generally show no obvious consistencies that can provide a basis for meaningful discussion of possible fault motions. Scour mark B slickenside data from trenches 1 and 2 do show clustering, although spread, that indicates general motion orthogonal to the line of intersection of low angle trough faults (Figure 43).

A similar left-side- and right-side-plunging set slickensides associated with low angle faults is apparent from trench 3 (Figure 44). The spread in plunge direction can be accounted for most easily by changes in the direction of fault motion as the scouring keel passed. Although based on scant data, a similar sense of fault motion may have occurred along the minor northeast-trending conjugate berm fault set below scour mark B (Figure 44). Dominant dip-slip motion is suggested along the low angle faults. The interpretation of 3.5 m dip-slip displacement along the right hand side low angle trough fault below scour mark B (trench 2) is thus further strengthened (see Figure 31).

Evidence for progressive deformation

The lack of a recognizable structural fabric from scour mark D can be interpreted in part as representing the incomplete development of one or more conjugate fault sets. Additionally, the large spread in orientation and dip angles of the fault surfaces from beneath all the scour marks reflects the dynamic nature of scouring. If a scouring keel is viewed as delivering an instantaneous, static, vertical load to the soil at any one time then a conjugate fault set, or sets, may begin to develop in response. But a parcel of soil, fixed in space, will experience continuous changes in stress regime as a scouring keel moves past it. Similarly a scour-induced fault, once initiated, will immediately experience changes in stress orientation. Some faults will be able to continue propagating in their initial orientation until normal stress exceeds shear stress thereby causing them to lock up.

Alternatively, faults may continue propagating in new orientations to enable stress relief to continue, or new faults will develop in response to the new instantaneous load. Changes in propagation direction may account for the development of small scale hummocky relief seen on exposed fault surfaces.

Continuous stress change could thus result in the development of short faults which reflect initiation followed by rapid abandonment as other, more favourably oriented faults develop. Also, longer faults should exist that have survived by continual changes in propagation orientation and in dip angle. Further modification may occur as a result of bulk soil displacements that cause rotation of both locked up and active faults. Such predicted short faults, and long faults that exhibit changes in dip and orientation, are present beneath all of the scour marks. The most pronounced features are the two long conjugate faults below scour mark B. These features represent accumulated strain involving significant soil displacements, with measured dip slip offset of at least 3.5 m.

Poorooshasb *et al.* (1989), in their analysis of physical model scour tests, and of data collected from scour mark B, interpret the long faults to have developed in response to bearing capacity failure in the sub-keel sediments. In this interpretation a triangular-shaped wedge of material, bounded by the low angle faults and the scour mark trough incision surface, is displaced downwards (zone I of Terzaghi, 1959). This interpretation indicates a normal sense of fault motion along the low angle faults, an interpretation supported by the observed normal offset (70 cm) of the horizontal fault on the left hand side of the scour

mark. The Terzaghi model also implies continuation of the faults well below the depth of excavations (Figure 47). Extrapolation of the apparent dips of the low angle faults below scour mark B (trench 2) indicates that they should intersect at a position approximately 9 m below the deepest point of the scour mark incision surface (Figure 48). Unfortunately, because of safety reasons, it was not possible to reach this depth to verify the extrapolation in the trench excavated across scour mark B. In the bearing capacity failure model two zones of radial shear (zone II of Terzaghi, 1959) are developed on either side of zone I that are displaced outwards along basal log spiral faults. Beyond these occur two triangular-shaped passive Rankine zones (zone III of Terzaghi, 1959) that are displaced upwards and outwards. Below scour mark B, the area where a Rankine zone would occur on the southwest side is characterized by a series of low angle faults each with progressively shallower apparent dips further from the scour mark. Such a geometry may be initiated by soil collapse along discrete failure planes in response to the upward movement of the zone. In this case fault motion would thus be normal.

The low angle trough faults from scour mark B showed evidence of post-scour reactivation from offsets in the scour mark incision surface and in overlying sediments of the tan-coloured unit in trench 1. Electron micrographs of the slickenside fault surfaces show a dominant as well as a subordinate set of micro-grooves that cross-cut the dominant set at a slight angle (see Figure 36). The dominant set is interpreted to correlate with large motions that occurred during the scouring event. The subordinate set is interpreted to have formed during the post-scour phase of normal faulting that may have been induced by

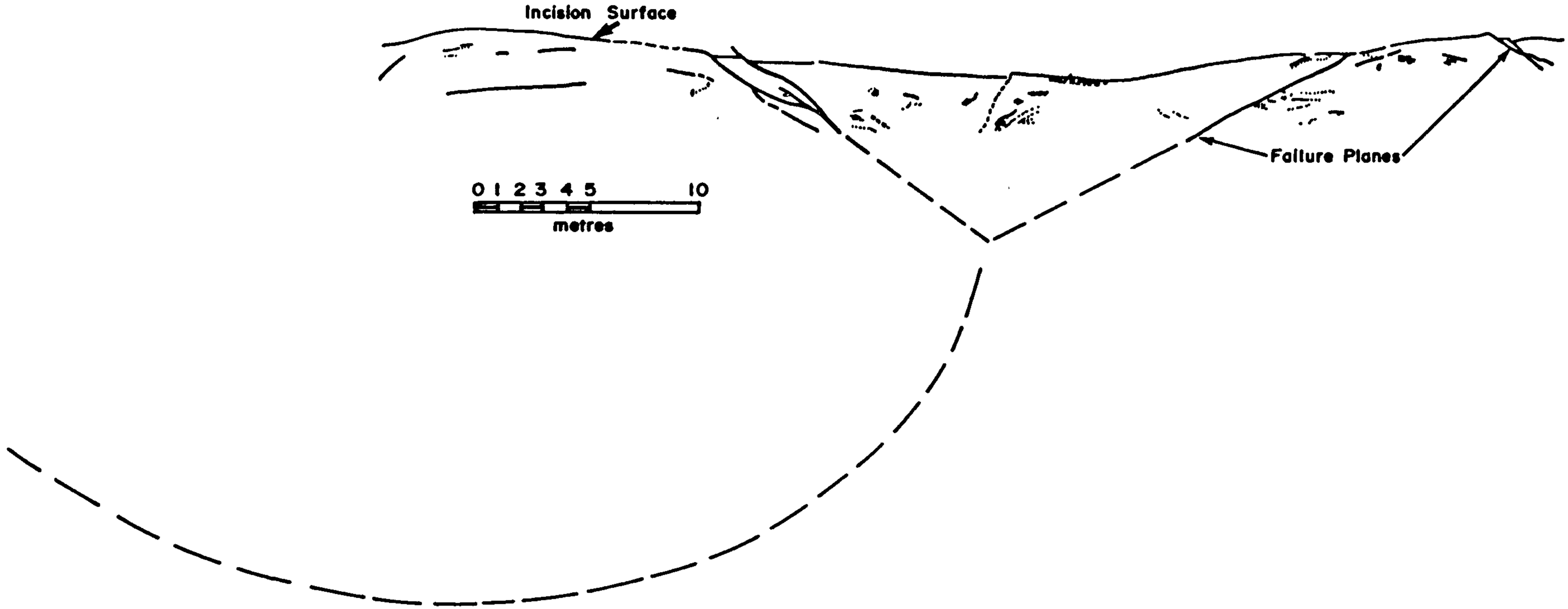


Figure 48. Diagram of scour mark B (trench 2) showing extrapolated depth of intersection of conjugate fault pair at about 9 m beneath the scour mark trough.

increasing overburden pressures as the tan-coloured unit increased in thickness.

Low angle faults associated with the down-faulted clay block in the northeast berm of scour mark B (trench 1) are interpreted to have formed in response to gravity collapse of outer berm material that had an initial relief greater than present. The sub-horizontal offshoot faults associated with low angle faults on the southwest berm, and the horizontal base of the clay block on the northeast berm, were probably originally sub-horizontal faults related to the lateral thrusting of clay slabs now preserved below the scour mark margin.

Discussion

Three types of scour-induced faults are recognized beneath scour marks developed in clay sediments. Conjugate fault sets occur beneath at least two scour marks (B and C). These sets have separation angles on the order of 100-120° but show random orientation of the intermediate stress axis $\sigma 2$. Dominant in these are long, low angle faults that occur beneath the central region of scour mark B. The hypothesis of shallow bearing capacity failure as a scouring mechanism advanced by Poorooshasb *et al.* (1989) and Woodworth-Lynas and Guigné (1990) is compatible with the presence of a dominant low angle fault set beneath scour mark B. This theory is supported by (1) the normal sense of offset of the sub-horizontal fault beneath the trough, (2) loose clustering of slickenside data that suggest sub-vertical displacements probably dominated movements along these faults, and (3) by a

dip-slip offset of at least 3.5 m indicated from one of the low angle trough faults. It is also likely that the smaller fault segments which create the dominant conjugate fabric beneath scour mark C, and the minor fabric beneath scour mark B, are related to bearing capacity failures which did not develop because of changes in the stress regime causing "old" faults to lock up and "new" ones to develop. The bearing capacity failure interpretation further implies that for wider ice keels the size of zone *I* (Figure 47) will increase, and correspondingly the slip surfaces, if they develop at all beneath wider scour marks, will penetrate deeper than below narrow scour marks.

The horizontal fault joining the low angle faults beneath the centre of scour mark B implies scour-induced horizontal translation of sediments above it, and indicates that shear forces propagated to as much as about 5 m below the deepest part of the scour mark trough. The sub-horizontal fault is offset by low angle trough faults on the southwest side indicating that in this region the horizontal fault propagated first. Conversely, on the northeast side the sub-horizontal fault is physically connected to the low angle trough fault. This apparent paradox can be explained by the following sequence of events: the horizontal fault was initiated on the southwest side slightly ahead of the encroaching keel, a short time before it was affected by bearing capacity failure. The horizontal fault propagated towards the northeast side, just as bearing capacity failure began in that region, and was favourably oriented for stress relief so that it joined the propagating low angle fault.

The scour marks described by previous authors, although developed in sediments of

widely varying grain size, display sub-scour structures significantly different from those reported here. In the descriptions of Longva and Bakkejord (1990) and Thomas and Connell (1985) bedding surfaces beneath the scour marks are clearly downfolded such that they mimic the topography of the scour mark incision surface. Also, in these examples scour-induced faults are all nearly vertical whereas vertical faults are not present beneath the Lake Agassiz features. Where undisturbed bedding can be seen beneath scour mark D the layers cannot be traced across the feature, and thus deflections that mimic the scour mark trough topography cannot be shown. Downfolding beneath the other Lake Agassiz features may have occurred but any record of it has been destroyed by intense reworking.

Although bedding beneath the feature described by Eyles and Clark (1988) does not appear to have been downfolded, faults are clearly divided into a left-dipping group beneath the right hand side of the scour mark and a right-dipping group beneath the left hand side. The distinction of a left- and right-dipping group associated with each side of the feature is also not generally observed beneath the Manitoba scour marks with the notable exception of the single, deeply penetrating fault set beneath scour mark B. The sense of offset beneath the Scarborough Bluffs feature is mostly normal, suggesting that they may have originated because of a bearing capacity-type of failure.

Comparison of observations of faults with experimental results

During undrained shear tests of ceramic clays, Maltman (1987) was able to create

conjugate shear planes over a wide range of water content (20-60%). In this range he showed that deformation was restricted to discrete shear zones and that the bulk of the material in the samples was undeformed. During distributed shear tests he reported that in low water content samples only one or two shear planes were produced and these were able to accommodate large additional displacements without further slip surfaces being produced. In some low strain rate unconfined triaxial tests of low water content clays (4-7%) the samples failed by axial splitting. In wetter clays the separation angle of the conjugates sets increased from 60° (15-25% water content) to 80° (25-50% water content), and the shear zones became more numerous and more closely spaced. Triaxial tests in clays with 25-50% water content showed that slip surfaces bifurcate and anastomose in complex arrangements with no single representative dip angle. Conversely, faster strain rates produced fewer shear zones in sediments with lower water content, and in very low water content sediments clay domains suitably oriented for shear may take up much, or all, of the bulk strain. He also noted that shear zones do not appear to grow in width, and that some actually decreased as the internal fabric intensified thereby restricting additional strain to propagation of the length of the zone. Shear zones began to form as peak strengths were reached at bulk strains of between 5-15%. He found that most clays exhibited a residual strength at strains greater than peak strength, and that strain hardening does not occur. Steady state deformation occurred by either continued slippage along existing shear zones or by the generation of new ones.

In discussing Maltman's results it should be borne in mind that the experimental

strain rates are much slower than in sediments experiencing deformations imposed by an ice keel moving at speeds probably on the order of 0.5 m/s. Also, the period of time during which strains occur is much shorter; on the order of 1-2 minutes. As a result it is likely that sediment below the scouring keel will be essentially undrained during a scour event, a condition which applies to the experiments.

Of greatest significance to results from the Lake Agassiz scour marks are Maltman's two observations:

1. that bulk strain, regardless of water content, is accommodated not by pervasive homogeneous flow but along discrete shear zones, and

2. that steady state deformation occurs either by propagation of dominant "old" slip surfaces (in the case of low water content sediments) or by creation of new ones.

The first observation implies that most of the Lake Agassiz sediment should have accommodated strain along discrete failure planes. While discrete failures have occurred, the eradication and reworking of sedimentary structure implies other mechanisms at work. Bulldozing of sediment may serve to effectively erase much if not all sedimentary structure in the region above the incised ice keel (see Chapter 3, Summary). The evidence for strongly homogenized sediments below the scour marks suggests this material may be the product of reworking, in surcharges, of earlier scour events. The second observation of

dominant "old" slip surfaces may be expressed by the existence of the dominant conjugate low angle trough faults of scour mark B.

Significance of results

The documentation of sub-scour effects to at least 5.5 m below scour mark troughs has practical implications for the burial protection of offshore oil and gas pipelines and power and communications cables in areas of active scouring today. Strains on buried oil and gas pipelines resulting from large (3.5 m or greater) offsets along scour-related faults need to be assessed. If the imposed strains are unacceptable it will be a federally-legislated requirement that pipelines and other facilities be buried deeper or be reinforced.

King William Island, Northwest Territories

In the southeast part of King William Island (Figure 49) iceberg scour marks were first identified in an area of very poorly sorted till and glacimarine sediments by Hélie (1983) (Figure 50). The scour marks were formed about 8,800 to 8,600 years ago when the McClintock ice dome collapsed, retreating southwards over King William Island and calving icebergs into the sea which was about 120 m deep (Hélie, 1983). A single feature was

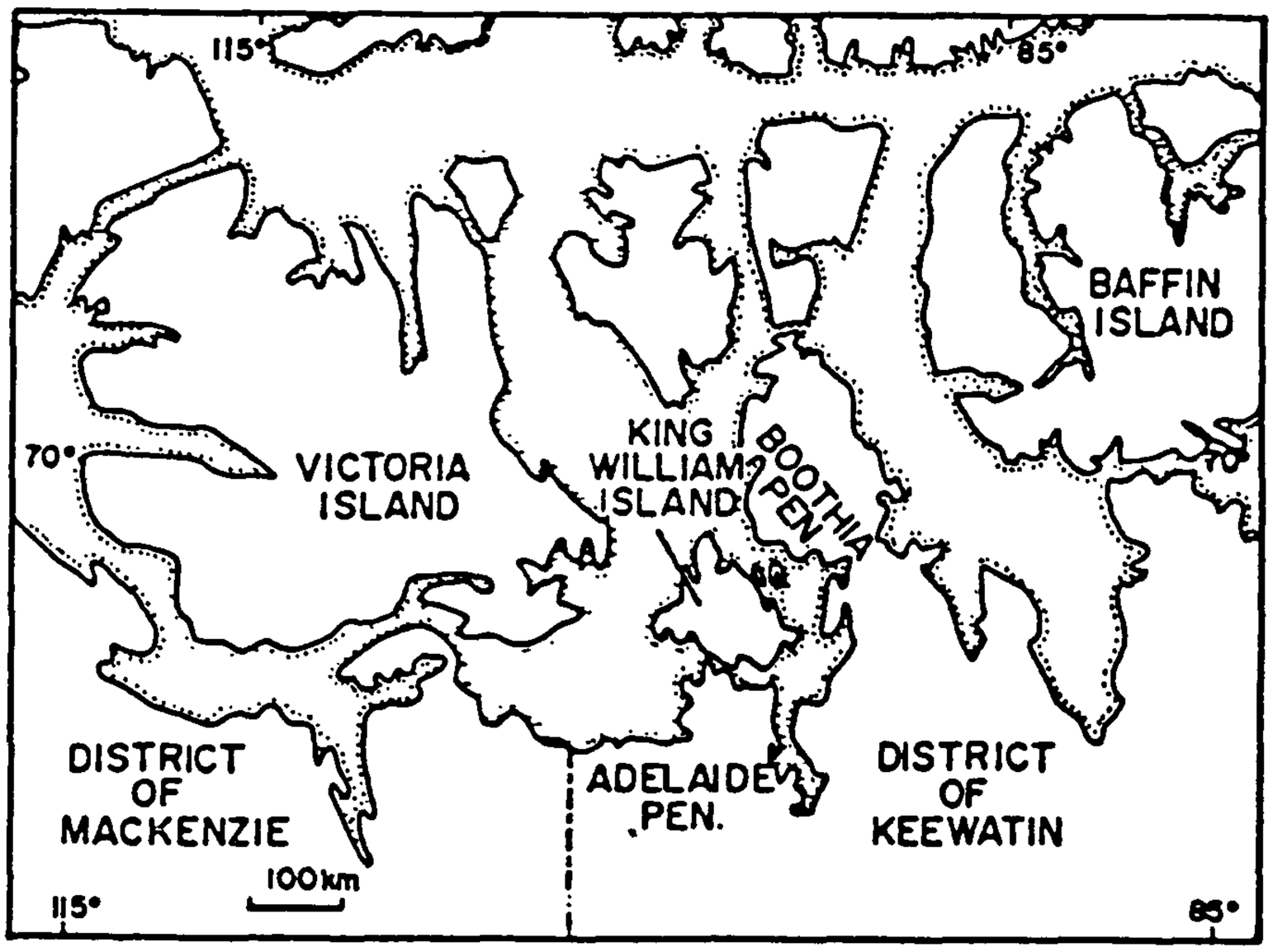


Figure 49. Location map of King William Island, Northwest Territories, Canada. Scour marks occur on the southern end of the island.

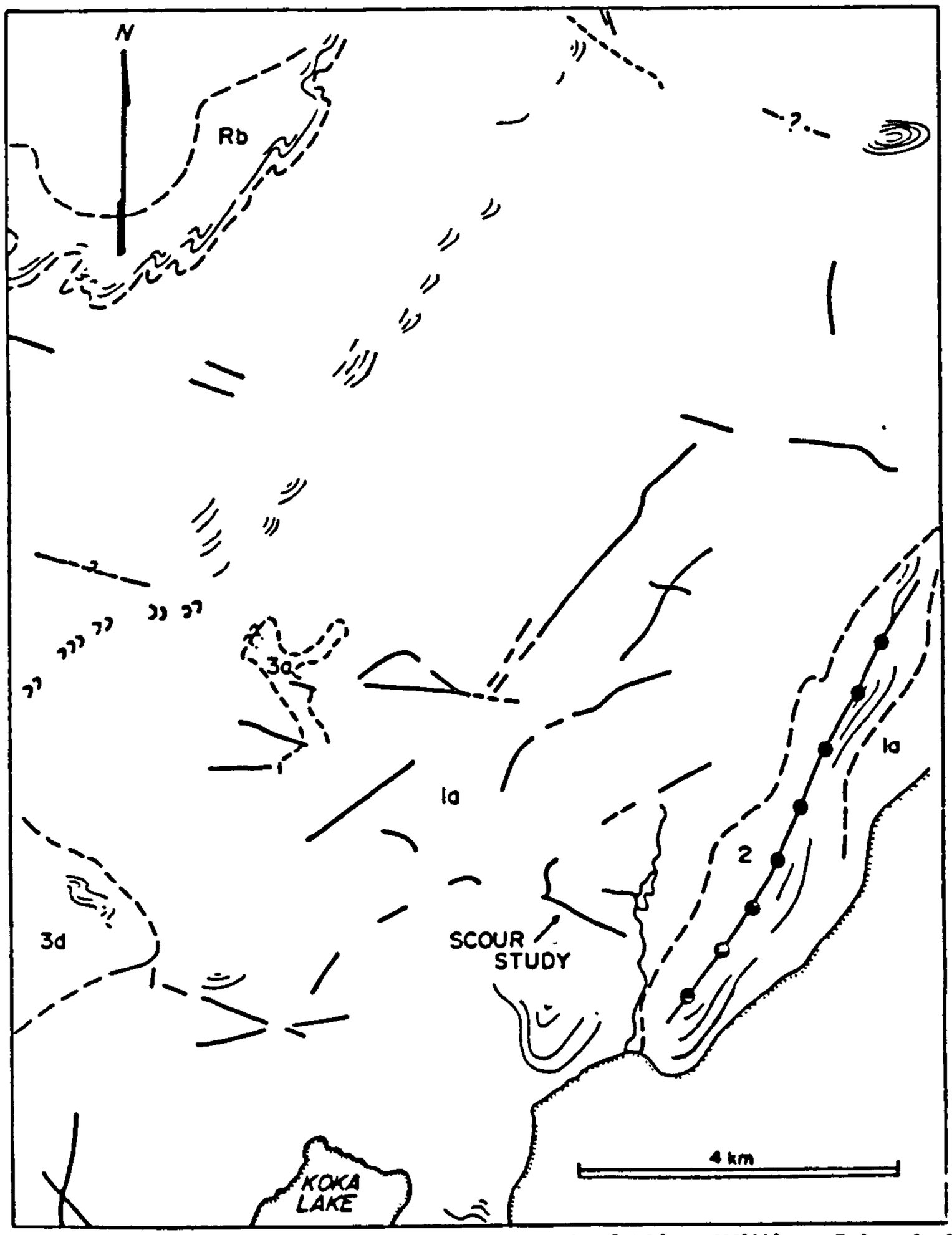


Figure 50. Surficial geology map of the southern end of King William Island showing scour marks.

iceberg scour marks

surficial geological boundary

esker

raised beaches

moraine ridge

1a till, 1-10 m thick
2 ice contact deposits (sand and gravel)
3a fine offshore sediments: silt and clay up to 8 m thick
3d beach sediments: gravel and sand up to 2 m thick, derived from glacial fluvial material and till (shallow water facies).
Rb carbonate bedrock: limestone and dolomite, sandy limestone and dolomite of Ordovician and Silurian (?) age. Beds flat lying, 0.1-1.0 m thick, commonly frost-shattered.

Geology from Hélie (unpublished map).

investigated in detail (Woodworth-Lynas *et al.* 1986b).

Results

The scour mark is about 1.8 km long and trends northwest-southeast. A 90° turn to the right at the northwest end alters the trend to approximately north-south (Figure 51). The feature has an average width of 43 m and average apparent depth of 1.3 m, measured to the top of post-scour sediments filling the trough. The surveyed portion of the scour mark passes through an elevation change of 5 m (Figure 51). Sediments of the ancient seafloor adjacent to the scour mark consist of poorly sorted bouldery, silt and clay sand (Figure 52). Sediments between the two berms within the scour mark consist of massive, well-sorted, clean-washed, yellow, medium-grained sand to a depth of at least 1 m. Small-scale cross bedding (amplitude ≈3 cm) was observed in one excavation at 20 cm depth with foresets dipping to the northwest along the scour mark axis. Similarly, well sorted sand was confined to the troughs in other scour marks nearby, and nowhere was it observed as a discrete unit beyond the berms. A berm excavation revealed massive, clean-washed sand with scattered matrix-supported pebbles passing upwards into silty, clayey sand with matrix-supported clasts of rounded pebbles and cobbles in the upper 25 cm. Cobbles are concentrated at the top on the modern ground surface along both berms (Figure 53).

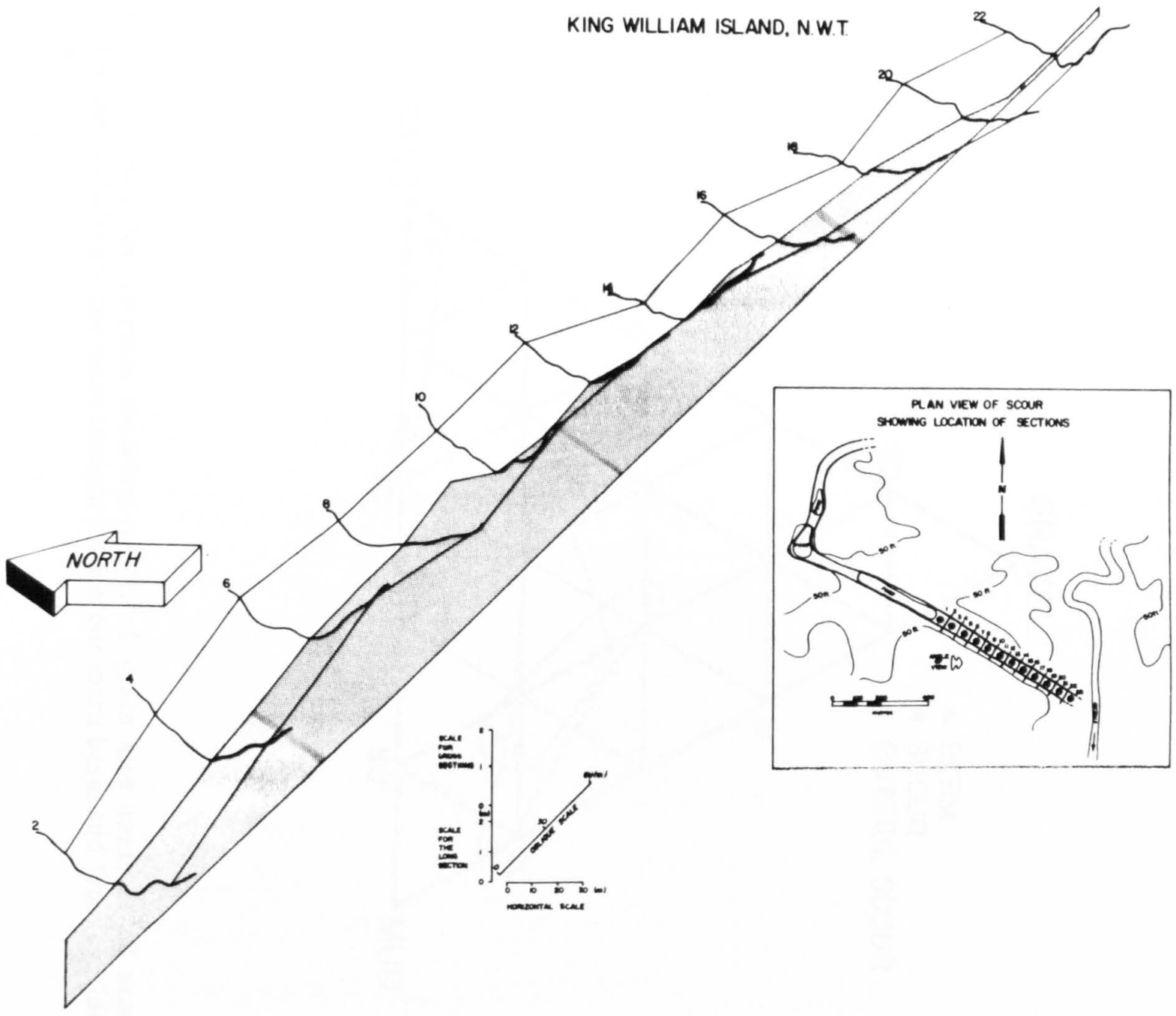


Figure 51. Map of scour mark studied in detail showing positions of surveyed sections (inset) and oblique representation of cross-section profiles and elevation changes along the scour mark.

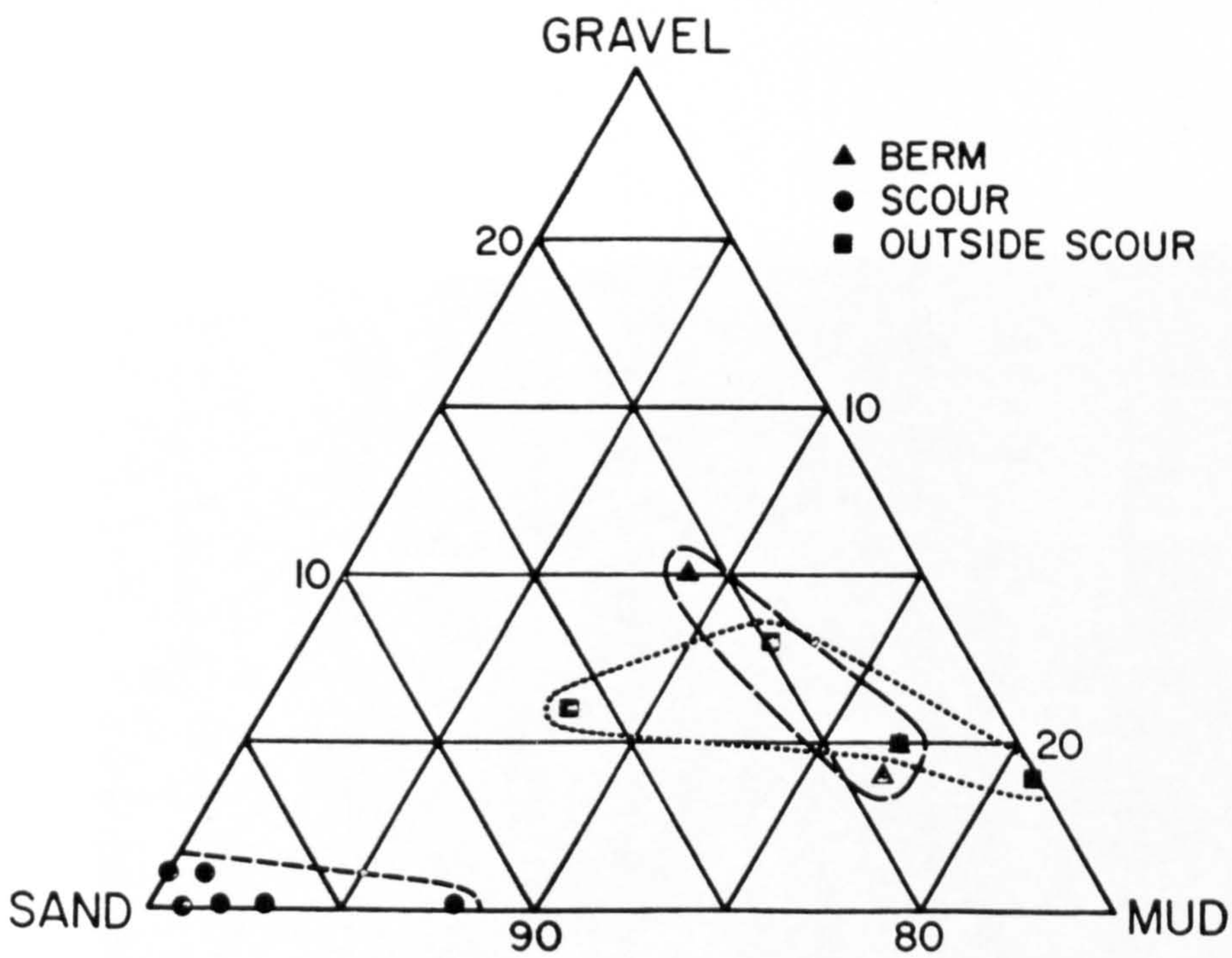


Figure 52. Triangular diagram showing results of grain size analyses of samples from sediments filling scour mark trough, from scour mark berm and from outside the scour mark.

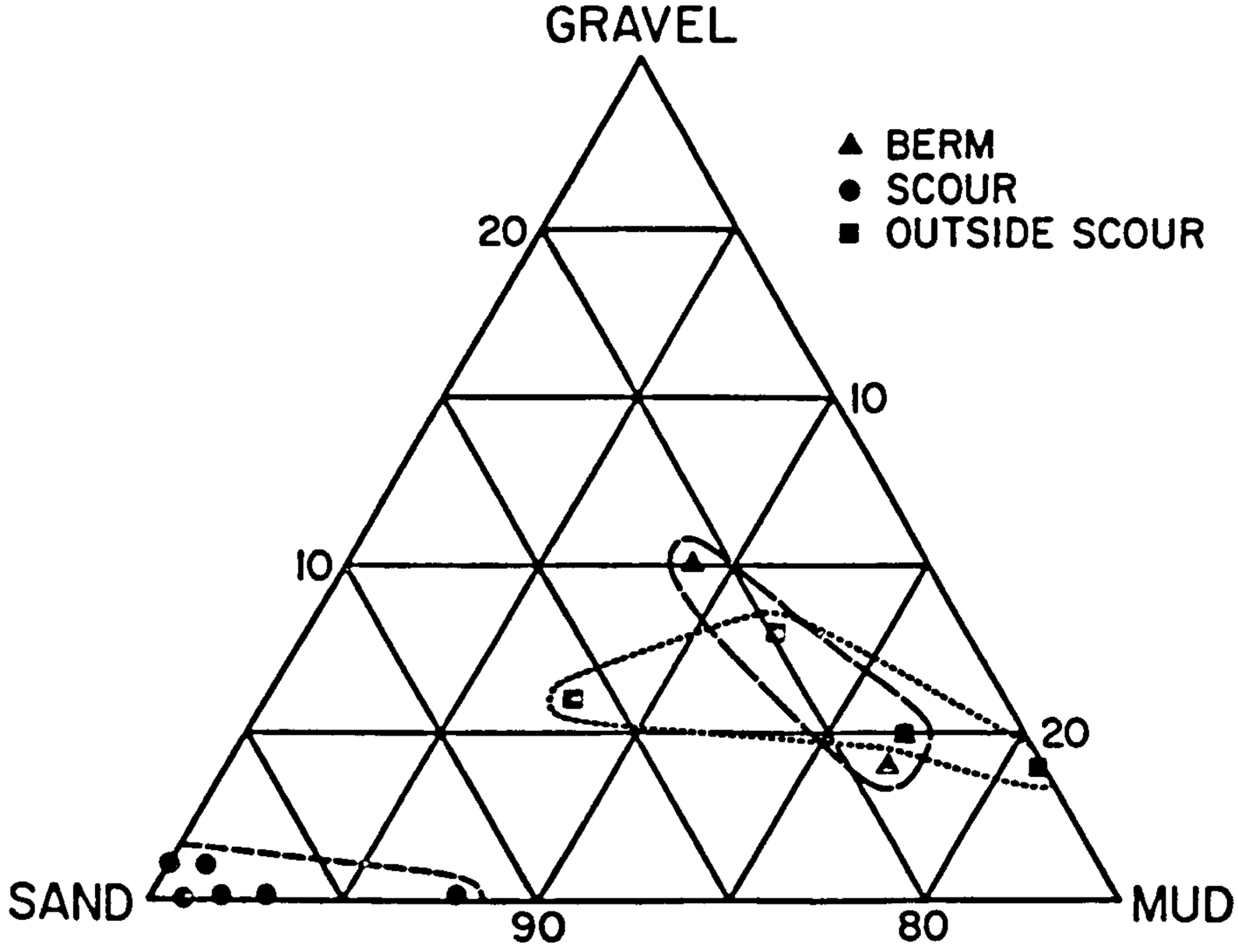


Figure 52. Triangular diagram showing results of grain size analyses of samples from sediments filling scour mark trough, from scour mark berm and from outside the scour mark.

Figure 53. View along crest of southern berm to show its positive relief and concentration of cobbles along the crest. Scour mark (filled with sand) on right, ancient seabed (poorly sorted) on left.

Interpretation

The difference in sediment texture and sorting between the clean-washed sands in the scour mark, the concentration of cobbles and pebbles in the berms, and poorly sorted material outside the scour mark is striking. A mechanism to account for this is suggested:

The mechanical action of scouring loosens and stirs the seafloor sediments sufficiently for enhanced currents, diverging around the keel at the seabed, to lift small grain sizes (clays to sand) into suspension. Wave-induced heave of the iceberg may have aided sediment loosening, suspension and winnowing by a pumping action causing vertical oscillatory current accelerations around the keel (pers. comm. Bill Roggensack, EBA Engineering Consultants Ltd., 1985). As the fines are lifted into suspension coarser-grained material (pebbles and cobbles) will become concentrated around the keel. This lag deposit of coarser sediment will, if in front, be bulldozed and displaced to either side of the advancing keel, resulting in concentration of this material on the surface of the scour mark berms. Once in suspension the clay and silt particles are winnowed away by ocean currents, the sand fraction redepositing in the scour mark trough as the keel passes (Figure 54). Coarse sediment lag that may have been generated behind the keel by lifting into suspension and winnowing of fines will be buried beneath the sand. If this hypothesis is correct then at least a 1 m thick layer of sand has redeposited in the scour mark trough since the scour mark formed, and a coarse lag layer may remain buried below this depth within the permafrost. The depth of the scour mark is 1.3 m, measured to the top of the sand unit, thus the original incision

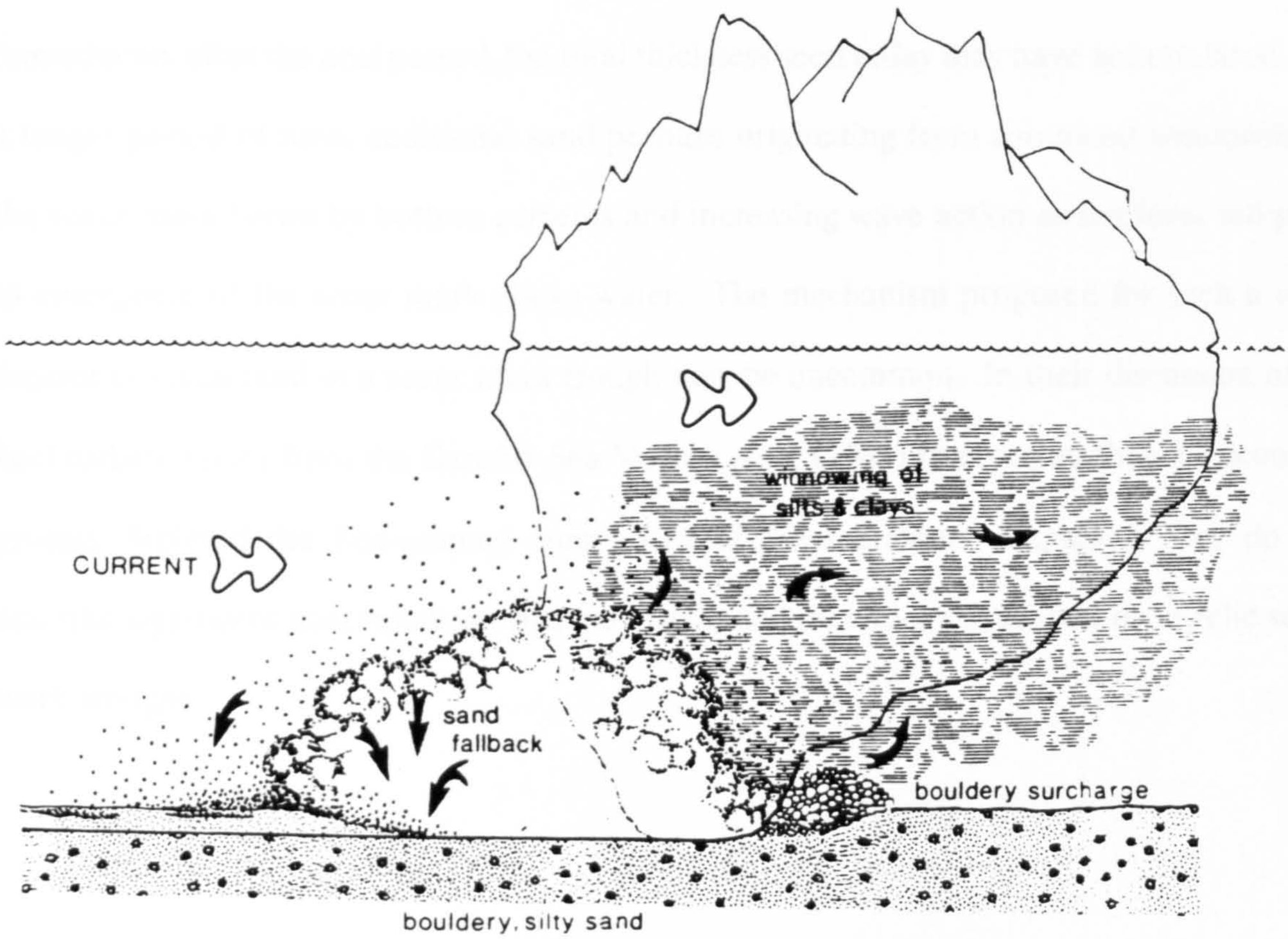


Figure 54. Interpretative diagram illustrating how a scouring iceberg may affect unconsolidated, poorly sorted sediment. Fine-grained sediment (up to sand fraction) is mechanically lifted into suspension. Silt and clay fraction is winnowed from the sand which falls back into the scour mark trough, masking the incision surface. Cobbles and boulders are concentrated at the leading edge of the scouring keel (as fine-grained sediment is preferentially lifted into suspension) and are displaced laterally to form coarse berms.

depth must have been at least 2.3 m. Although some sand may have redeposited immediately after the keel passed, the total thickness seen today may have accumulated over a longer period of time, additional sand perhaps originating from continued winnowing of the scour mark berms by bottom currents and increasing wave action as sea level fell prior to emergence of the scour mark above water. The mechanism proposed for such a thick deposit of clean sand in a scour mark trough may be uncommon. In their discussion of ice keel turbate facies from the Barents Sea Vorren *et al.* (1983) interpreted that the scouring process depleted the fine-grained component of the sediment. However, they do not describe significant accumulations of sand distributed on either the seabed or in relic scour mark troughs.

CHAPTER 6

DEFORMATION BENEATH SMALL SCALE ICE SCOUR MARKS

In this Chapter sub-scour deformation structures are described from modern small scale scour marks formed by pan ice during spring breakup on the tidal flats of Cobequid Bay, Nova Scotia (Figure 55), and the St. Lawrence estuary, Québec. These scour marks are generally much smaller than those from King William Island and glacial Lake Agassiz, ranging in width from a few tens of centimetres and, exceptionally, up to 35 m in the St. Lawrence, and from 1 to 2 m in Cobequid Bay, and in depth up to about 25 cm. In both regions the scour marks are formed each year in a short period, usually in April or May, during breakup of the floating ice canopy which forms during the winter months. In Cobequid Bay where rates of sedimentation are high the preservation potential of scour marks is good, and they can be seen in section along erosional bluffs adjacent to the meandering thalweg of the Salmon River. Along the St. Lawrence river, scour marks are obliterated within a few weeks of their formation as the soft muds, that accumulate beneath the ice canopy in winter and in which the scour marks are formed, are eroded soon after the protective ice disappears (pers. comm. J-C. Dionne, Université Laval, Quebec, 1990).

Results from these small-scale features are compared and contrasted with results from the large scour marks described in Chapter 5. A discussion of variations in the scouring processes at different scales is presented.

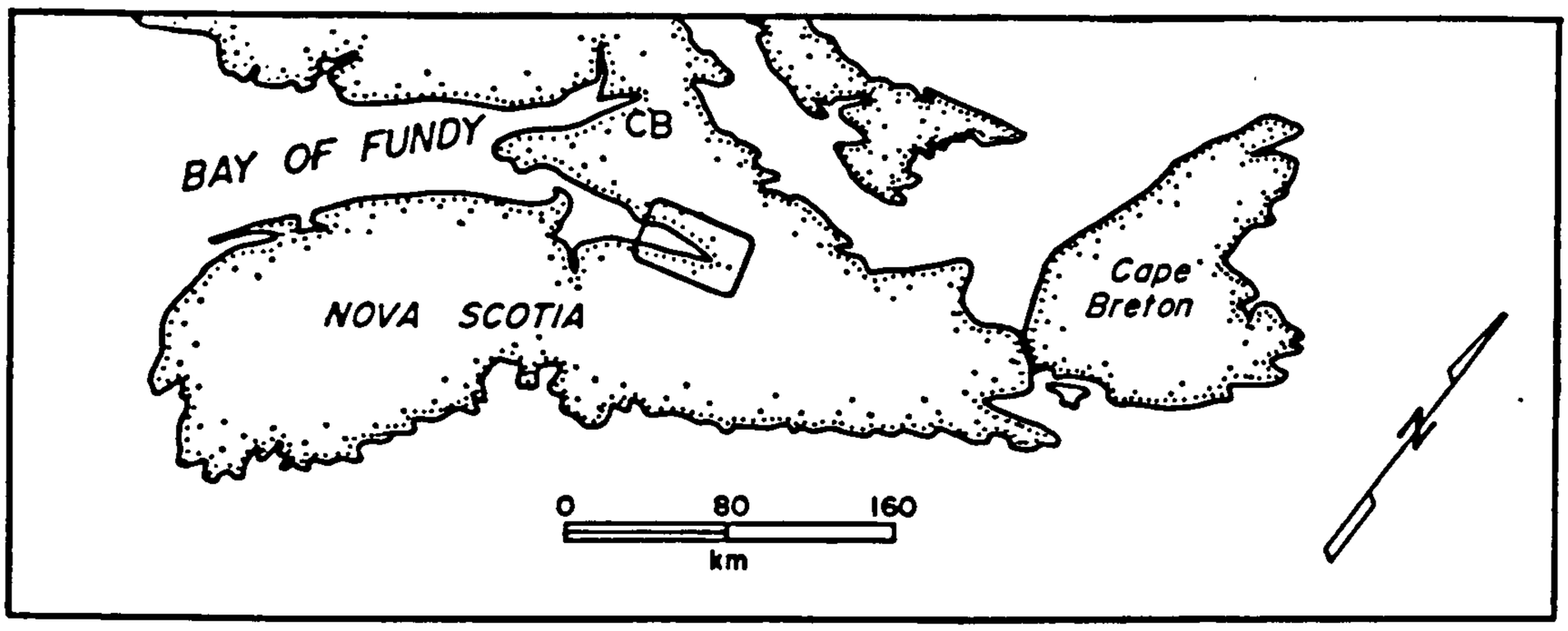


Figure 55. Map of Nova Scotia showing the Bay of Fundy and area of study in Cobequid Bay (inside box). CB = Cumberland Basin.

Cobequid Bay

Cobequid Bay (Figure 56) is a macrotidal estuary with tidal ranges on the order of 8 m. Large volumes of water (6 x 10^6 m^3 during each half tide) pass in and out of the study area with each tidal cycle (Dalrymple *et al.* 1990). Suspended sediment concentrations in the upper part of the estuary are high, ranging from a minimum of at least 200 mg/l to nearly 2000 mg/l immediately downstream from the town of Truro (Dalrymple *et al.* 1990). Wave action is negligible in this sheltered portion of the estuary, wave height rarely exceeding 0.25 m (Dalrymple *et al.* 1990). Typically during each full tidal cycle a sand-mud couplet is deposited on the mudflats. A couplet consists of a layer of sand <1-38 mm thick overlain by a mud lamina <1-18 mm thick. Couplets range in thickness from 1-45 mm and may be laterally extensive over distances greater than 100 m. Mean grain size in the three sections where scour marks were studied is 15% clay, 66% silt and 19% fine sand.

Ice begins to form in December reaching its maximum extent in late February. A coherent ice sheet never develops because tidal currents break up the floes which are in constant motion, and it is likely that the mudflats are subject to scouring throughout the winter as in the adjacent Cumberland Basin which is heavily scoured by moving ice from January through March (Gordon and Desplanque, 1983). In Cobequid Bay floating ice exists as pans 10-15 cm thick and up to 10 m across, as equidimensional blocks (cake ice) commonly less than 1 m in diameter, and as composite ice (Figures 57 and 58) formed from the freezing and amalgamation of small blocks, by rafting and from snow and sea water

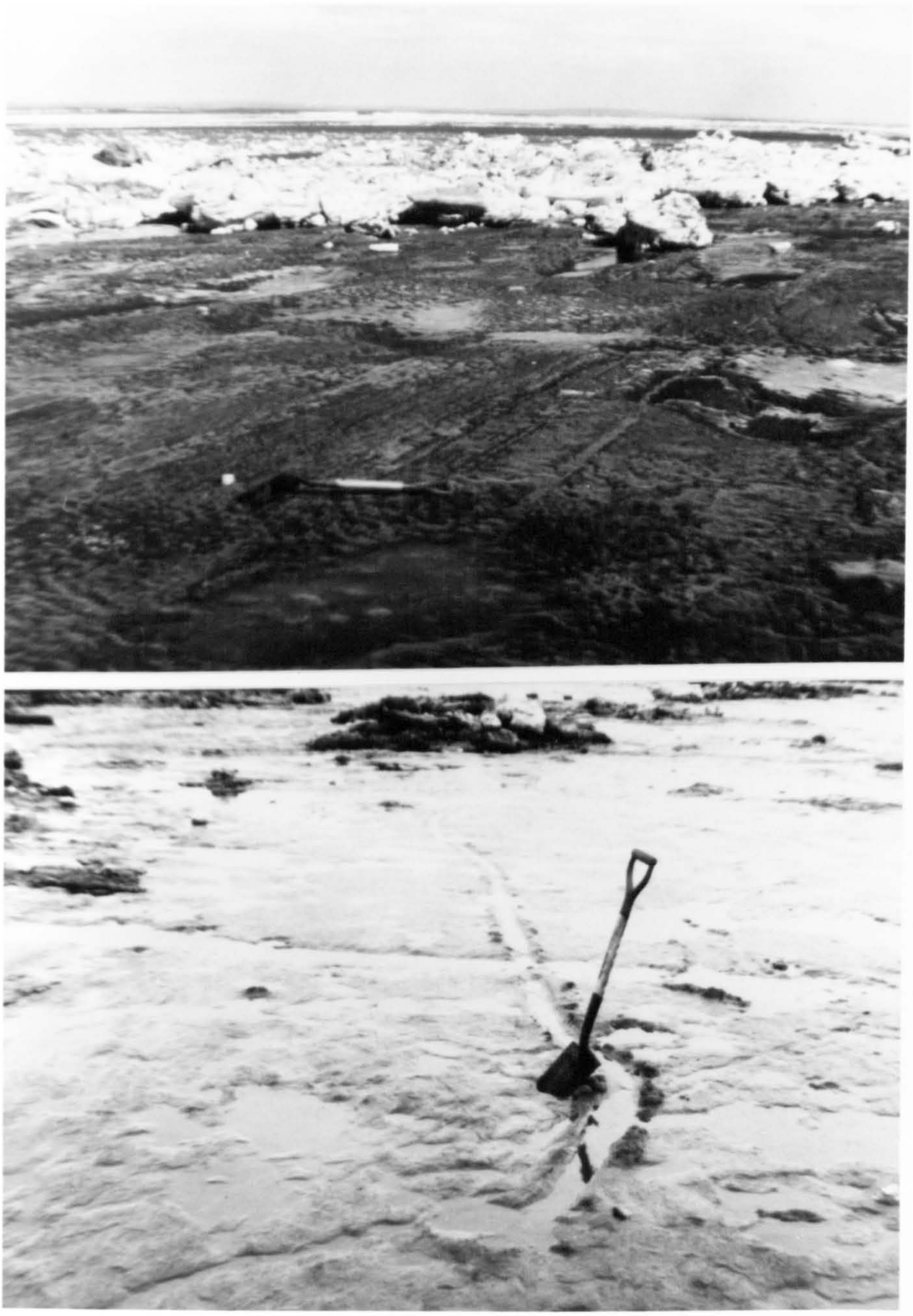


Figure 57a. Jumble of pan ice, cake ice and small composite ice blocks in background, and ice scour mark in foreground during low tide (photo courtesy of R. Dalrymple).
b. Example of a typical, curvilinear ice scour mark several metres long, approximately 20 cm wide and 5-10 cm deep. Shovel is 1 m long. (Photo courtesy of R. Dalrymple).

Figure 58. Example of a sediment-laden composite ice block approximately 4 m high.

accretion to form blocks that may be more than 5 m thick (Knight and Dalrymple, 1976).

Black Rock section

Two scour marks were investigated in sediment of mean grain size 11.5% clay, 75.5% silt, 8.0% fine sand (Table 7). Scour mark 1 was excavated to a depth of about 50 cm below the mudflat surface at two sections spaced 10 cm apart (Figures 59 and 60). The scour mark trough, although exposed on the mudflat surface, was filled with sediment. The trough is about 35 cm wide measured between the inner berm slopes along a line approximating the pre-scour mudflat surface. Scour mark incision depth, measured from the same line, varies from 5 cm in section 1 to 10 cm in section 2. Laminated sediments are deflected downward beneath the trough. The maximum deflection in all layers is least beneath the margins and greatest (up to 3 cm) beneath the trough axis. Deflections become less pronounced with increasing depth, and scour-related deformation cannot be discerned beyond about 15 cm below the deepest part of the scour mark trough. Decrease in layer thickness correlates with decrease in downward deflection, becoming thinnest beneath the centre of the scour mark trough. Layers are affected at distances up to 30 cm on each side of the centre of the scour mark in both sections. The mudflat surface in both sections is displaced upwards between 2-4 cm adjacent to the scour mark trough, and in section 2 this is associated with two small reverse faults beneath the left margin. The berms consist of material that is largely *in situ* having been created by upwarping of sediment adjacent to the

Table 7. Grain-size analysis and scour mark dimensions, Black Rock, Masstown Flats and Irving oil dock, Cobequid Bay.

	CLAY (%) <0.002 mm	SILT (%) 0.002-0.075 mm	FINE SAND (%) 0.075-0.5 mm
BLACK ROCK			
Scour mark 1	15	77	8
Scour mark 2	18	74	8
Mean	**11.5**	**75.5**	**8**
MASSTOWN FLATS			
Scour mark 1	10	55	35
	20	75	5
Scour mark 2	13	74	13
	18	77	5
Mean	**15.25**	**70.25**	**14.5**
IRVING OIL DOCK			
Samples from	17	23	60
other scour marks	18	69	13
	18	42	40
	13	72	15
Mean	**16.5**	**51.5**	**32**

Scour mark dimensions.

	Width (cm)	Depth (cm)	Max. depth of disturbance (cm)
BLACK ROCK			
Scour mark 1	35	5-10	15
Scour mark 2	80	20	10
MASSTOWN FLATS			
Scour mark 1	20-25	2-5	0-15
Scour mark 2	50	10	20
IRVING OIL DOCK			
Scour mark	60	15-20	50

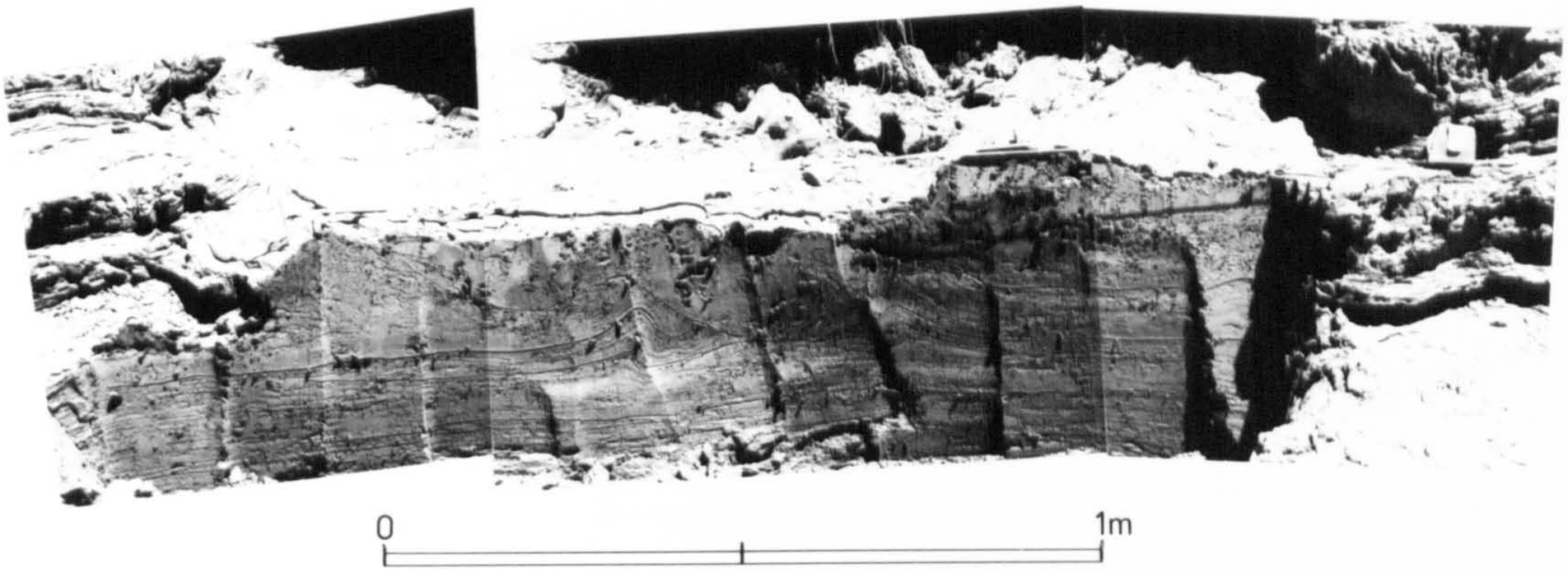


Figure 59. Photograph mosaic cross-section of scour mark 1, Black Rock Section, Cobequid Bay.

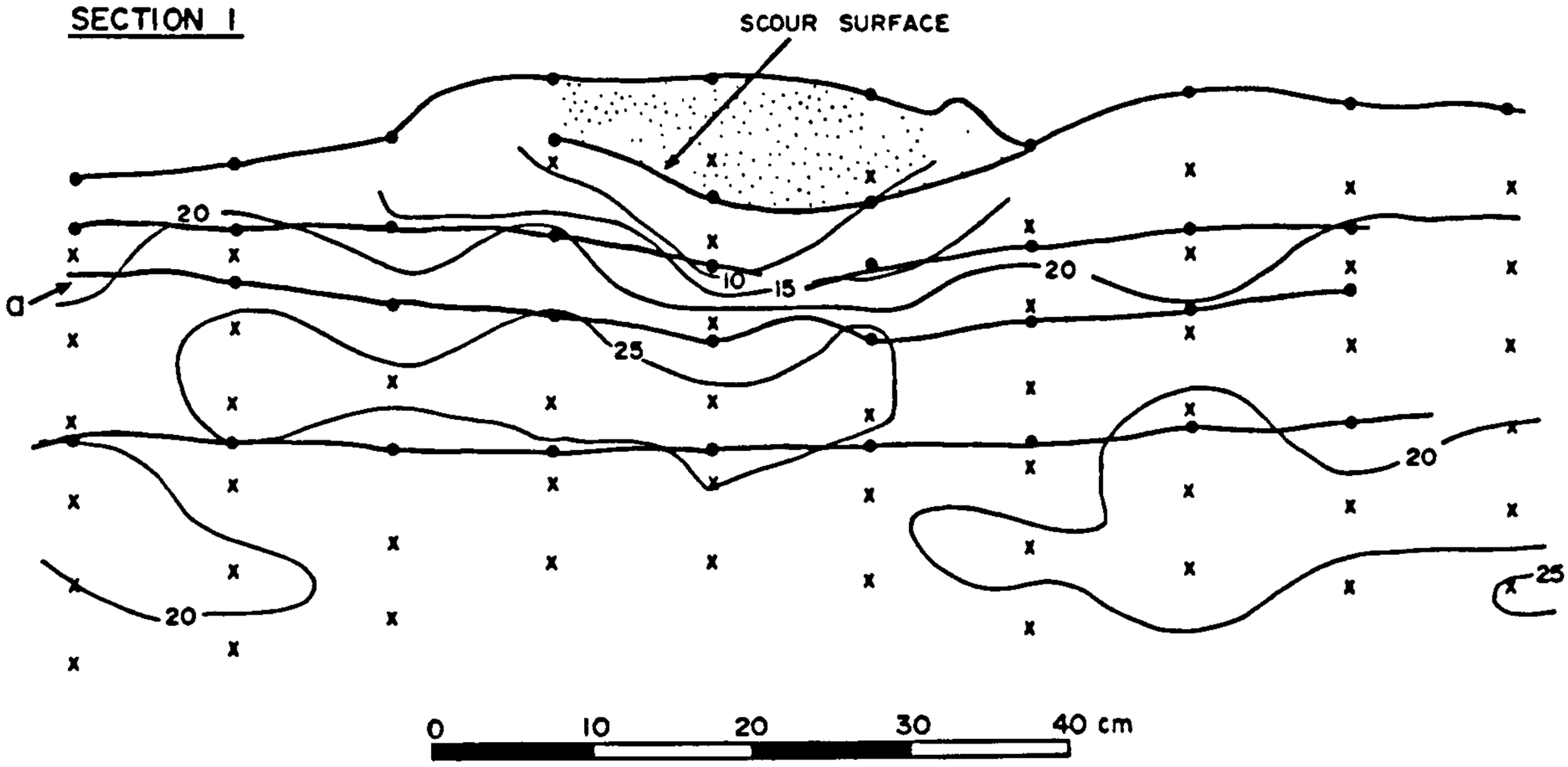


Figure 60. Scour mark 1, Black Rock Section, Cobequid Bay. The sections are 10 cm apart and are oriented normal to the scour mark axis. The diagrams are constructed from measurements made directly from vertical trench surfaces. Heavy lines joining circles indicate bedding planes. Small x's represent shear vane sampling depths from which contours of shear strength, in kPa (light lines), are derived. Stipple indicates sediments filling the scour mark trough. No vertical exaggeration.

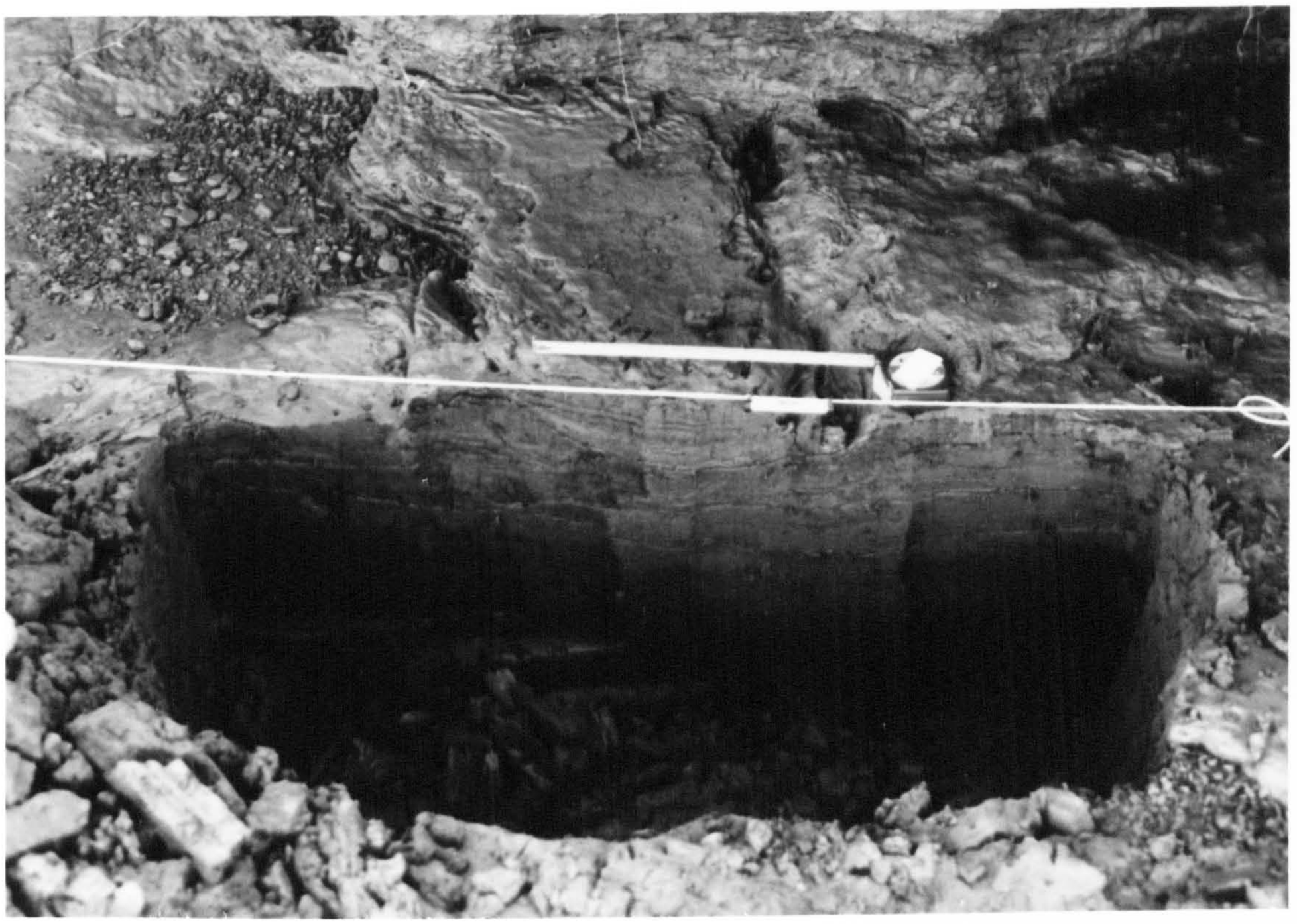


Figure 61. Oblique photograph of excavation of scour mark 2, Black Rock Section, Cobequid Bay, showing surface form and cross-sectional view of sediment-filled scour mark trough. Behind the excavation the trough passes beneath the river bank cliff foot of laminated sediments.

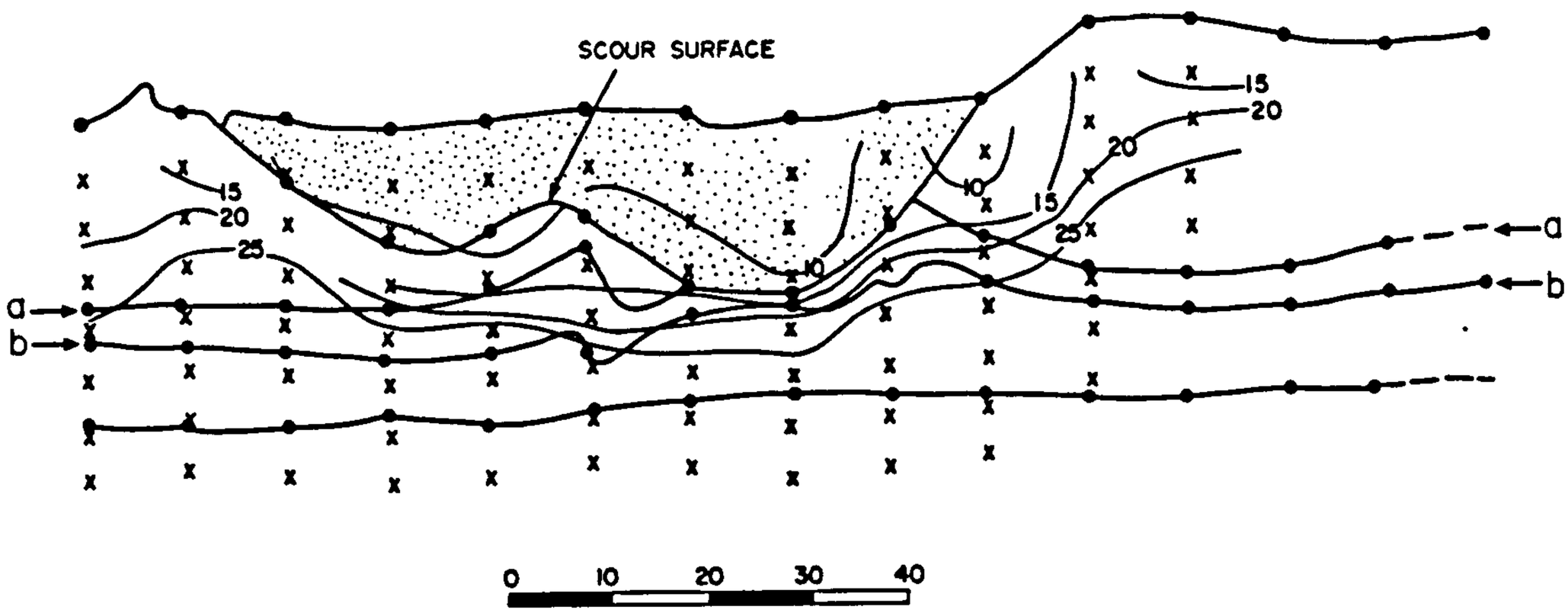


Figure 62. Scour mark 2, Black Rock Section, Cobequid Bay. This diagram is constructed from measurements made directly from the vertical trench surface. Heavy lines joining circles indicate bedding planes. Small x's represent shear vane sampling depths from which contours of shear strength, in kPa (light lines), are derived. Stipple indicates sediments filling the scour mark trough. No vertical exaggeration.

deflected upward towards the incision surface, and then downward beneath the right hand trough. Beneath the central ridge both layers "a" and "b" define a small scale asymmetric fold structure. Fold amplitude decreases from 10 cm (in layer "a") to 4 cm (layer "b"). The fold axial surface inclines slightly towards the left margin of the right hand trough. The mudflat surface is displaced upwards to form an *in situ* berm 5 cm high and 25 cm wide on the right side of the scour mark trough. The left hand berm is less well developed possibly because of erosion (see Figure 62). Shear strength contours approximate the outline of the scour mark trough, but cross layers "a" and "b" on the right side, and behave similarly, though less discordantly, on the left side.

Masstown Flats

Two scour marks were investigated at this location. Mean grain size was 15.25% clay, 70.25% silt, 14.5% fine sand. Scour mark 1 was excavated in three sections spaced at 10 cm intervals. This shallow feature had a clear surface expression but was covered by post-scour sediments in sections 2 and 3. The feature has a maximum incision depth of 5 cm (section 1) decreasing to about 2 cm in sections 2 and 3 (Figure 63). Scour mark width is between about 20-25 cm. Layers 4 and 5 in section 1 closely mimic the scour mark incision surface, with maximum downward deflection apparent beneath the deepest part of the scour mark trough. Slight downwarping of layer 3 has occurred but layers 1 and 2 are unaffected. The two vertical lines on the left side of section 1 are thought to indicate the

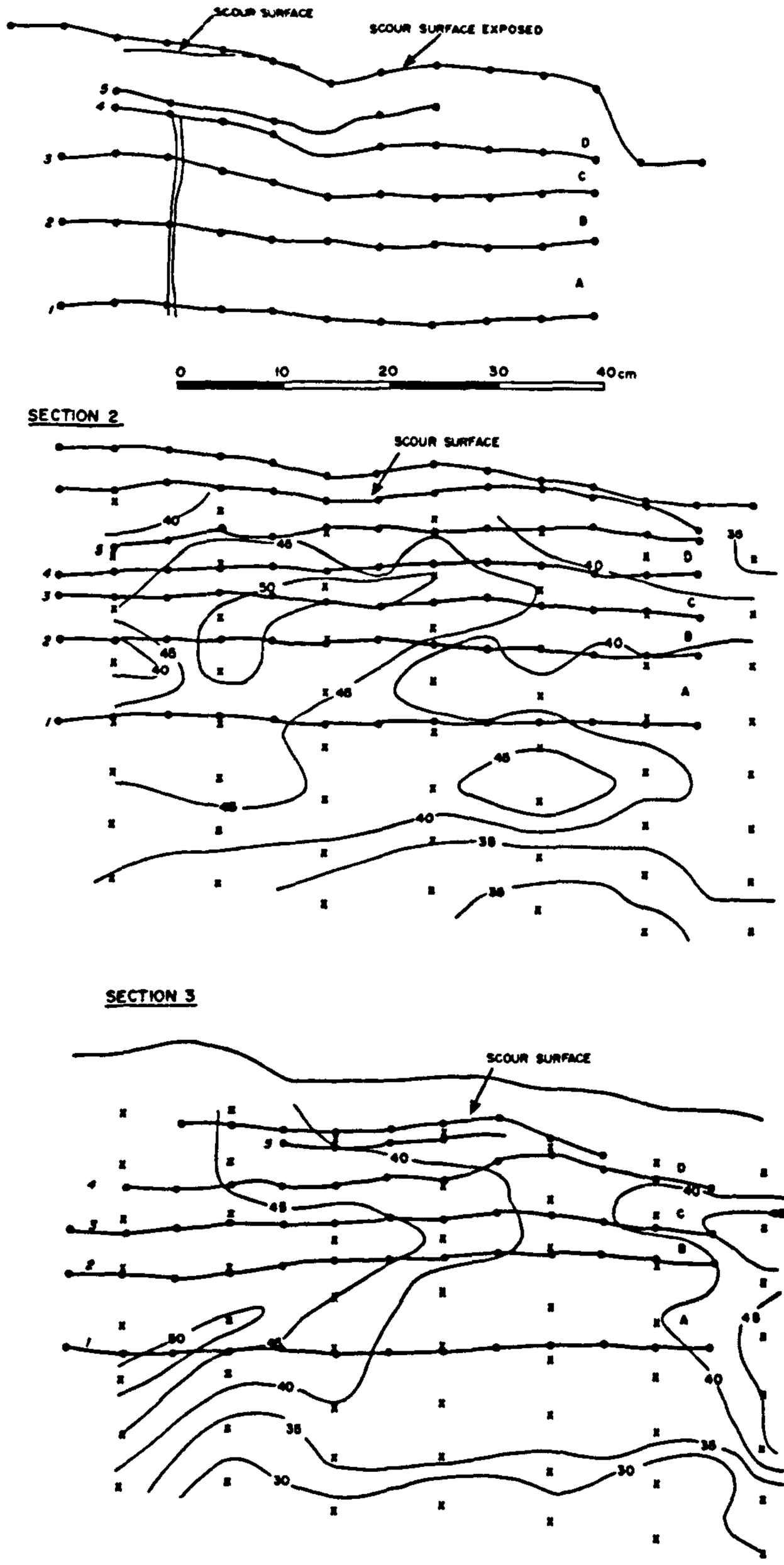


Figure 63. Scour mark 1, Masstown Flats, Cobequid Bay. The diagrams are constructed from measurements made directly from vertical trench surfaces. The sections are 10 cm apart and are oriented normal to the scour mark axis. Heavy lines joining circles indicate bedding planes. Small x's represent shear vane sampling depths from which contours of shear strength, in kPa (light lines), are derived. No vertical exaggeration.

burrow trace of *Macoma balthica*. Sections 2 and 3 show no apparent deflections that can be correlated with the scour mark trough outline. Shear strength contours are widely spaced and meander across sedimentary layers and show no obvious associations with the scour mark.

Scour mark 2 was sectioned in three places at 10 cm intervals. Maximum scour mark depth is 10 cm and width is about 50 cm. (Figures 64 to 67). Although sedimentary layering has a natural dip to the right in each section the depth to which layers are deformed beneath the deepest part of the scour mark trough extends to about 20 cm. Layering (2 and 3) is generally deflected downwards beneath the trough, greatest deflections occurring beneath the deepest part of the trough. Layer 3, nearest to the surface, exhibits upwarping beneath the berm regions in sections 1 and 3. On the left side of section 2 this layer is deformed into a small (2 cm amplitude) overturned fold with a nearly horizontal axial surface. The fold faces towards the scour mark axis. In section 1, layer 3, although visible on either side, cannot be resolved beneath the scour mark trough. The zone between the scour mark trough and layer 3 is severely turbated. Laminations above layer 3 can be traced laterally into this zone on either side of the scour mark but cannot be distinguished within it (See Figures 64 to 66). Shear strength contours are closely spaced in a curved zone about 20 cm beneath the scour mark trough in all sections and, although some meandering occurs, closely approximates the curvature of downward-displaced layers. Contours are more tightly compressed immediately beneath the deepest part of the scour mark trough, correlating with reduction in thickness of the regions between layers. Contours above and below this

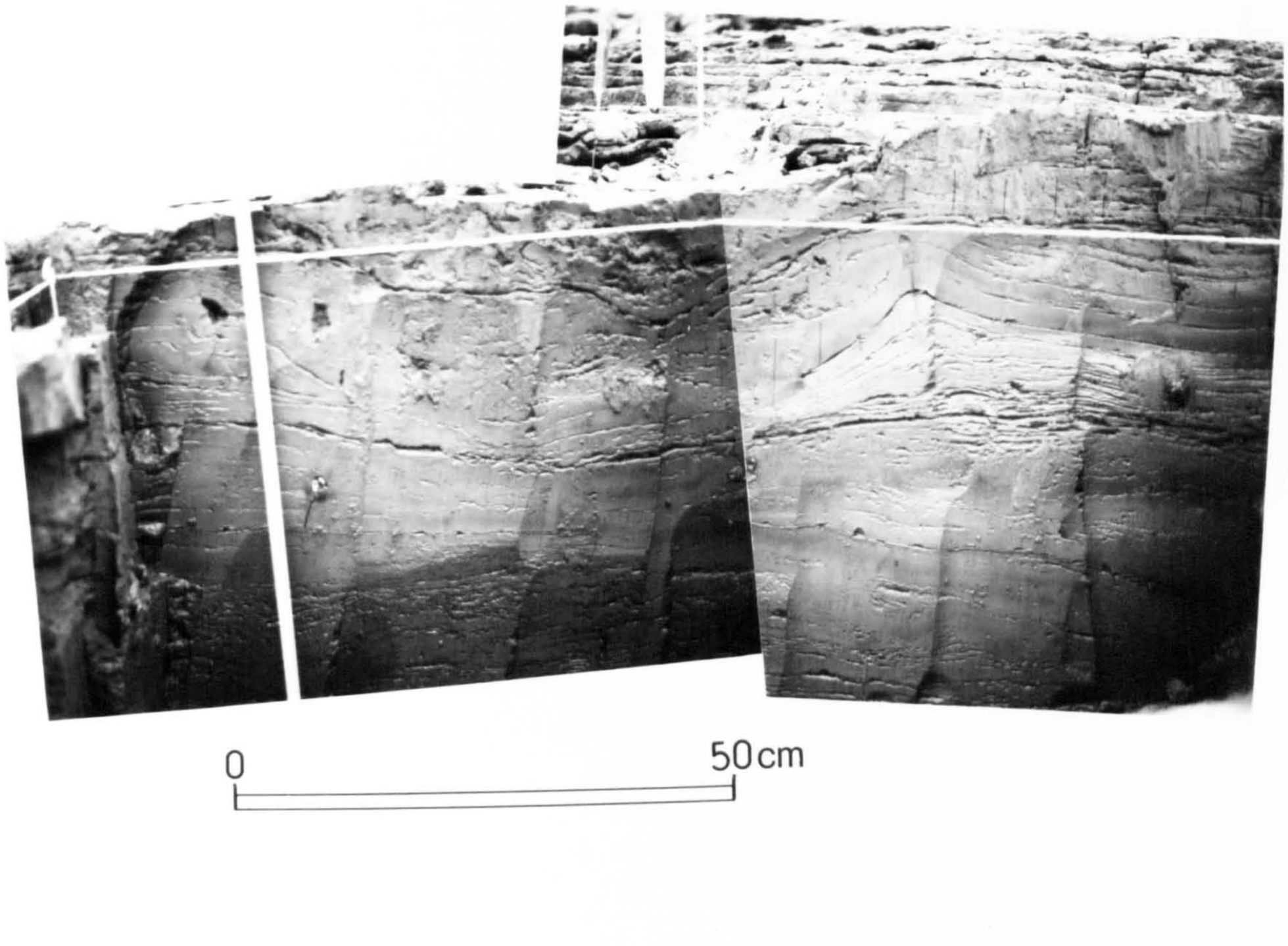


Figure 64. Photograph mosaic of section 1 scour mark 2, Masstown Flats, Cobequid Bay. There is a turbated layer immediately below the scour mark trough within which individual laminae, traceable on either side of the trough, cannot be distinguished. This turbated layer can be seen in the other sections (Figures 65 & 66).

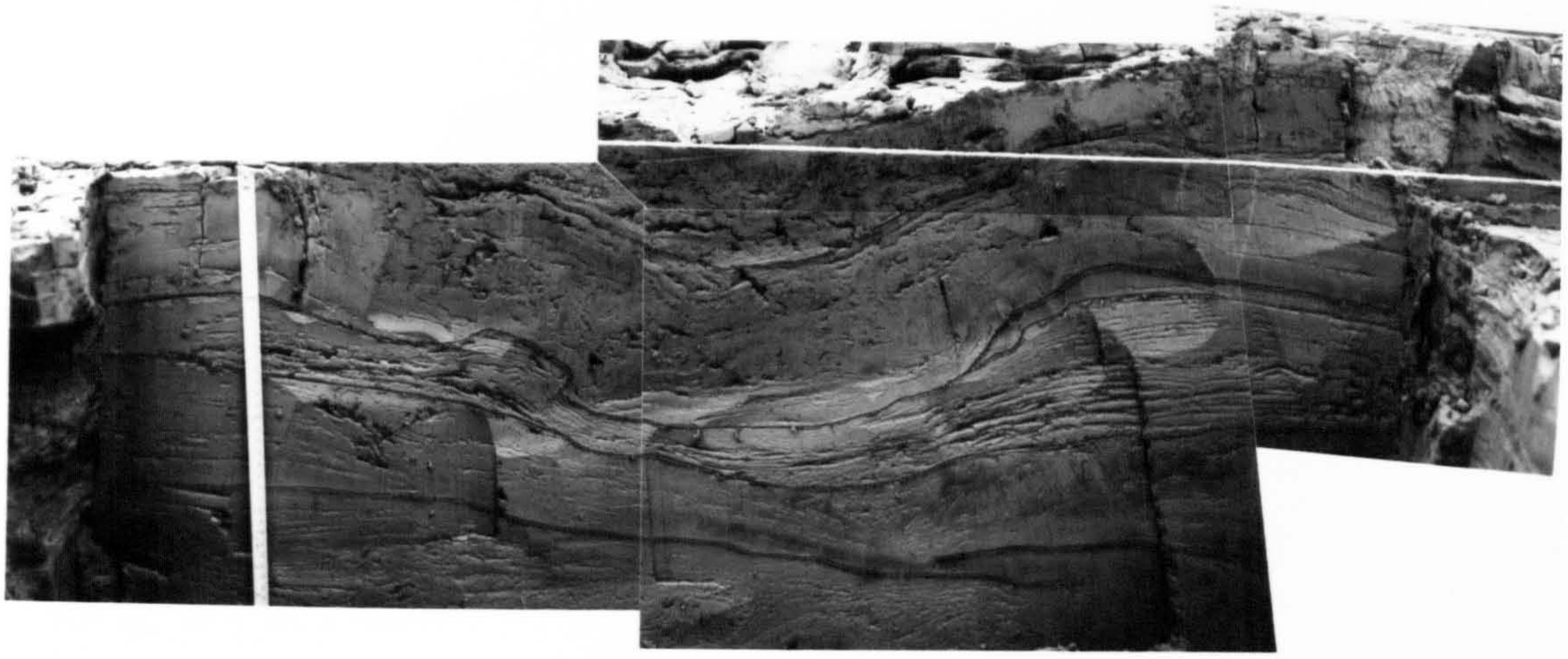


Figure 65. Photograph mosaic of section 2 scour mark 2, Masstown Flats, Cobequid Bay.

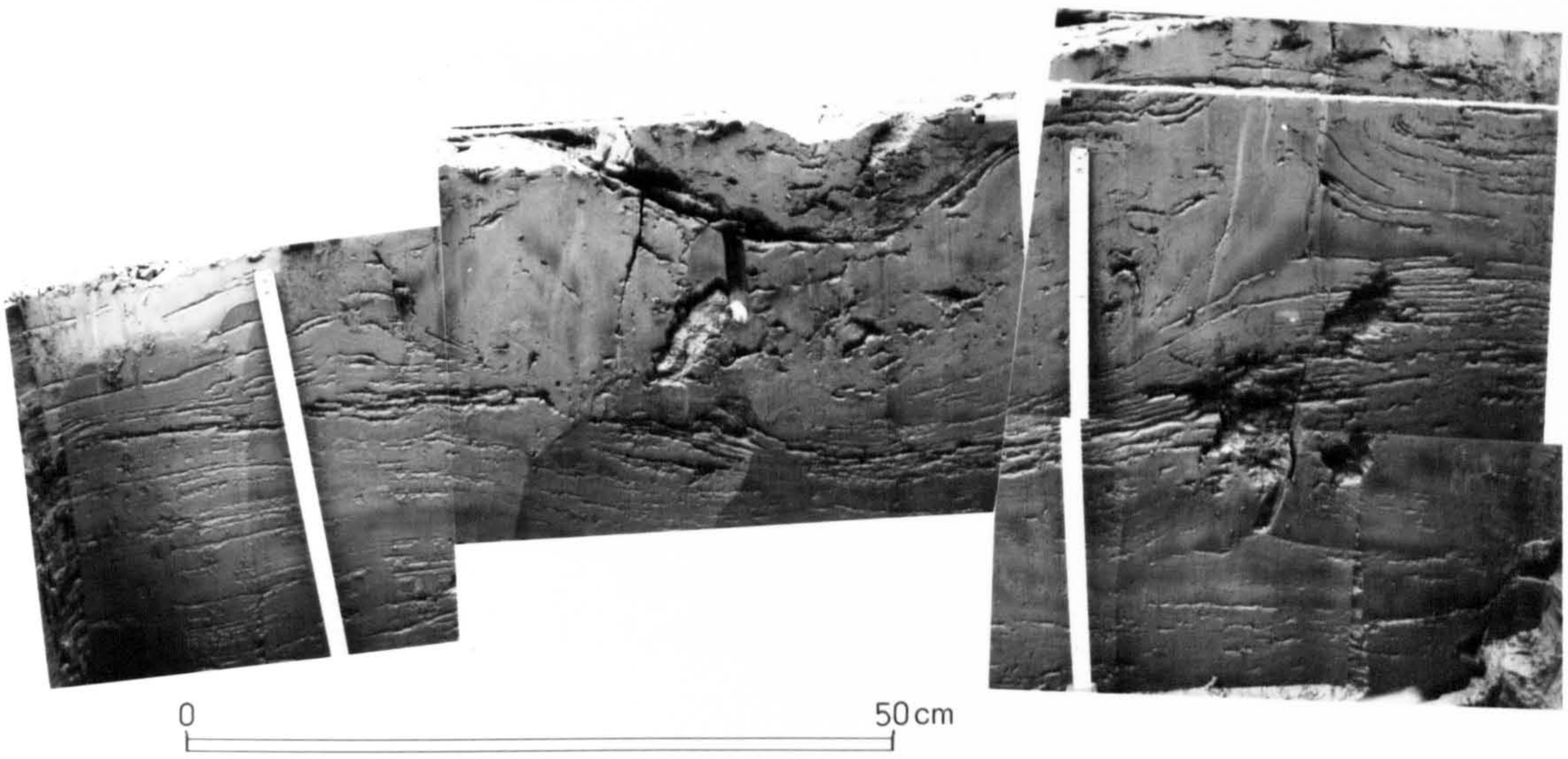


Figure 66. Photograph mosaic of section 3 scour mark 2, Masstown Flats, Cobequid Bay.

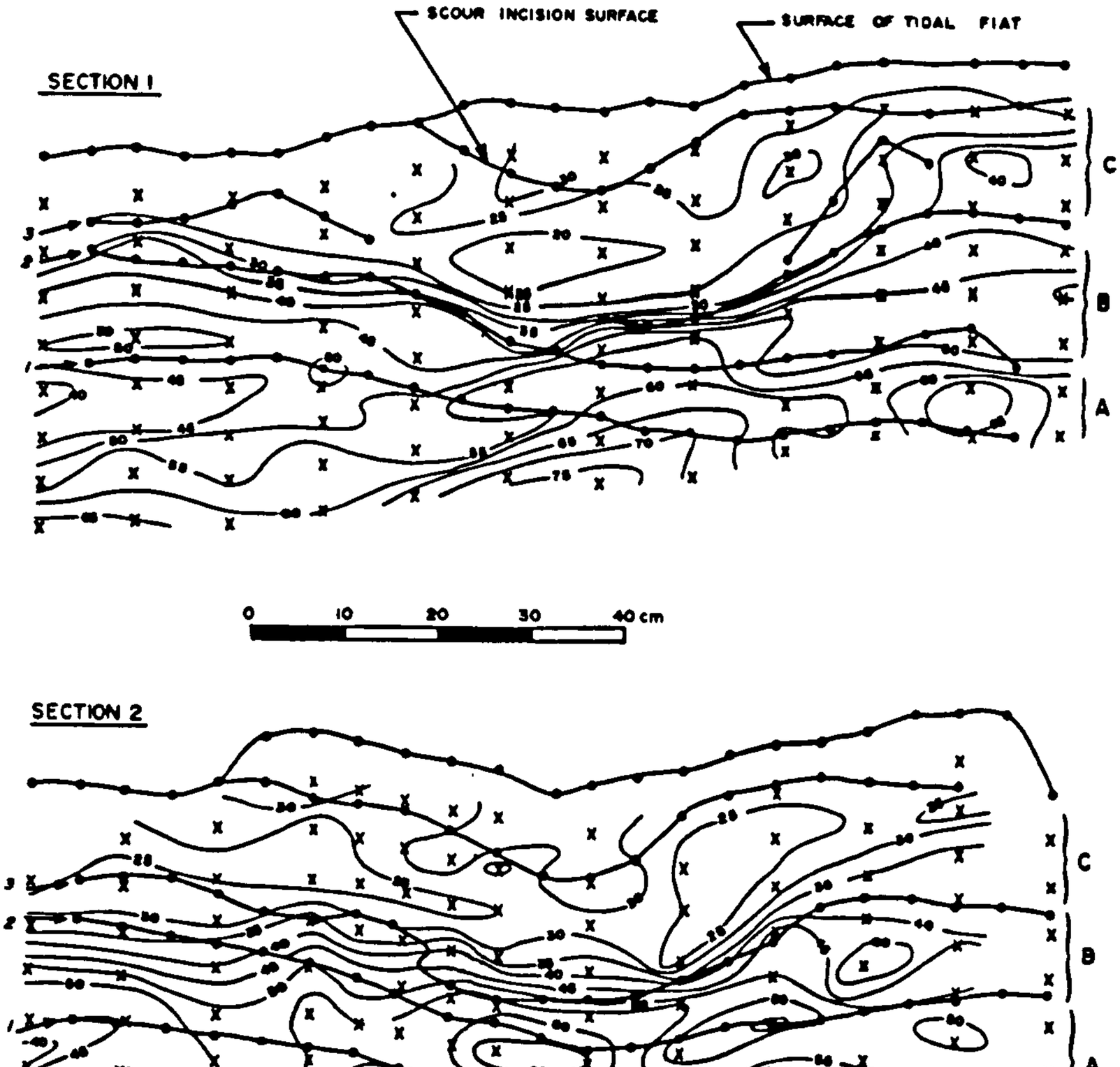


Figure 67. Scour mark 2, Masstown Flats, Cobequid Bay. The diagrams were constructed from measurements made directly from vertical trench surfaces. The sections are 10 cm apart and are oriented normal to the scour mark axis. Heavy lines joining circles indicate bedding planes. Small x's represent shear vane sampling depths from which contours of shear strength, in kPa (light lines), are derived. No vertical exaggeration.

zone show no obvious trends.

Irving oil dock

Several scour marks were observed at this locality. Mean grain size was 16.5% clay, 51.5% silt, 32% fine sand. One scour mark was selected for detailed study and was mapped in four sections spaced at intervals of 30 cm (Figures 68 to 73). The scour mark trough, filled with sediment, was exposed on the mudflat surface. Scour mark depth is 15-20 cm and width is about 60 cm. Six prominent layers were mapped and correlated between each section (except section 3 where layer 6 could not be distinguished). In all sections the layers have been deflected downwards beneath the scour mark trough, the amplitude of deflection decreasing with depth to layer 1 (50 cm beneath the deepest part of the scour mark trough) which shows little deformation. In places, layers beneath the trough are so disturbed that continuity is lost at depths below the trough up to 40 cm. On both sides of the scour mark trough the mudflat surface and sediment layers have been deflected upwards in zones greater than 80 cm wide. Thickness reduction has occurred in sediments beneath the scour mark trough as shown by a converging trend of the layers in this region. Greatest reduction is associated with the point of maximum downward deflection of layers. Change in thickness was quantified by measuring the vertical distance between each layer in the interlayer zones A-E at cross-profile intervals of 10 cm. Original, pre-scour thickness of each layer was measured from each section at a distance as far from the scour mark as possible, either on

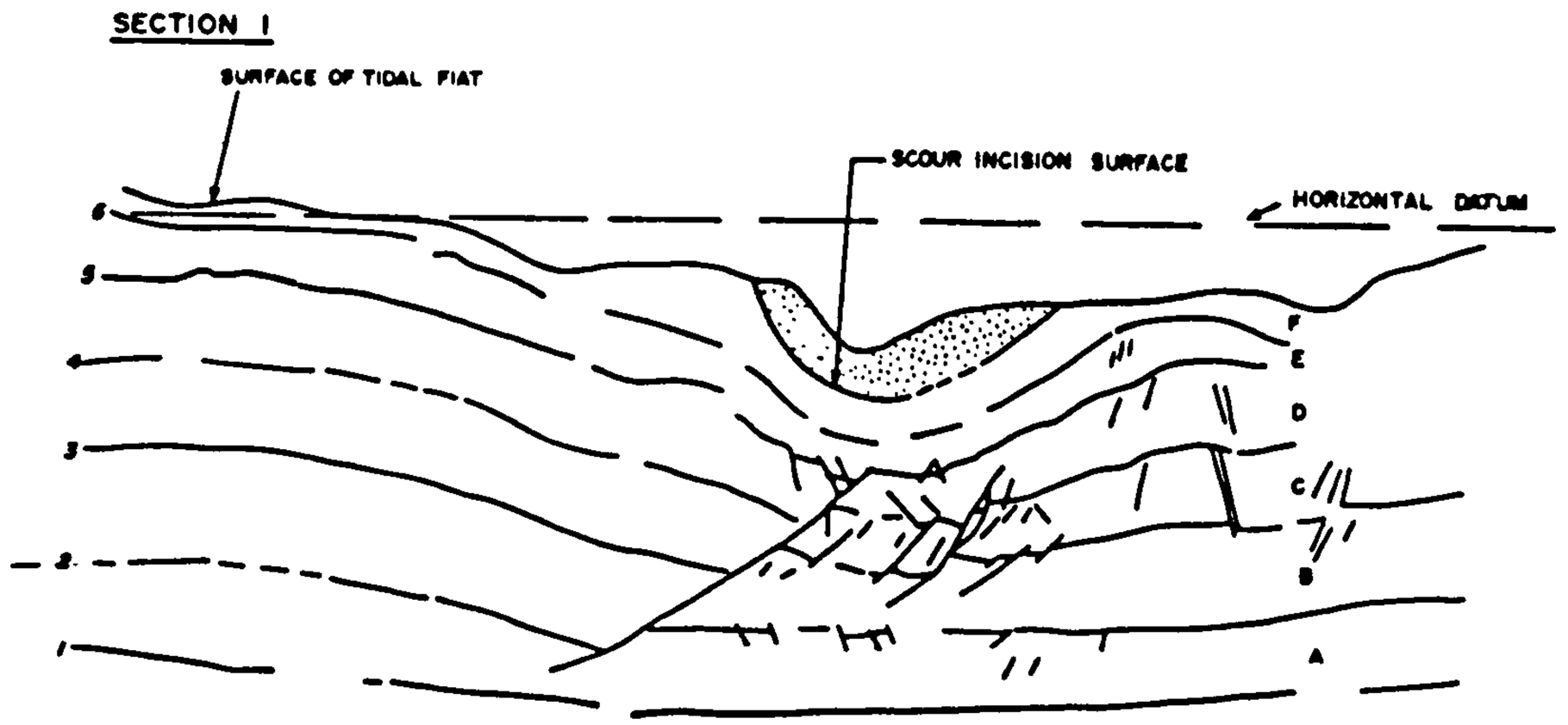
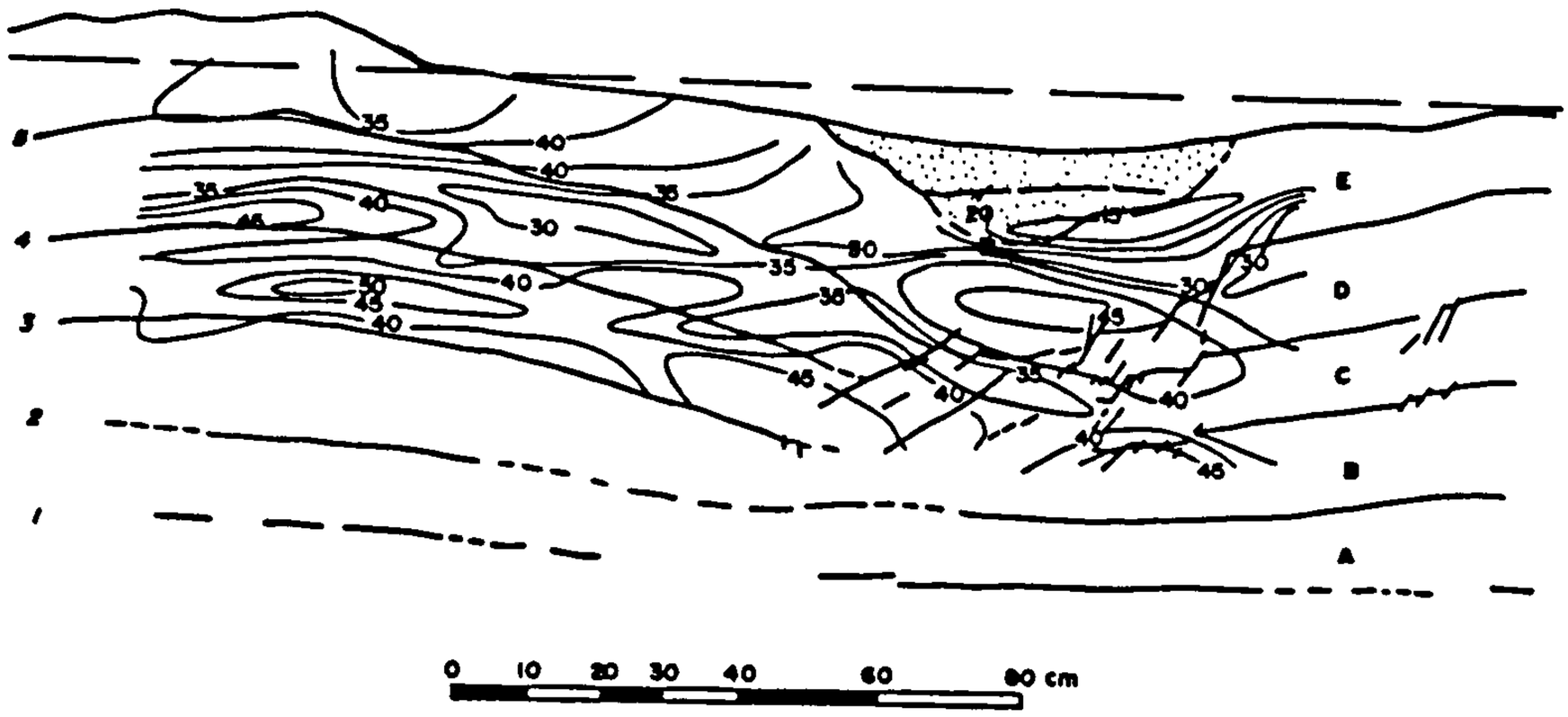


Figure 68. Scour mark, sections 1 and 2, Irving Oil Dock, Cobequid Bay. These sections are reproduced from the photographs in Figures 69 & 70 and are 30 cm apart. The sections are oriented at about 60° to the scour mark axis. Heavy lines represent bedding planes that are offset by small scale (5-60 cm long) faults (truncating bedding planes) in all sections. Light lines are contours of shear strength in kPa. Stipple indicates sediments filling the scour mark trough. The horizontal datum line is at the same relative elevation in all sections. No vertical exaggeration.

SECTION 3



SECTION 4

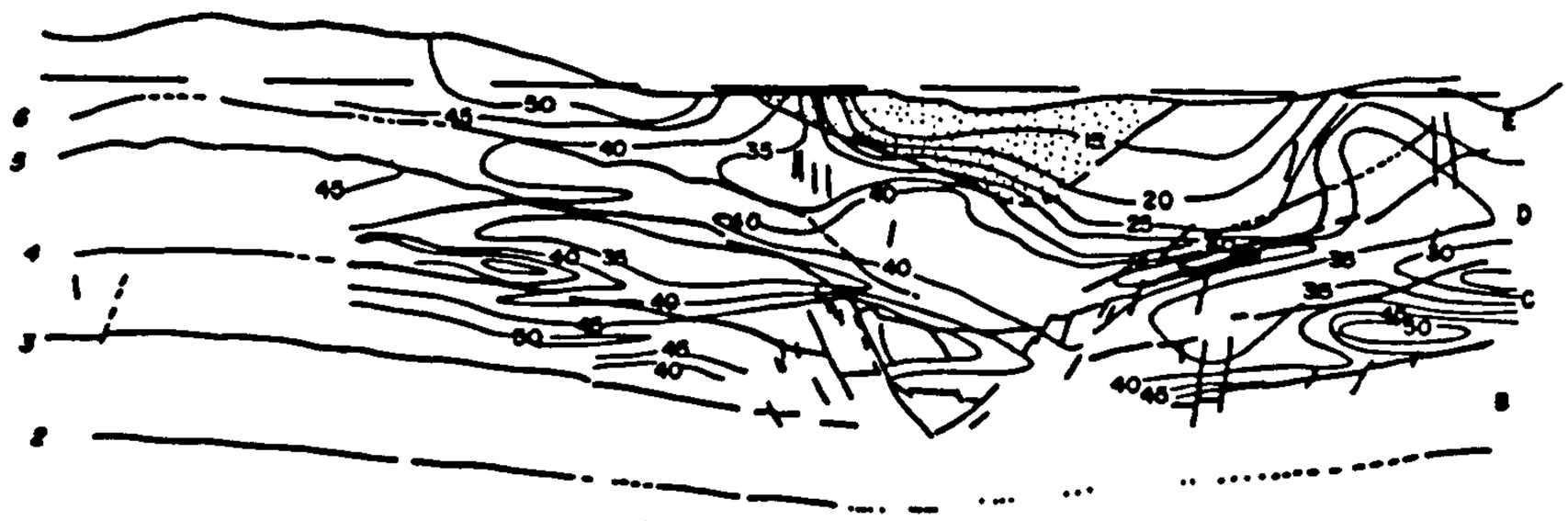


Figure 69. Scour mark, sections 3 and 4, Irving Oil Dock, Cobequid Bay. These sections are reproduced from the photographs in Figures 71 & 72 and are 30 cm apart.

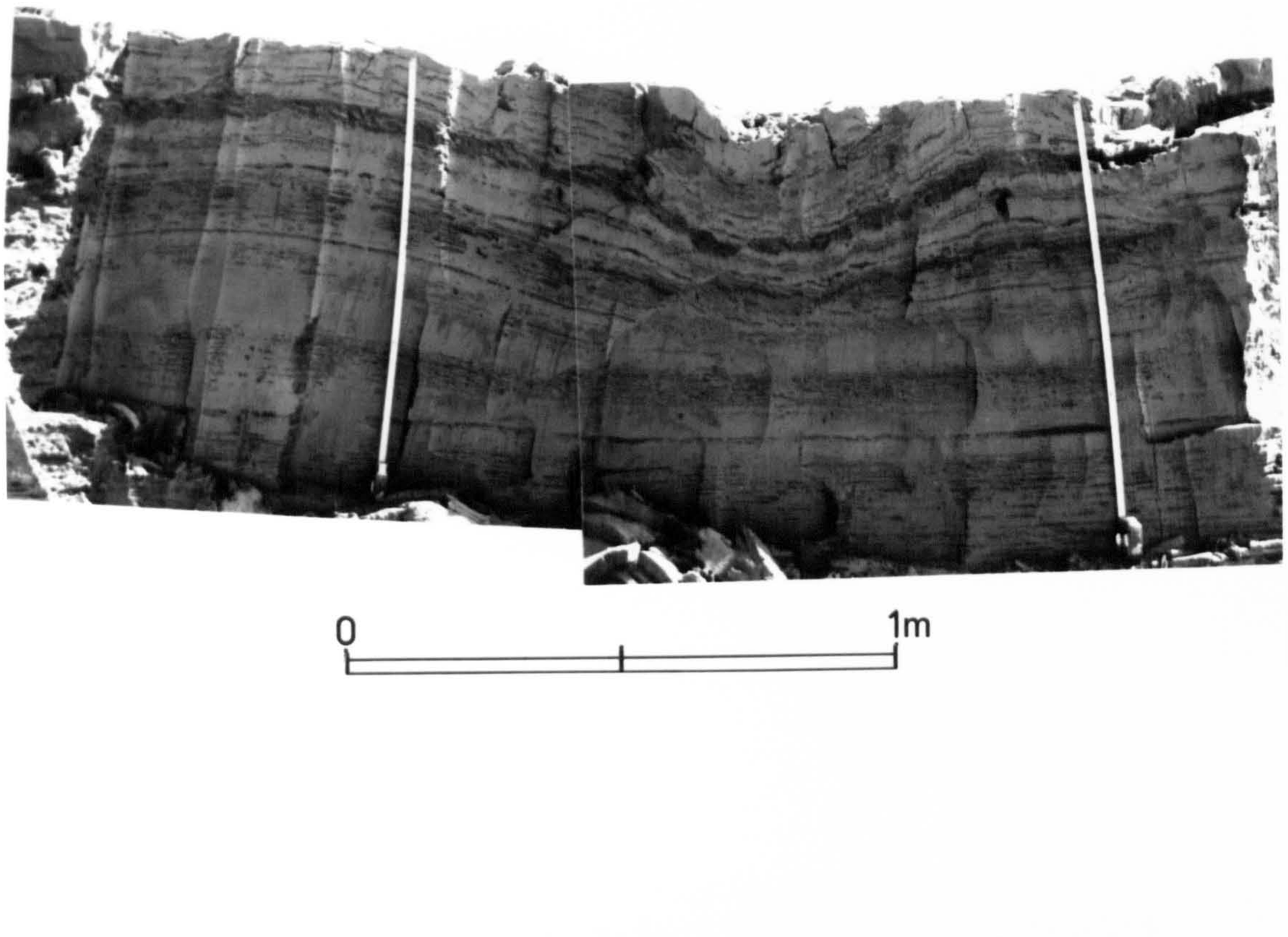


Figure 70. Photograph mosaic of scour mark section 1, Irving Oil Dock, Cobequid Bay.

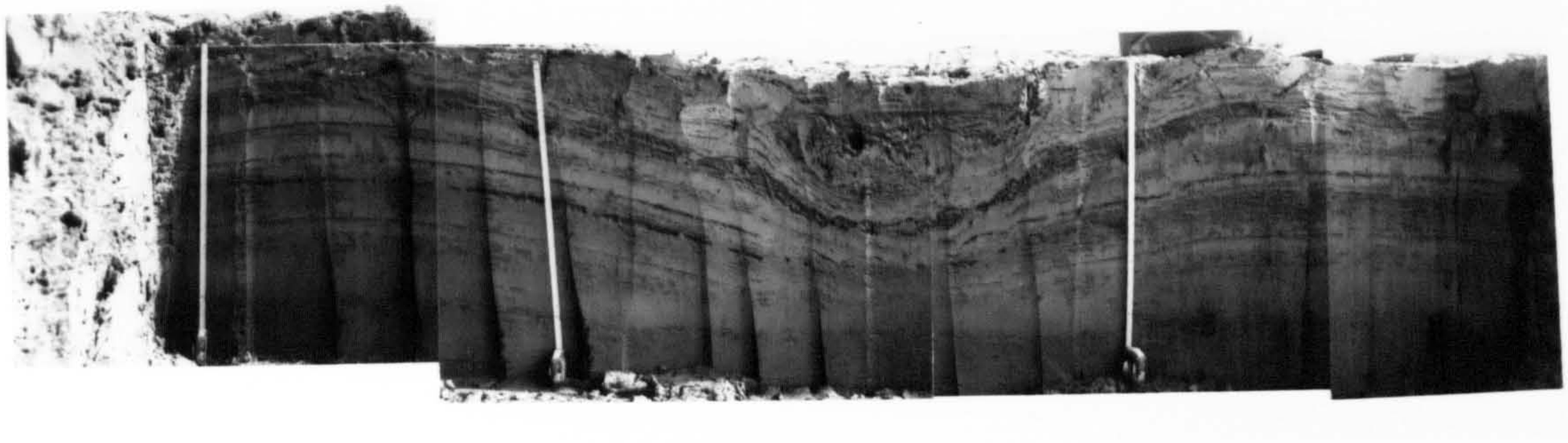


Figure 71. Photograph mosaic of scour mark section 2, Irving Oil Dock, Cobequid Bay.

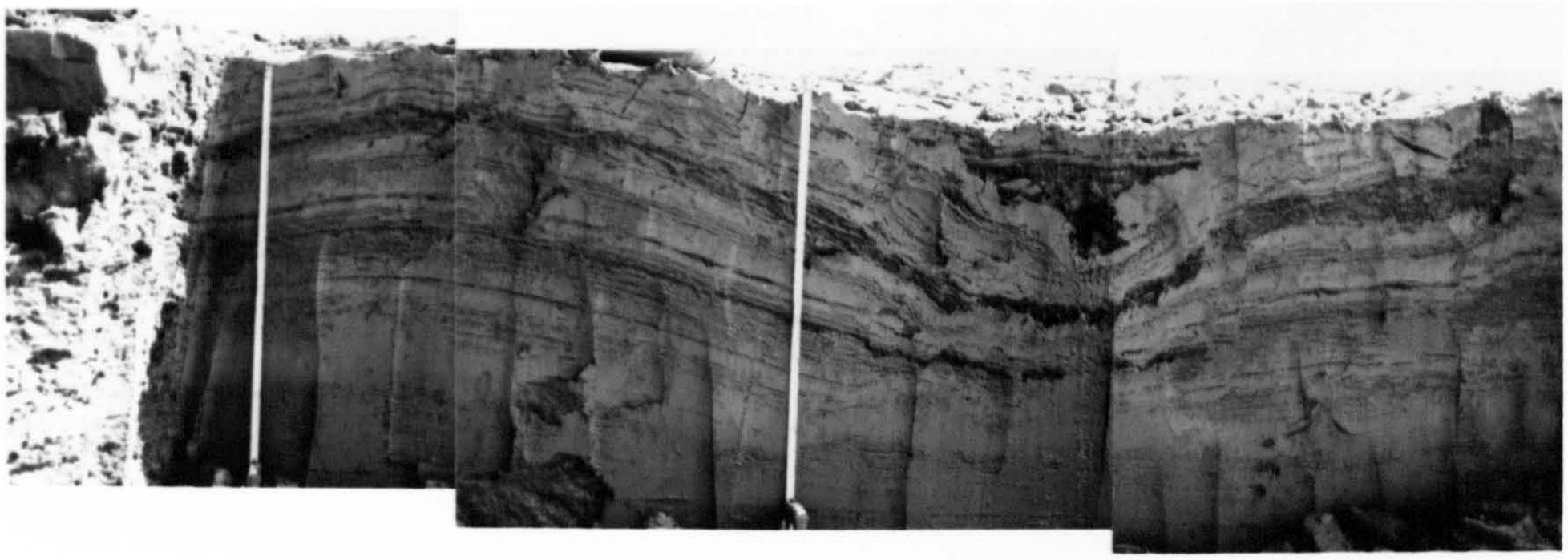


Figure 72. Photograph mosaic of scour mark section 3, Irving Oil Dock, Cobequid Bay.

Figure 73. Photograph mosaic of scour mark section 4, Irving Oil Dock, Cobequid Bay.

the extreme left or right side of the cross-profile. Change in relative thickness of each layer was calculated by dividing disturbed thickness by original thickness. Figure 74 illustrates the change in relative layer thickness, and shows that greatest reduction, rarely exceeding 50 %, generally occurs in layers D and E closest to the scour mark incision surface in a narrow zone approximately defined by the scour mark width. Thickness increase, with maxima between 25 - 50%, occurs adjacent to the scour mark margins in two broad zones. Vertical deflection of interlayers (Figure 75) clearly illustrates how such deflections are greatest closest to the scour mark incision surface, and decrease with progressive increase in distance from the incision surface.

A suite of small scale normal faults (5-60 cm long) affect layers below and immediately adjacent to the scour mark trough in all sections. The faults have apparent dip slip offsets ranging from a few millimetres to 7 cm. Two sets of faults can be identified: a left-dipping set and a right-dipping set. The left-dipping set are more profuse below the right side of the scour mark trough axis, and the right-dipping set more abundant below the left side. The left-dipping set dominates in sections 1 and 3, and both sets are equally developed in sections 2 and 4. In places where the two sets intersect, the left-dipping faults always truncate the other set (sections 1 and 2) and the separation angle of the two sets ranges between 80-90°. In both sets faults closest to the scour mark trough have steep apparent dip angles that approach vertical, the angle decreasing with increasing depth below the trough to as little as 15° (bottom of long, low angle, left-dipping fault, section 1). Unlike the sedimentary layers it is not possible to trace individual faults between sections.

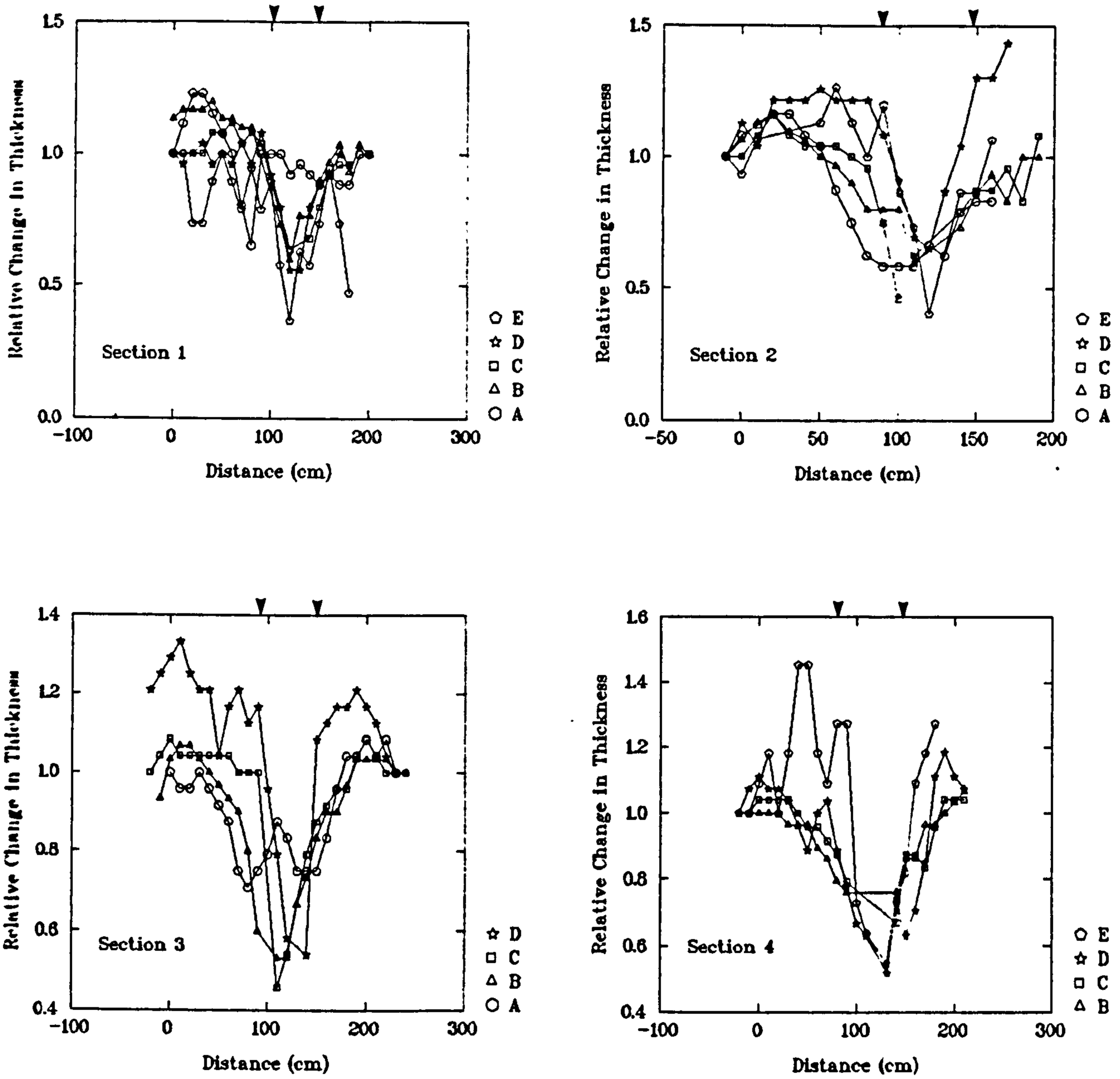
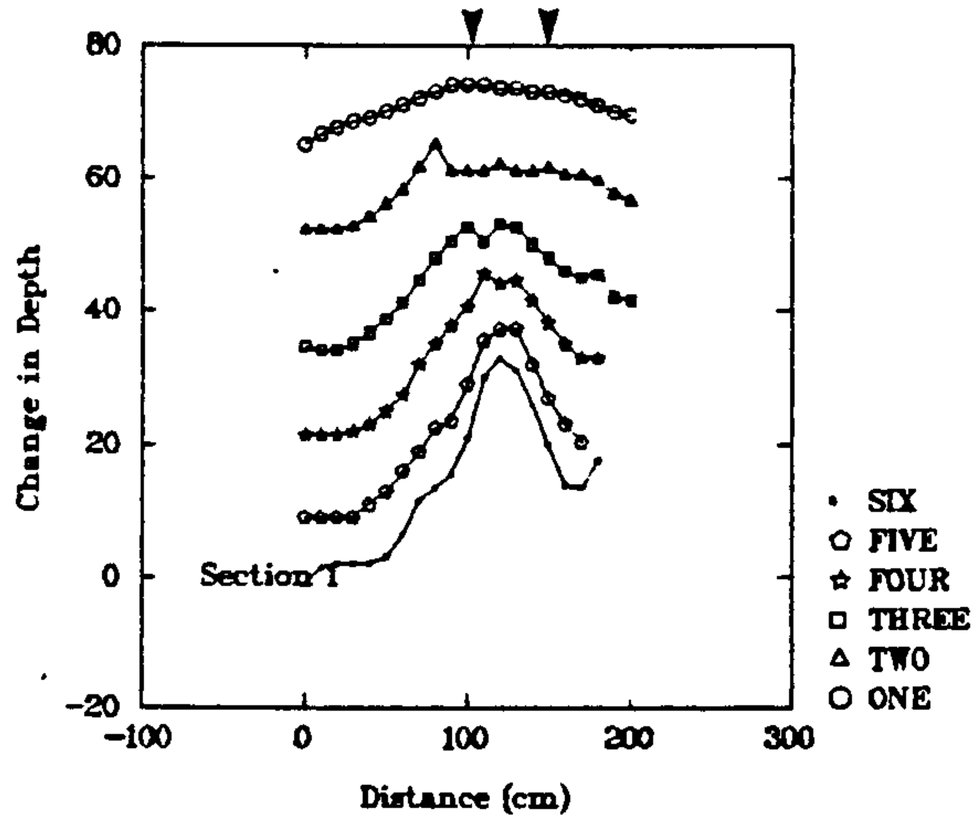
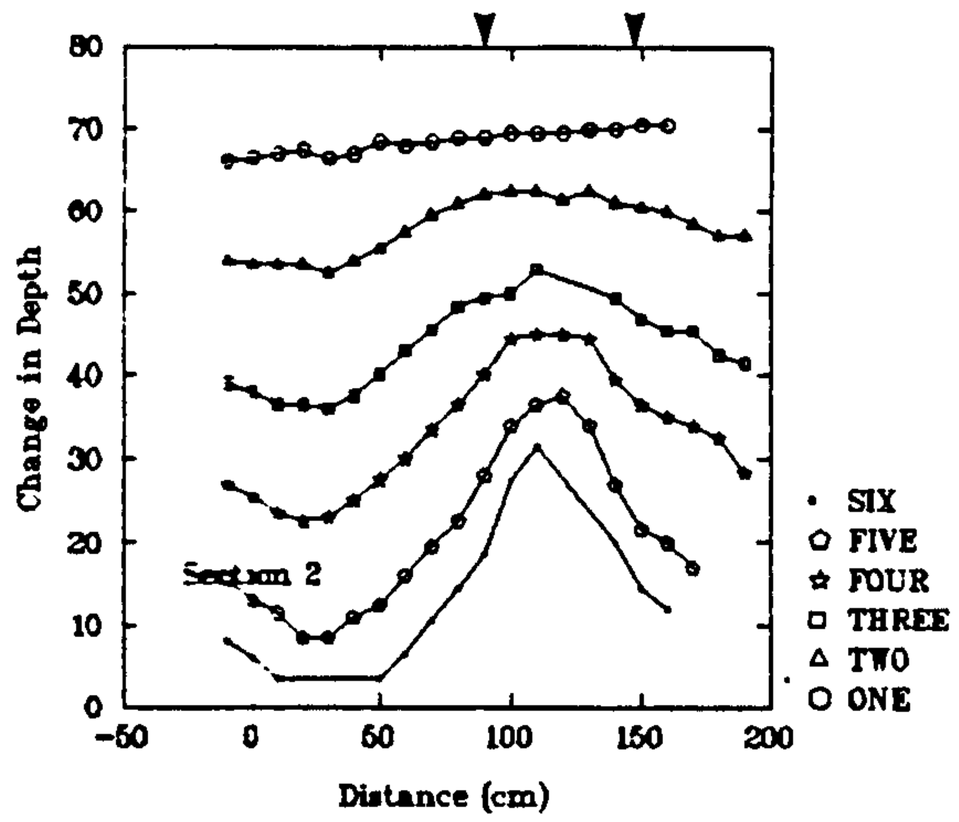
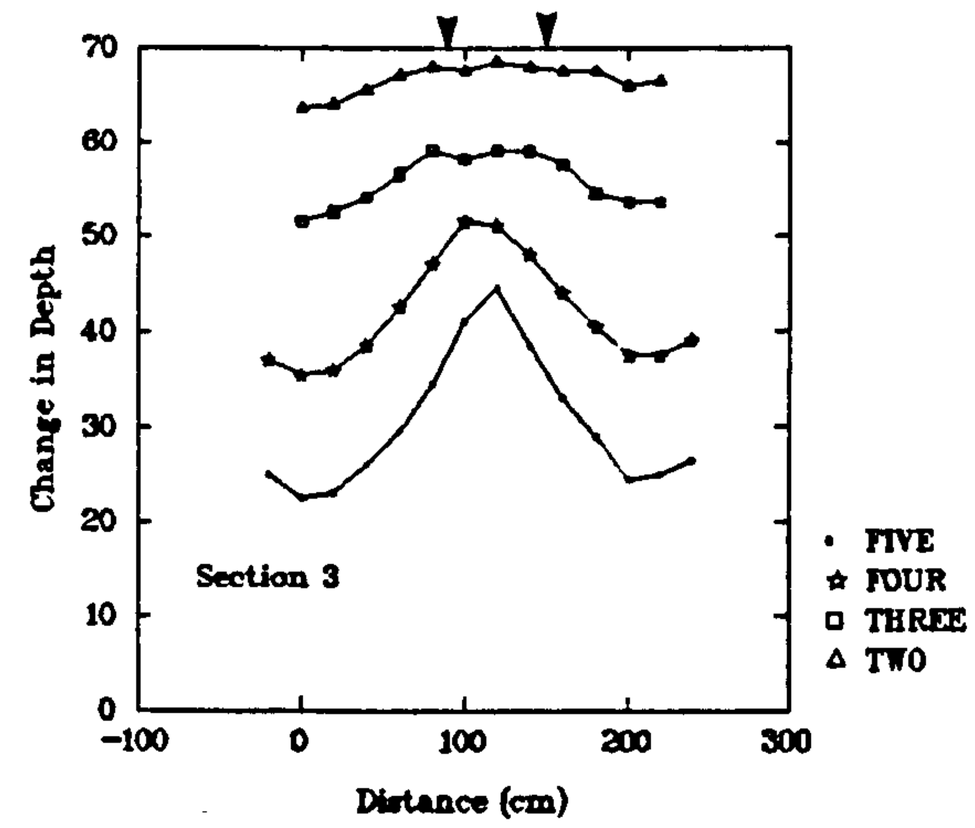


Figure 74. Graphs showing change in relative thickness of layers A - E beneath the scour mark at Irving Oil Dock, Cobequid Bay. Arrows show positions of the scour mark margin. 1.0 indicates no change in thickness; a value of 1.5 indicates a net increase in thickness of 50%; a value of 0.5 indicates a net decrease in layer thickness of 50%.







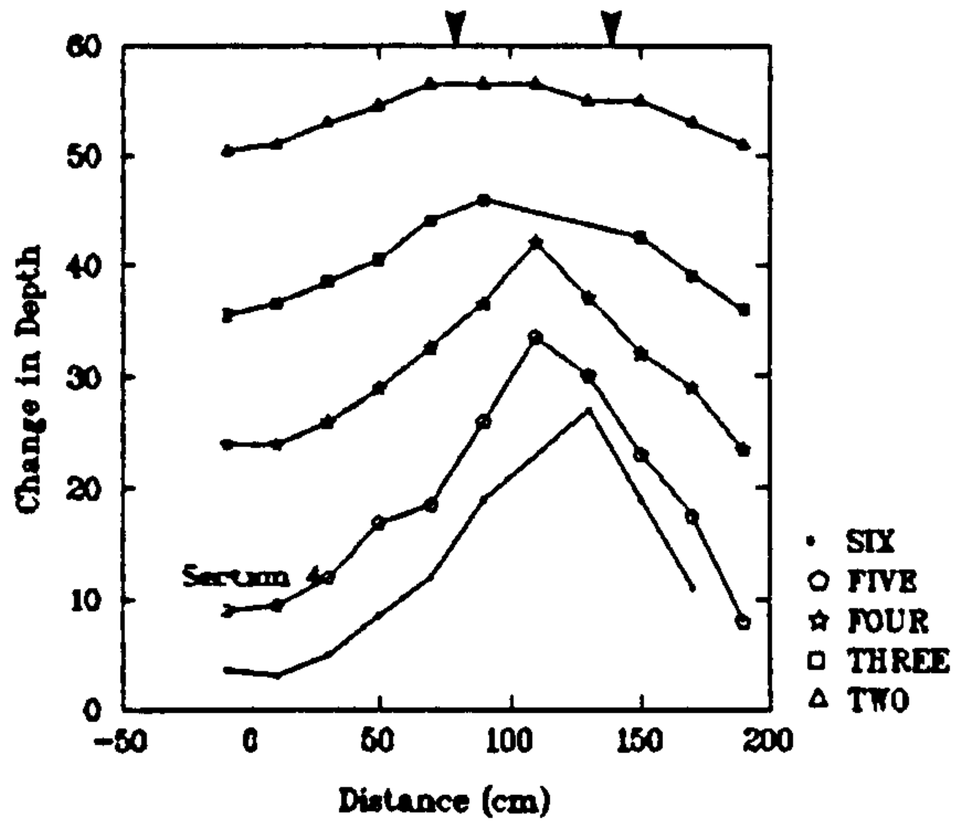


Figure 75. Graphs showing the amount of vertical deflection (in cm) of interlayer surfaces 1 - 6 beneath the scour mark at Irving Oil Dock, Cobequid Bay. Arrows show positions of the scour mark margin.

Shear strength contours (collected from sections 2-4), although varying considerably in value between the same layer in different sections, show a generally concordant trend with layers on either side of the scour mark trough. However, beneath the trough contours deflect upward, becoming more closely spaced, and are strongly discordant with downward-deflected layering. This results in a poorly-defined zone of slightly increased shear strength that is about 50 cm wide extending to about 20-25 cm below the deepest part of the scour mark trough.

St. Lawrence estuary

In this section ice scour marks are described from the tidal flats in the vicinity of Montmagny on the south shore of the St. Lawrence estuary (Figure 76). Here tidal flats extend over an area of about 20 km^2 (Dionne, 1974). The tidal flat sediments comprise a surface unit of soft grey-brown mud 10-50 cm thick. Mean grain size for this surface unit is 14.7% clay, 72.8% silt, 8.2% fine sand, 4.3% medium-grained sand (Table 8). Beneath this is a compact light brown mud 100-250 cm thick which rests above a late Pleistocene, light blue marine clay (Dionne, *op. cit.*). The tidal flat surface has a gentle slope of 2-3° towards the river. Maximum tidal ranges reach up to 6.5 m and ebb tidal currents have velocities less than 1.8 m/s. In January and February an ice canopy 40-150 cm thick develops by *in situ* freezing of river water. Break up occurs over a 2-3 week period in April during which the upper grey-brown and light brown muds are reworked by bottom-dragging

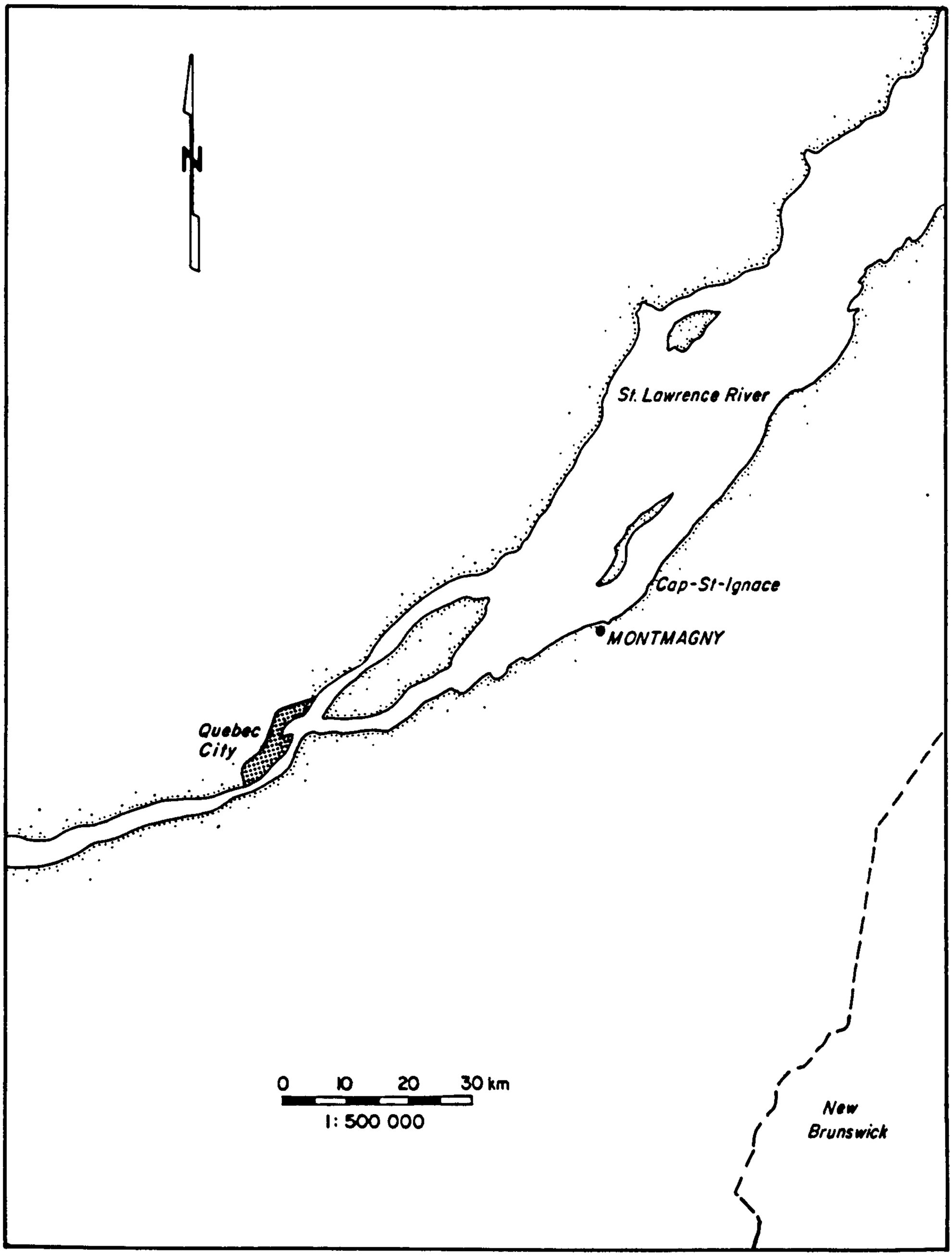


Figure 76. Location map of the Montmagny study area, St. Lawrence estuary, Quebec.

Table 8. St. Lawrence estuary grain size analysis.

SAMPLE #	CLAY (%) <0.002 mm	SILT (%) 0.002-0.075 mm	FINE SAND (%) 0.075-0.42	SAND (%) >0.42
A	13	85	2	-
B	12	83	5	-
C	18	65	9	8
D	28	67	5	-
F	17	81	2	-
G	15	71	11	3
J	14	85	1	-
K	12	78	5	5
L	3	40	34	23
Mean	**14.7**	**72.8**	**8.2**	**4.3**

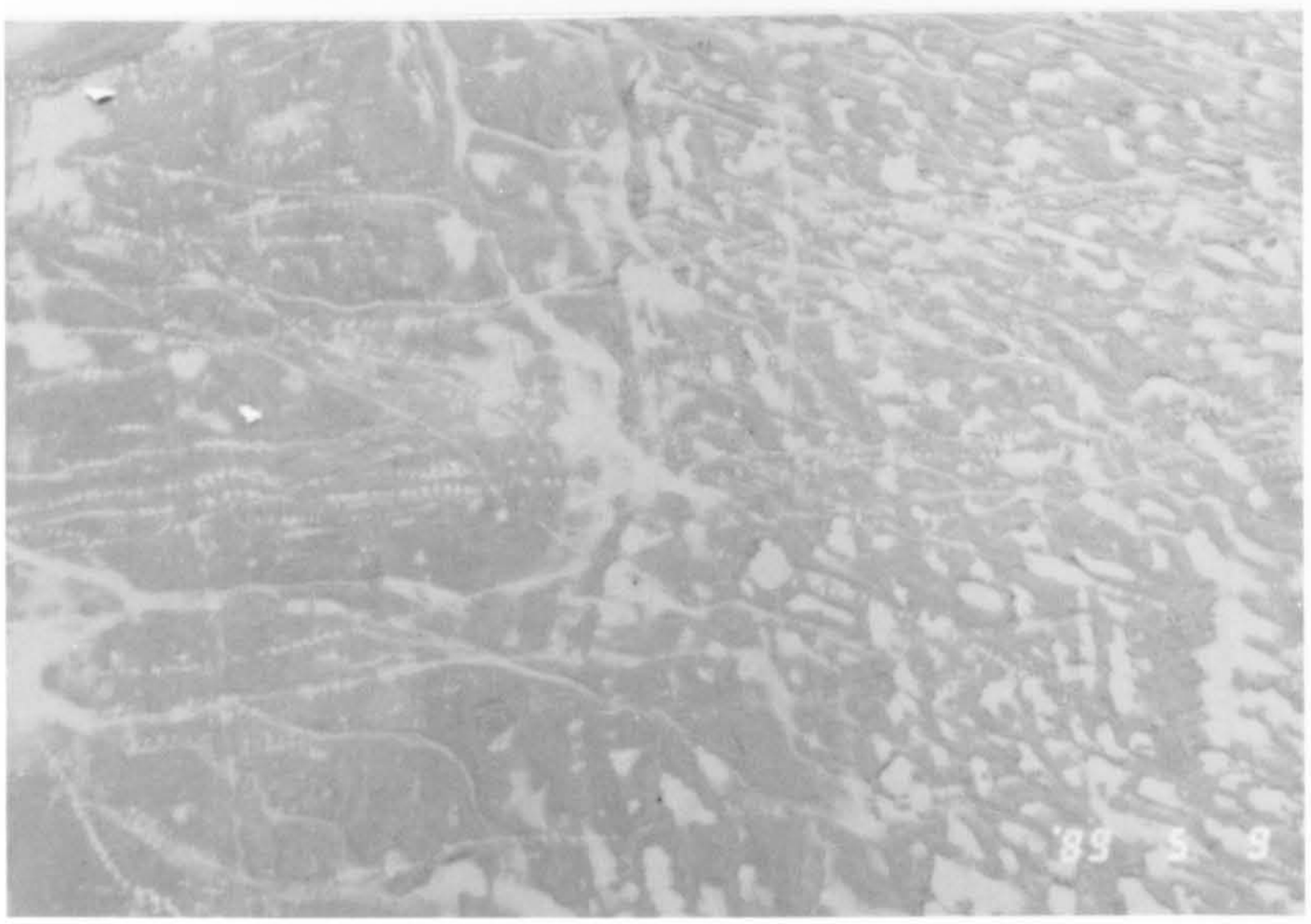


Figure 77a. Oblique aerial view of St. Lawrence estuary tidal flats in the vicinity of Montmagny, Québec. Stranded ice pans during low tide.

b. Oblique aerial view showing the boundary between former landfast ice (right) and region affected only by scour marks (left). Note the profusion of crater chain scour marks. These were probably made by floating ice floes oscillating in a swell and alternately touching down and lifting free from the tidal flat (see Chapter 4: **Rotations during upslope and downslope scour**).

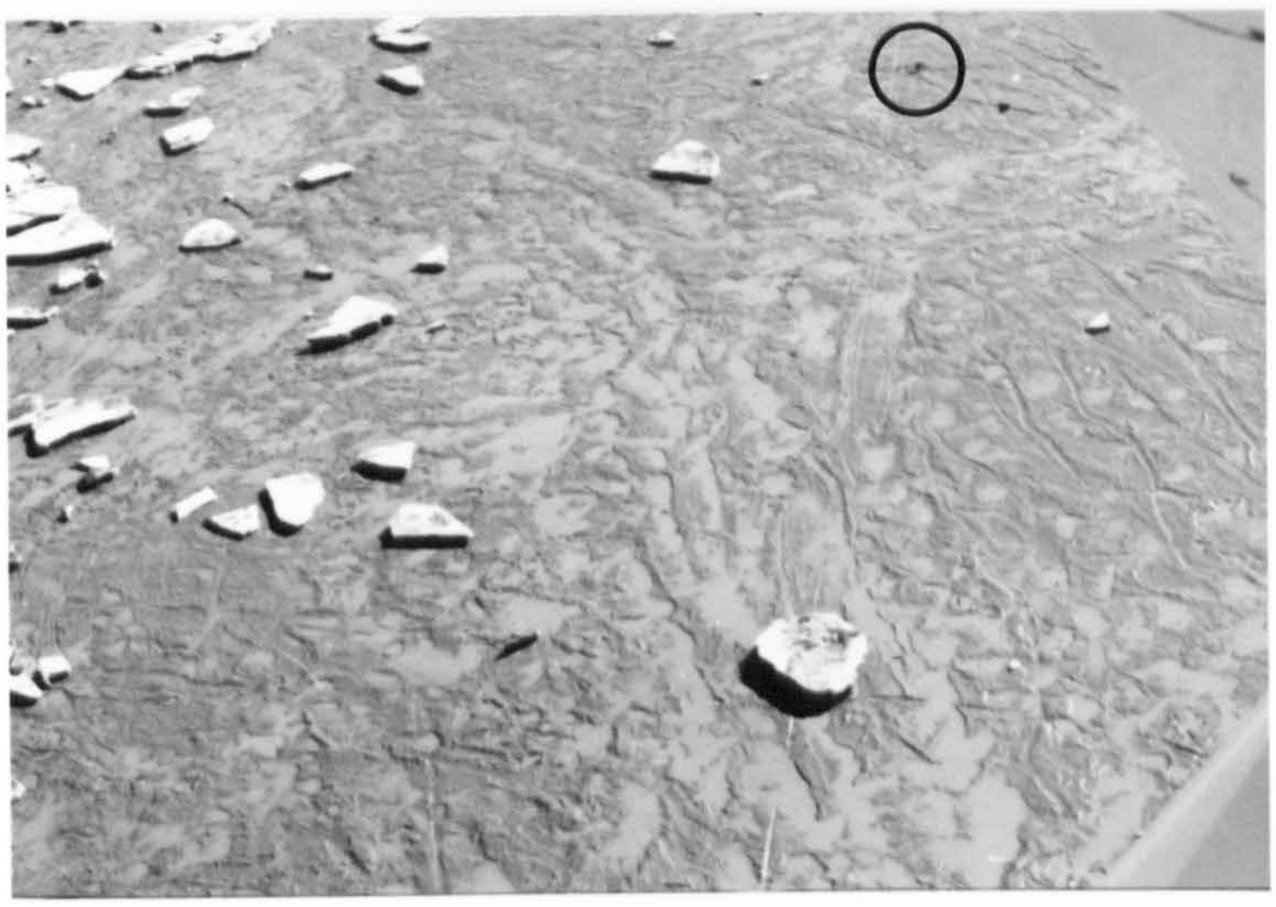


Figure 78a. Stranded, sediment-laden composite ice block at the end of a scour mark, Montmagny tidal flats.

b. Oblique aerial view of scour mark 1, Cap St. Ignace. Scour mark is on the right side of the picture extending from top to the position of the stranded floe which created it, near the bottom. The person (circled) is at the location of the cross-sections.

(Figure 79). Berms were not present, either in the form of bulldozed or upwarped material. Contours of corrected shear strength values are undulose, in places appearing to mimic the scour mark incision surface. A layer of pebbles occurred at about 20 cm depth, which explains why so many of the shear strength profiles stop at this depth. Below about 20 cm horizontal strength stratification is not evident and the sediment appears massive.

Scour mark 2 was about 1.5 m wide, 15 cm deep and berms were absent (Figure 80). As with scour mark 1 near-surface strength contours roughly parallel the shape of the incision surface, but because of a pebble layer at about 20 cm, the trend could not be established below this depth.

Interpretation

Cobequid Bay

Downward- and upward-deflected layering, small scale folds and faults are clearly localized beneath and immediately adjacent to ice scour mark troughs, and are thus interpreted as the product of sediment response to loading by scouring ice keels. With one exception (Black Rock scour mark 2) bedding is not truncated by scour mark troughs, which means that troughs are generally produced by downward pressing of sediments and not by horizontal bulldozing. Accommodation of strain in sub-scour sediments creates a space

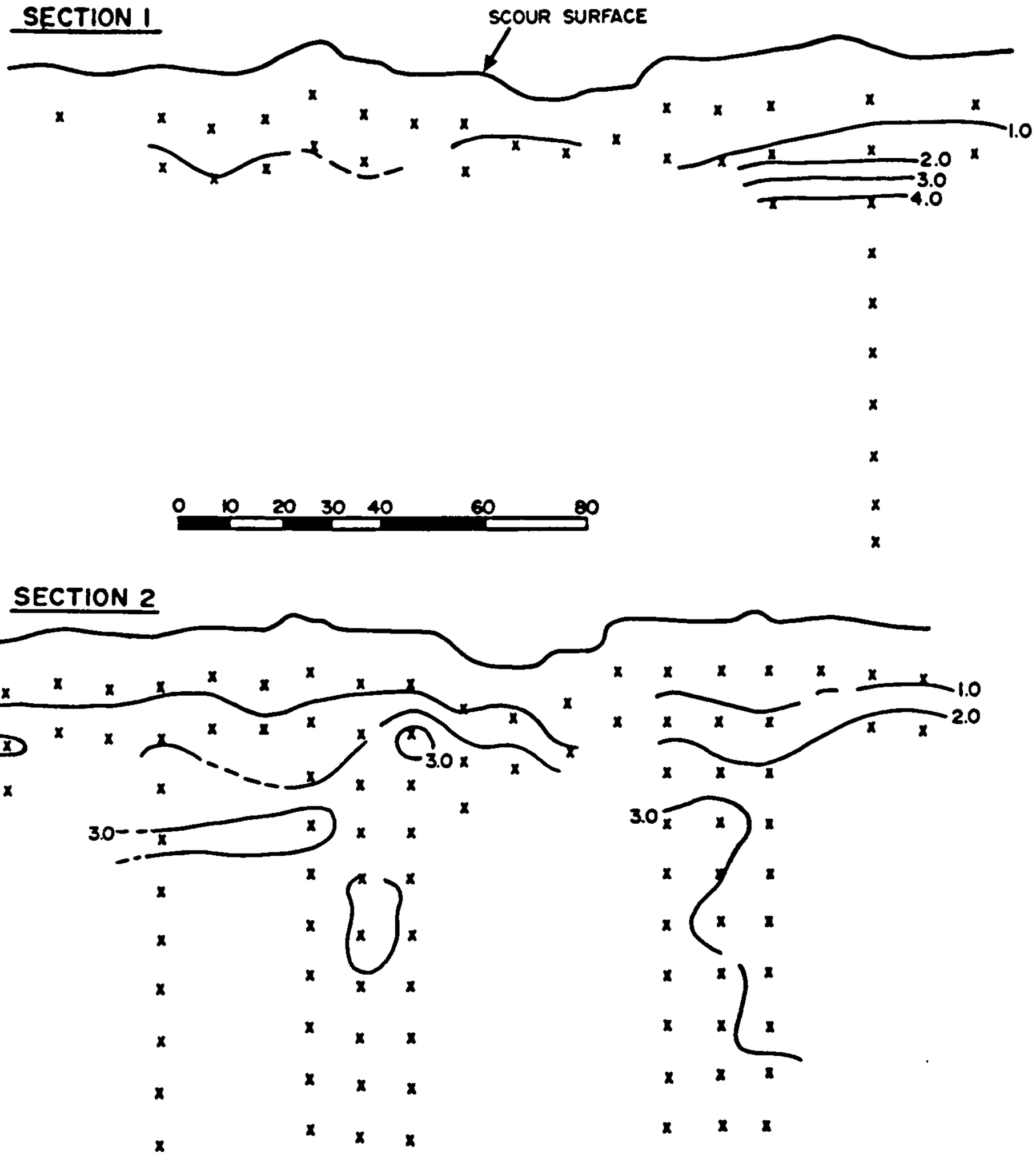


Figure 79. Scour mark 1, Cap St. Ignace, St. Lawrence estuary. Sections 1 and 2 are 1 m apart and are oriented normal to the scour mark axis. Small x's represent shear vane sampling depths from which contours of shear strength, in kPa (light lines), are derived. The sections were not excavated because bedding surfaces, and therefore visible indications of sediment deformation, were not present. No vertical exaggeration.

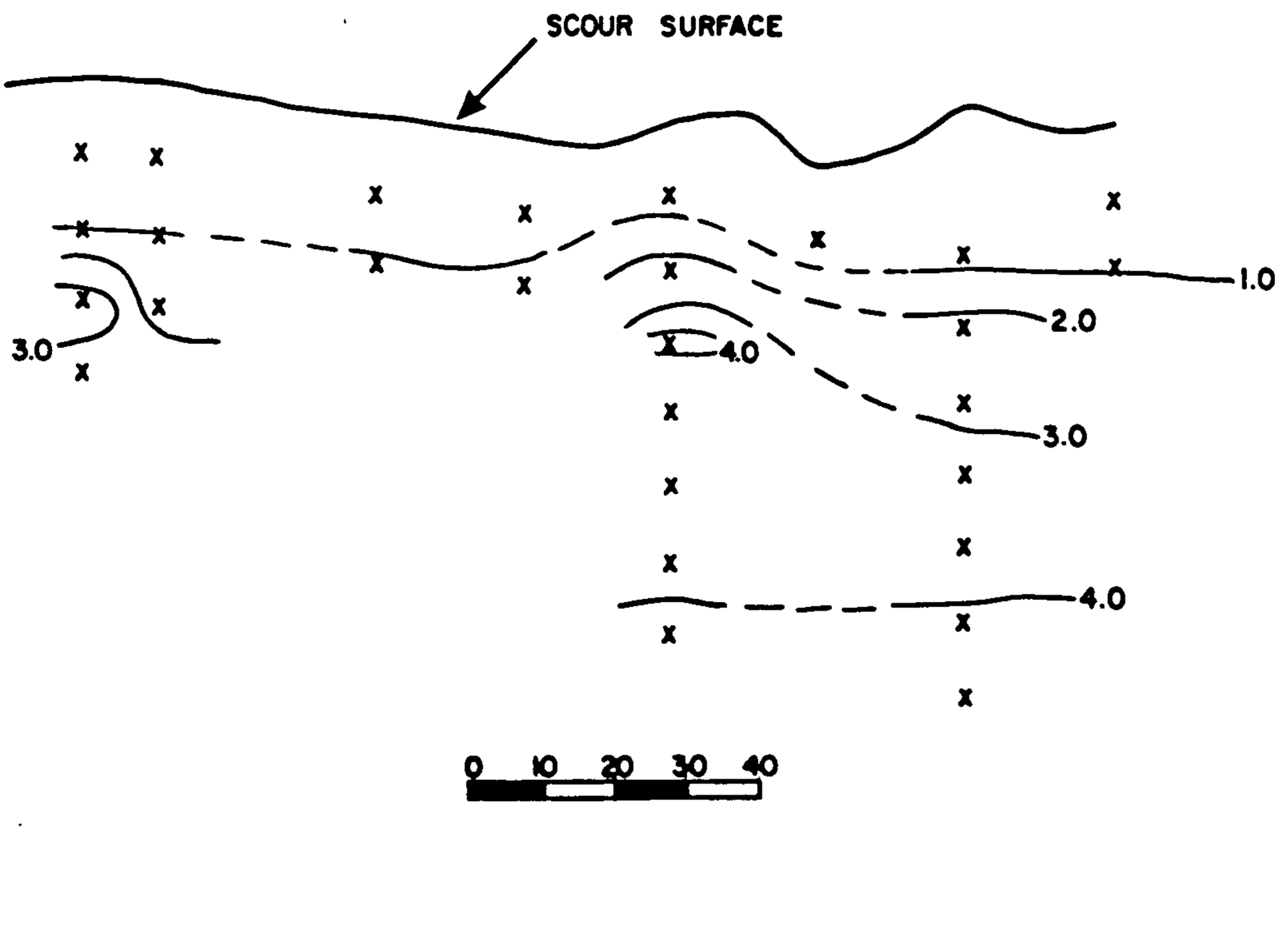
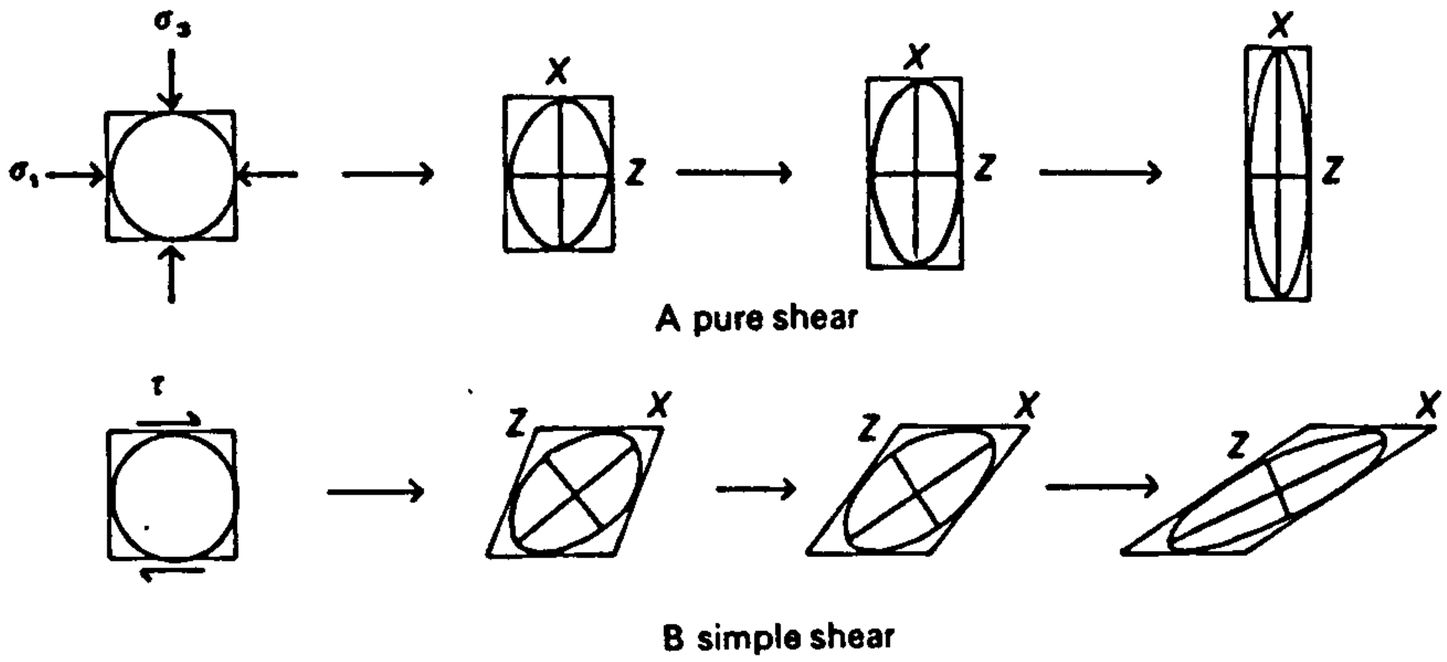


Figure 80. Scour mark 2, St. Lawrence estuary. Small x's represent shear vane sampling depths from which contours of shear strength, in kPa (light lines), are derived. Bedding surfaces were not observed and the section was not excavated. No vertical exaggeration.

problem that may be resolved by downward displacement of sediment through faulting, layer deflection and layer thickness reduction.

Faulting is associated with two scour marks (Black Rock 1 and Irving Oil Dock). Beneath the Irving Oil Dock feature faults account for significant displacements along a system that has a conjugate geometry in the two-dimensions of the cross-section. Where they intersect the faults have separation angles of 80-90°. Normally a material that exhibits brittle failure develops slip surfaces which have an acute angle with respect to the principal stress $\sigma 1$. However, in undrained conditions the angle may approach 45°, failure occurring along slip surfaces very close to the planes of maximum shear stress (cf. Maltman, 1987). The separation angle of these faults will be close to 90°. Faults beneath the Irving Oil Dock scour mark are thus interpreted as conjugate slip surfaces that developed close to the angle of maximum shear stress. A diagram summarizing stress trajectories in the plane of the cross-sections for this scour mark is shown in Figure 81.

Layer thickness reduction and deflection probably occurs by extensional thinning as layers are "stretched", and may be the combined result of both simple shear and pure shear. The effect of simple shear "stretching" can be seen particularly well beneath the Irving Oil Dock scour mark where layer C (section 1) is affected by a number of faults of the left-dipping conjugate set, that have caused slight clockwise rotation of the bounding surfaces (3 and 4) (see Figures 68 and 70). Simple shear cannot be demonstrated as an operative "stretching" mechanism beneath the other scour mark troughs because sub-scour



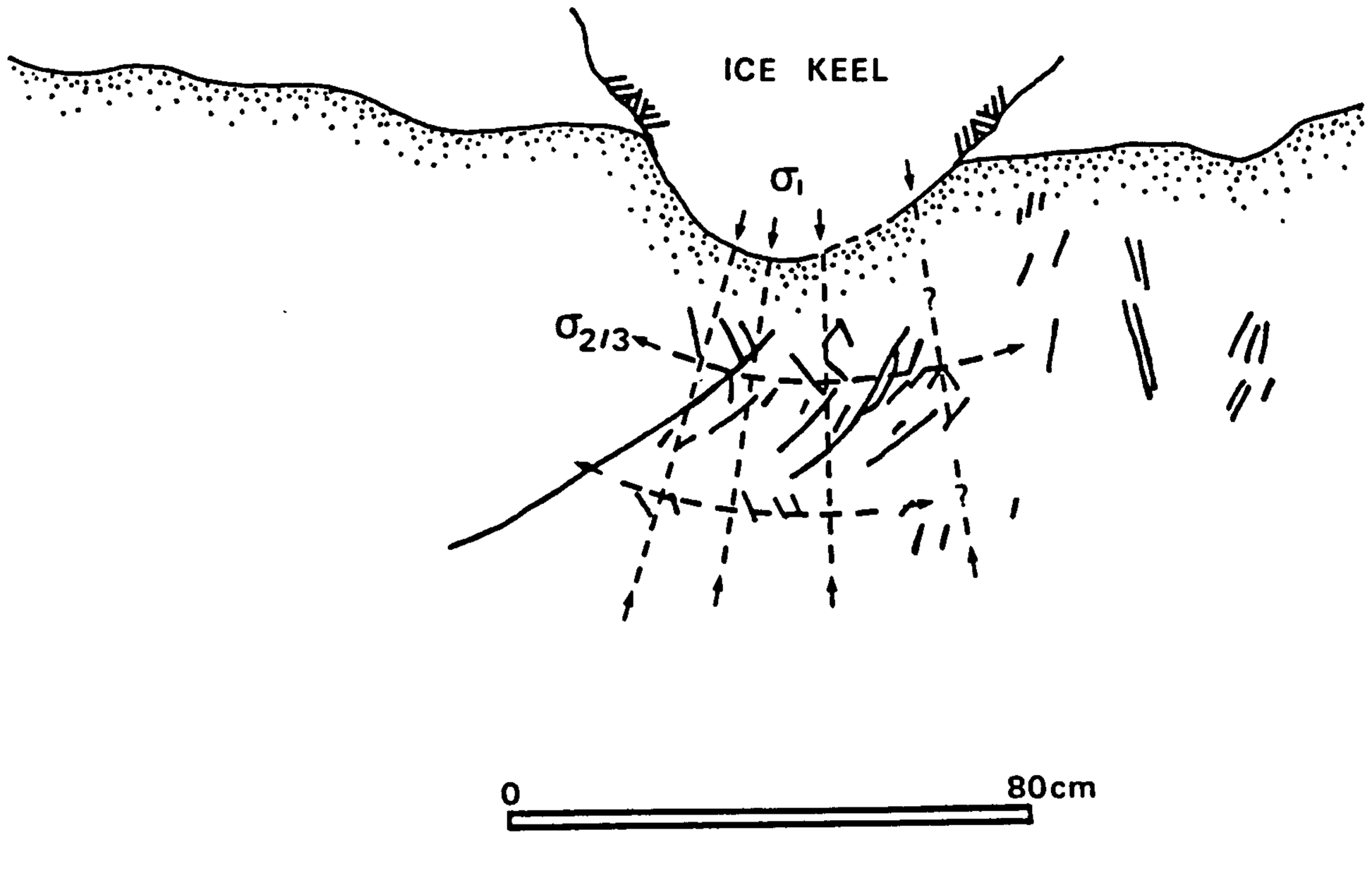


Figure 81. Interpreted trajectories of principal stresses (dashed lines: σ1 and σ2 or σ3) based on the angle of intersection of faults (heavy lines beneath scour mark trough) in the plane of cross-section for scour mark section 1, Irving Oil Dock, Cobequid Bay.

faults are not present. However the operation of pure shear may explain net displacement of sediment from beneath the scour mark, resulting in layer thinning, to a zone of net accumulation beyond the scour mark margins, resulting in layer thickening. Below scour mark 1 (Black Rock) thickness increase is localized in the surface layer in narrow zones (< 15 cm wide) immediately adjacent to the trough (see Figure 60). Extreme thickness increase on the left side is accommodated along two reverse faults. Thickness increase is also localized in narrow zones adjacent to the trough margins in scour mark 2 (Masstown Flats), and in section 2 is accomplished by development of a small scale fold on the left hand side (see Figure 67). Layer thinning and thickening is a little ambiguous below scour mark 2 (Black Rock). Thinning occurs below the right hand trough, but local thickening is largely restricted to a small fold (affecting bedding planes A and B) beneath the left hand trough (see Figure 62). Layer thickening beyond the double trough does not appear to occur. However, truncation of layers (e.g. A) by the trough indicates that at least some of the strain has been accommodated by incision of the ice keel and removal of material by ploughing rather than by down-pressing. Scour mark 1 (Masstown Flats) exhibits little sub-scour deformation (see Figure 63). This is interpreted as a function of the small incision depth (2-5 cm), the result of loads smaller than for the other scour marks.

Increases in shear strength immediately beneath scour marks (Black Rock scour mark 2; Masstown Flats scour mark 2; Irving Oil Dock scour mark) is indirect evidence of a change in material property, interpreted as an increase in internal friction through more efficient packing of sediment grains as a result of consolidation. Consolidation is interpreted

to occur as a result of pure shear within sediment layers.

St. Lawrence estuary

Lack of sedimentary stratification of tidal flat sediments negates the possibility of defining sub-scour deformation structures. Shear strength data suggests downwards pressing of the sediments has occurred because contour shapes mimic the scour mark surfaces. Beneath the deepest part of the troughs contours are more closely spaced (e.g. scour mark 1, section 2, Figure 79) perhaps indicating consolidation similar to that interpreted for the Cobequid Bay features, and similarly implying the operation of pure shear.

Discussion

In general, scour marks in Cobequid Bay are created by ice keels that press sediment downwards beneath the trough, and heave sediment upwards adjacent to the trough, rather than by keel incision and excavation of troughs by bulldozing. Downward bending causes extension and thinning of sediment layers that is generally accommodated by pure shear, and in one case (Irving Oil Dock scour mark) additionally by simple shear along discrete normal faults. Although there is local volume loss where sediment layers thin, there is corresponding volume increase of the same layers adjacent to the scour mark troughs, so

that for all sediments affected by a scour event, there need not be a net change in sediment volume. Indeed, faults below one feature (Irving Oil Dock scour mark) are evidence for undrained conditions, and therefore that significant volume change has not occurred.

Local increase in shear strength occurs immediately below scour mark troughs in Cobequid Bay, and is probably the result of consolidation during scour by pure shear. Similar shear strength contour shapes from beneath scour marks in the St. Lawrence estuary also suggest downward-pressing of sediment as the mechanism of trough formation, and local increases in shear strength may also indicate consolidation by scour-induced pure shear.

From Norway Longva and Bakkejord (1990) described layered sediments that were deflected downwards below scour mark II, and which mimic the topography of the incision surface. Layer-thickening occurs in the hinge zones of the broad, open, low amplitude (0.7 m) upright anticlinal folds that mimic the trough surface. One layer has been truncated at the incision surface. Although the Norwegian feature is much wider (30 m) the sub-scour structures (Figure 2c) are similar to those beneath the Cobequid Bay scour marks. Collectively these features imply that down-pressing of sediment has occurred in conjunction with keel incision and removal of material by bulldozing (cf. scour mark 2, Black Rock), a conclusion confirmed by Longva and Bakkejord (*op. cit.*) who ascribed the removal of 67% of the cross-sectional area to bulldozing ("erosion") and 33% to down-pressing ("deformation"). Layer thickening in the anticlinal hinge zones of the Norwegian scour mark

may indicate the operation of pure shear.

Although similar mechanisms can be inferred to have operated at both small and large scale from the above examples, the same inference cannot be made when comparing these examples with the large scale scour marks, described in Chapter 5, from southern Manitoba. Although down-pressing may have occurred beneath the Manitoba features, the severe reworking of bedding laminae means that marker horizons, which might have indicated layer thickness-reduction, are absent. Instead, interpretation of scouring mechanisms for the Manitoba scour marks is based largely on fault geometry. The development of conjugate fault sets, similar to those beneath the Irving Oil Dock feature in Cobequid Bay (compare Figure 32 with Figure 68) indicate the operation of bearing capacity failure in sub-scour sediments. Bearing capacity failure is therefore a possible failure mechanism to account for the conjugate fault sets beneath the Irving Oil Dock scour mark. Such failure is suggested by development of the single, left-dipping fault beneath the Irving Oil Dock scour mark (see Figure 68, section 1), which recurves at its deepest point, similar to the failure surface(s) that define the lower envelope of the zone(s) of radial shear in Terzaghi's (1959) model (see Figure 47).

A feature unique to the Manitoba scour marks is the development of horizontal faults beneath the berms. These faults are interpreted to have originated by horizontal translation, and vertical stacking of cohesive clay blocks, a process that cannot operated below the other scour marks. A single, horizontal fault is interpreted to have originated from scour-related

shear forces that propagated to as much as 5 m beneath the deepest part of Manitoba scour mark B (see Figure 32). Such deep-seated, horizontal faults have not been observed beneath any other feature.

CHAPTER 7

SCOURING IN THE GEOLOGICAL RECORD

Prolonged reworking of submerged sediments by the action of grounding and scouring iceberg keels can produce a number of distinct facies termed *iceberg turbate* (Vorren *et al.* 1983), or more generally *ice keel turbate* (Barnes and Lien, 1988). The characteristics of the facies will depend heavily on the composition of the initial sediment prior to ice keel turbation. Although ice keel turbates have been recognized in Quaternary surficial sediments from marine acoustic profiles (e.g. Vorren *et al.* 1983; Josenhans *et al.* 1986; Barnes *et al.* 1987), criteria for their visual recognition in outcrop have not been established and consequently they have never been documented in the rock record. Ice keel turbates are the result of multiple ice scour events each of which produces a single ice scour mark, for which identification criteria are also lacking. It is first useful to establish criteria for the visual recognition of ice scour marks in outcrop, and then establish some common elements that define ice keel turbates in outcrop, based on a knowledge of scour mark recognition.

This chapter presents a discussion of why it is important to be able to recognize scour marks and ice keel turbates in the pre-Quaternary rock record. Criteria for identifying scour marks, based on the results from Chapters 3, 5 and 6. This is followed by a review of some published examples of glacial facies from the Late Precambrian to Permian, with emphasis on their possible re-interpretation with respect to ice scour.

The recognition of fossil ice scour marks and ice keel turbates is important for two reasons. The first is a practical one. The definition of sub-scour deformation structures, in particular deep-seated faults, from beneath large scale iceberg scour marks in southern Manitoba has caused a profound reappraisal of the need for and method of protection of offshore oil and gas pipelines by the Canadian and United States oil industry in the last two years (Clark *et al.* 1990). However, from an engineering standpoint, the results from the Manitoba study must be used with caution because the deformation structures are developed in relatively pure clays which are not common in the areas of concern offshore. In addition, the Manitoba clays have had a history of deposition, subaerial exposure and re-submergence prior to scouring which may have affected their response to ice keel loading; in Canada most continental shelf surficial sediments presently affected by scouring icebergs have never been exposed (except for parts of the Grand Banks of Newfoundland and the Beaufort Sea). The major question arising from acceptance of the Manitoba results by offshore engineers concerns the effects of variation of grain size on the behavioural response of sediment to ice scour. In geological terms this can be translated into an analysis of the types and depths to which deformation structures occur in different sediment types.

The second reason is an environmental geological one. Scouring of sediments by floating ice keels is a phenomenon that affects a considerable portion of the world's ocean seafloor, occurring seasonally over vast areas of high latitude and temperate continental shelves and lakebeds (Figure 82), and probably reworking large volumes of sediment. For example, the volume of sediment reworked by scouring icebergs on the Labrador continental

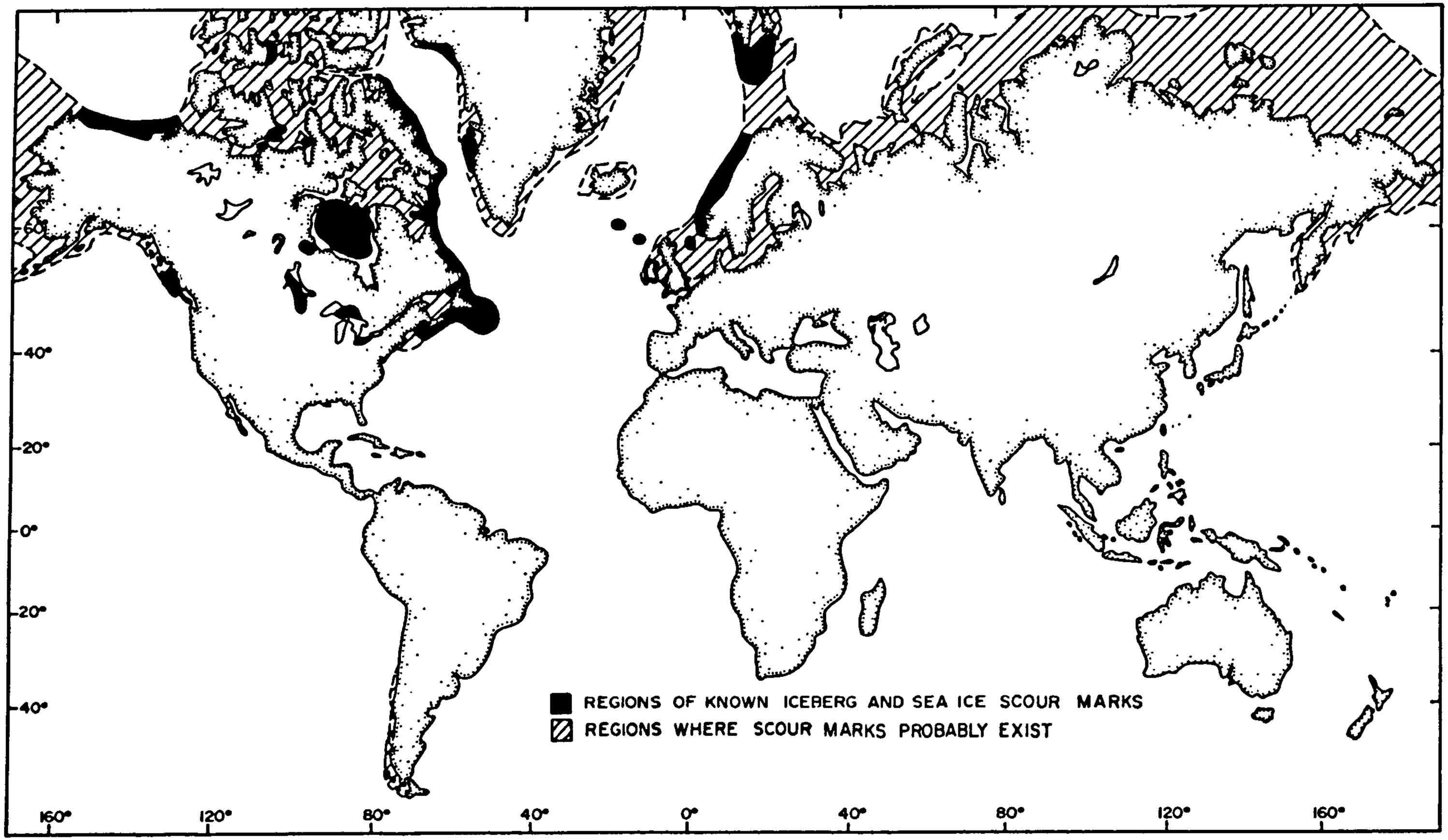


Figure 82. Map showing distribution of scour marks for northern and mid-latitudes.

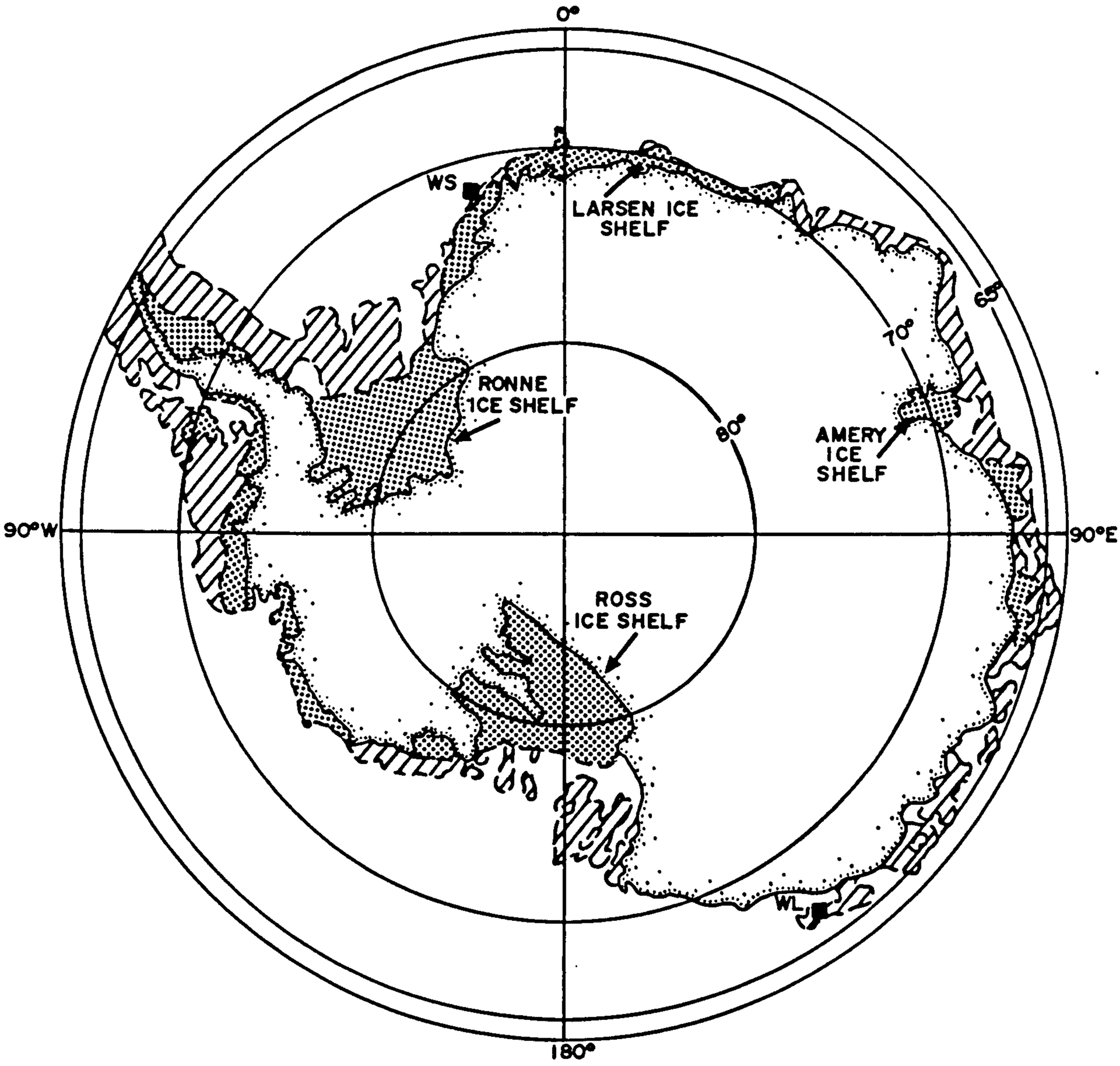


Figure 82 (cont.). Map showing probable distribution of scour marks (diagonal stripes) around Antarctica (generally above the 500 m contour). WS and WL are the Weddell Sea and Wilkes Land scour mark study areas respectively, reported in Barnes and Lien (1988).

shelf each year is estimated as 0.03 km^3 by Lewis *et al.* (1989), or 300 km^3 in the last 10,000 year period. The latter figure must be regarded as a very conservative estimate because it is based on modern iceberg flux rates which are probably far smaller than they would have been during deglaciation in the Holocene epoch. Prolonged exposure to scouring by many keels can modify sediments that were originally stratified to the point of almost total homogenization of original structures (e.g. Vorren *et al.* 1983, Norwegian shelf; Josenhans *et al.* 1986, Labrador shelf). In Lake Agassiz, for example, the period of scouring probably lasted for as little as about 1,200 years (9,900-8,700 B.P., see Chapter 5) and resulted in severe reworking of primary layering. With the potential for such profound effects over geologically short periods of time (thousands of years) it is reasonably likely that scour marks, and ice keel turbates, are present in sediments of marine and lacustrine origin in the pre-Quaternary glacial rock record. Ice scouring occurs typically in continental shelf ice proximal and ice distal facies settings (Eyles and Eyles, 1992). Temperate ocean areas receive large amounts of glacial sediment, resulting in thick sequences that are more likely to preserve the effects of ice scour than sediment-starved settings typical of polar areas (Eyles and Eyles, *op. cit.*).

If sedimentary structures diagnostic of the ice scour process can be recognized they may, in conjunction with other indicators (such as depositional sedimentary structures and fossils), provide a new, powerful indicator of environment. However, scour marks and ice keel turbates alone do not constitute evidence of glaciation. For example, ice keel turbation by sea ice or lake ice keels can occur in non-glacial, cold environments (e.g. modern lake

ice scouring in Lake Erie, and modern scouring by icebergs on the Labrador continental shelf). The problem is further compounded by the inability to distinguish between turbation caused by seasonal sea or lake ice and turbation caused by icebergs.

Glacimarine rocks are more likely to be preserved than their corresponding continental equivalents and marine evidence of glaciation may be more aerially extensive (e.g. Hambrey and Harland, 1979; Eyles *et al.* 1985), for example ice rafting today affects some 80,000,000 km^2 of ocean floor (Heezen and Hollister, 1964). Thus in searching for evidence of ice scour, the most likely chance of finding its occurrence is in the marine record. Also, scouring may be registered in marine sediments far removed from direct glacial action (Eyles *et al.* 1985), and thus may be present in the "interglacial" record as well.

Despite the wide geographic extent of Pleistocene-age ice scour marks preserved on land, and of those in modern intertidal zones, the range of grain size is restricted to clays and silts. Glacimarine sediments generally offer a wide range of grain sizes, and because multiple tillites are common in glacial stratigraphic sequences the probability of encountering a range of grain sizes in one locality is higher than it might be for "bedding plane" exposures for example offered by Lake Agassiz, Cobequid Bay and the St. Lawrence estuary. Thus with: (1) a demonstrated engineering need, (2) the demonstrated importance of ice scour as a geological agent, and (3) potential for the preservation of its effects, a careful re-examination of glacimarine and glacilacustrine lithified sediments over a wide range of grain sizes is warranted.

Scour marks in lithified sediments

In order to recognize the effect of ice scour in the pre-Quaternary glacial record, a definitive set of diagnostic features which must be present in affected sediments have to be established. A review of the scour marks described in this work and in others reveals common elements which are always present, and unique elements which may or may not be present. These elements can be used as a guide to the identification of scoured sediments.

The key to successful identification of sub-scour deformation structures in this study has been first to positively identify ice scour marks as they appear on the present ground surface above water (e.g. Lake Agassiz, St. Lawrence estuary, Cobequid Bay and the work of Longva and Bakkejord, 1990). With scour marks thus positively identified it is relatively straightforward to establish correlations between the surface expression of scour marks and sub-surface features. In this way a complete three-dimensional appreciation of scour marks is obtained. However, in the pre-Quaternary record it is not usually possible to observe an association between features developed on bedding surfaces and sub-scour deformation structures. This is largely because expansive bedding surface outcrops are uncommon, and geologists are generally restricted to dealing with structures as they appear in cross-section. This is not always the case, and initially it might be prudent to examine exposures where bedding surfaces are exposed in order to identify diagnostic surface features (provided in Chapter 3) and to link these with diagnostic cross-sectional features (provided in Chapters 5 and 6). A synthesis of data from these chapters provides criteria for identifying single

scour marks, and these are presented below. Following the identification criteria several localities are described from around the world where there exist bedding plane rock exposures of potential scour marks. To paraphrase Hambrey and Harland (1979) concerning criteria to define the glacial origin of a sediment '*Few of the criteria in themselves demonstrate a glacial origin, but normally, to be certain, a combination of these factors on a sufficient scale is necessary.*' This well-advised caveat applies here.

Criteria for identifying single scour marks in lithified sediments

BEDDING SURFACE - Morphological features

- Flat or dish-shaped trough with defined margins (usually of positive relief). Trough may vary in width from a few tens of centimetres to hundreds of metres. Correspondingly depth may range from a few centimetres to several metres.

- Ridge-and-groove microtopography and striations parallel to margins. Ridge-and-groove relief on the order of 30 cm.

- Ridges-and-grooves on the inner berm margin may be at an angle to the main set in the centre of the trough.

- Cobble or boulder may mark beginning of a ridge.

- Width and relief of ridges and grooves may change significantly over a few metres.

- Occasional ice dissolution voids between scour mark margins which truncate ridge-and-groove microtopography. Coarse material may fill bottom of void.

- Irregularly-shaped flat-topped mounds in trough. Mounds have ridge-and-groove microtopography. Inter-mound space may be filled with sediment from overlying units.

- Berms. Width varies proportionately with width of trough, but may range from a few centimetres to 10-20 m.

- Blocky berms: tension cracks on inner flank. Berm crest of discrete subangular blocks. Outer berm of disaggregated sediment possibly incorporating rafts of blocky material in matrix.

- Round berms: may be original (if sediment was underconsolidated at time of scour) or the result of

winnowing. Winnowed berms may be armoured with coarse lag deposit if sediment is poorly sorted.

- Surcharge. Undulose pile of disaggregated material at leading edge of scour mark. Truncates ridge-and-groove microtopography behind it.

Other features

- Trough and associated grooves have disjunct orientations with respect to regional glacial flow patterns and to other scour marks, where present.

- Scour marks may have cross-cutting relationships on a bedding surface.

- Transverse ridges may be present in the trough reflecting keel oscillations (e.g. Reimnitz et al. 1973; Lien, 1981).

- Trough may be filled with well sorted sediment from winnowing of material put into suspension by the scouring keel.

CROSS-SECTION - Sub-scour structures

- Flat or dish-shaped trough with defined margins (usually of positive relief). Trough may vary in width from a few tens of centimetres to hundreds of metres. Correspondingly depth may range from a few centimetres to several metres.

- Conjugate normal faults. Faults normally in short segments, may or may not intersect, and may be folded. Possibly a single dominant fault set beneath centre part of trough defining a passive wedge of downward-displaced sediment. Later fault reactivation, caused by increasing overburden pressures, may cause normal offset of trough surface (few centimetres), and penetrate a short distance into overlying unit

- Sub-horizontal faults beneath berms. Possibly a large, continuous fault beneath centre of trough offset by or connected with conjugate faults.

- Fracture cleavage in small scale fold hinges in fine-grained sediments, unrelated to regional tectonism.

- Berms. Width varies proportionately with width of trough, but may range from a few centimetres to 10-20 m.

- Berm blocks defined by sub-vertical cracks (?1-2 m+ deep) filled by superseding unit which may drape over berm topography. Collapsed outer berm blocks resting in disaggregated matrix.

- Round berms, may be defined by lag deposit on upper surface.

- Downward deflection of layering where present. Maximum deflection and bed thickness reduction beneath central

trough.

- Possible zone of upwarping on either side of and immediately adjacent to trough.

Other features

- Ridge and groove microtopography may show as undulations or more angular crenulations with relief on the order of 30 cm.

- Trough may be filled with well sorted sediment from winnowing of material put into suspension by the scouring keel. If laminated, sediment unit filling trough may show onlap towards inner berm flank.

- Uncommon pits (dissolution voids) with steep walls may truncate the incision surface in the trough. Bottom of pit may be filled with coarse material derived from the underlying, scoured unit, and clasts may show signs of surface abrasion.

- Flat-topped mounds may appear similar to dissolution voids but trough floor between mounds may be characterized by flat surface of undisturbed seabed and absence of coarse material resting on it.

Associated environmental indicators

- facies with above features contained in or bounded by facies indicative of lacustrine or marine conditions, especially dropstones/lonestones and other drop structures.

Pre-Quaternary ice ages: potential for fossil ice scour marks

Since Precambrian times between 6-9 glacial "ages" have been recognized (including the Quaternary) (Harland and Herod, 1975; Hambrey and Harland, 1979). The following is a selective discussion of some of the "tillites" which define these ice ages with respect to

various features (often striated surfaces) which should be re-examined in the context of criteria for identifying the effects of ice scouring.

Late Precambrian

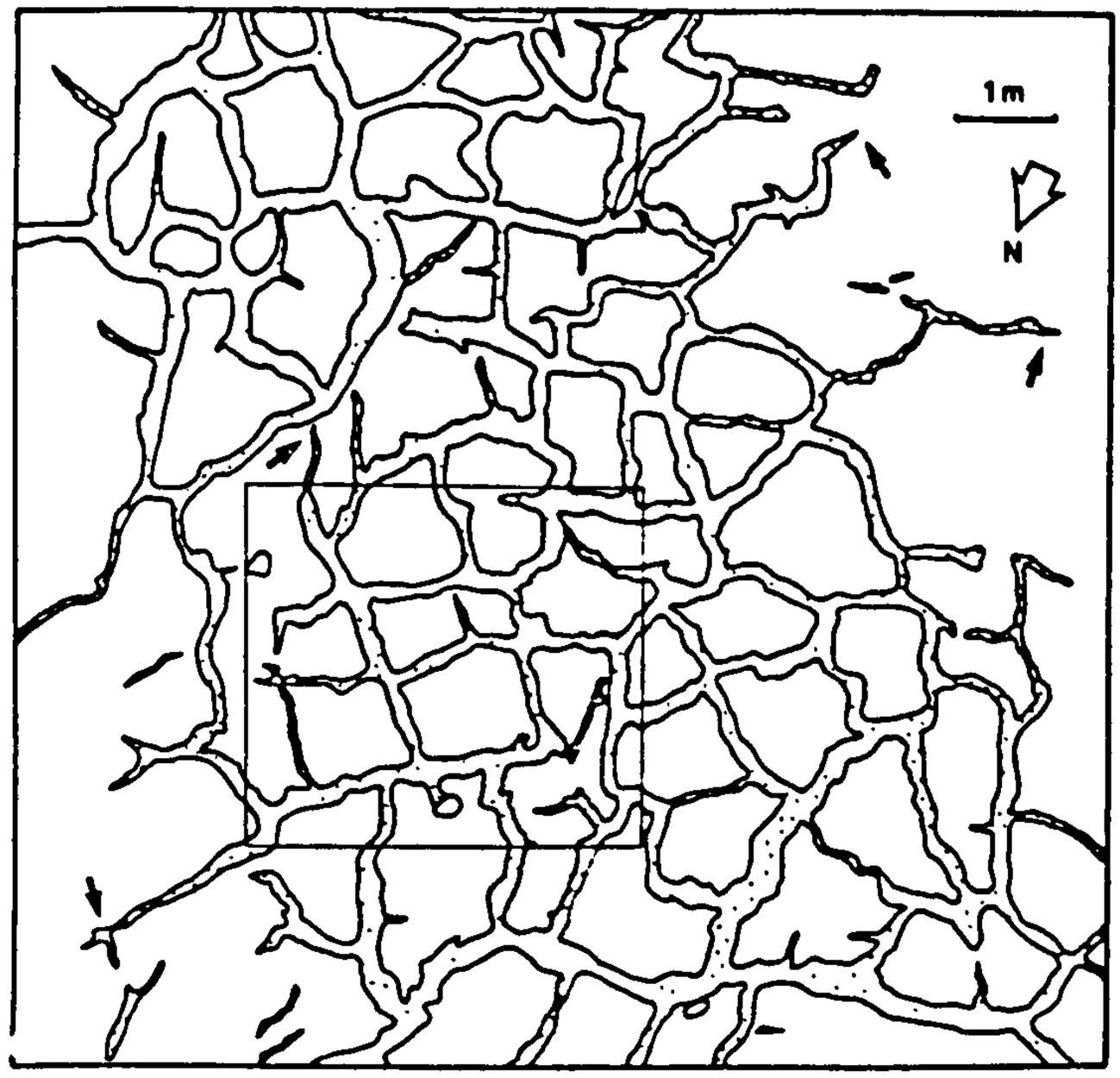
Short (< 1 m), randomly oriented furrows occur on bedding surfaces of the Kuibis Series quartzite within the Nama System of Namibia (Figure 83). These features, and meandering low-amplitude (< 1 m) soft-sediment ridges (Figure 84), have been attributed to the grounding and scouring action of ice floes by Martin (1965) and Kröner and Rankama (1972). In Brazil, Montes *et al.* (1985) described a striated and grooved pavement on a disconformity surface that separates the glacigenic dropstone-bearing Bebedouro Formation from underlying deltaic deposits of the Morro do Chapéu Formation. Grooves have relief between 1-5 cm, and the striae curve and intersect and have abrupt terminations. Dropstones in this transgressive sequence certainly imply formation of the curvilinear grooves by free-floating ice, although a scour mark interpretation was not made.

In their reinterpretation of soft-sediment deformation structures from the Port Askaig Formation exposed on the Garvellach Islands of western Scotland, Eyles and Clark (1985) note the restricted development of a polygonal network of sandstone wedges on the upper surface of diamictite 22 (Figure 85). In his monograph Spencer (1971) interpreted these as permafrost contraction cracks in a subaerial environment. Instead Eyles and Clark (*op. cit.*)

PLATE XI

Figure 83. Short (< 1 m), randomly-oriented, soft-sediment furrows on a bedding surface of Kuibis Series quartzite, Nama System, Namibia. These features were interpreted by Martin (1965) to have been formed by grounding ice floes. Taken from Martin (*op. cit.*), Plate XI, Figure 1.

Figure 84. Meandering, low-amplitude (< 1 m) ridge on a bedding surface of Kuibis Series quartzite, Nama System, Namibia. This type of feature has been attributed to the possible action of scouring ice floes by Martin (1965) and Kröner and Rankama (1972). This particular feature was described as a "pseudo-*roche moutonnée* (formed when the sediment was unconsolidated) by Martin (*op. cit.*). Taken from Martin (*op. cit.*), Plate X, Figure 2.



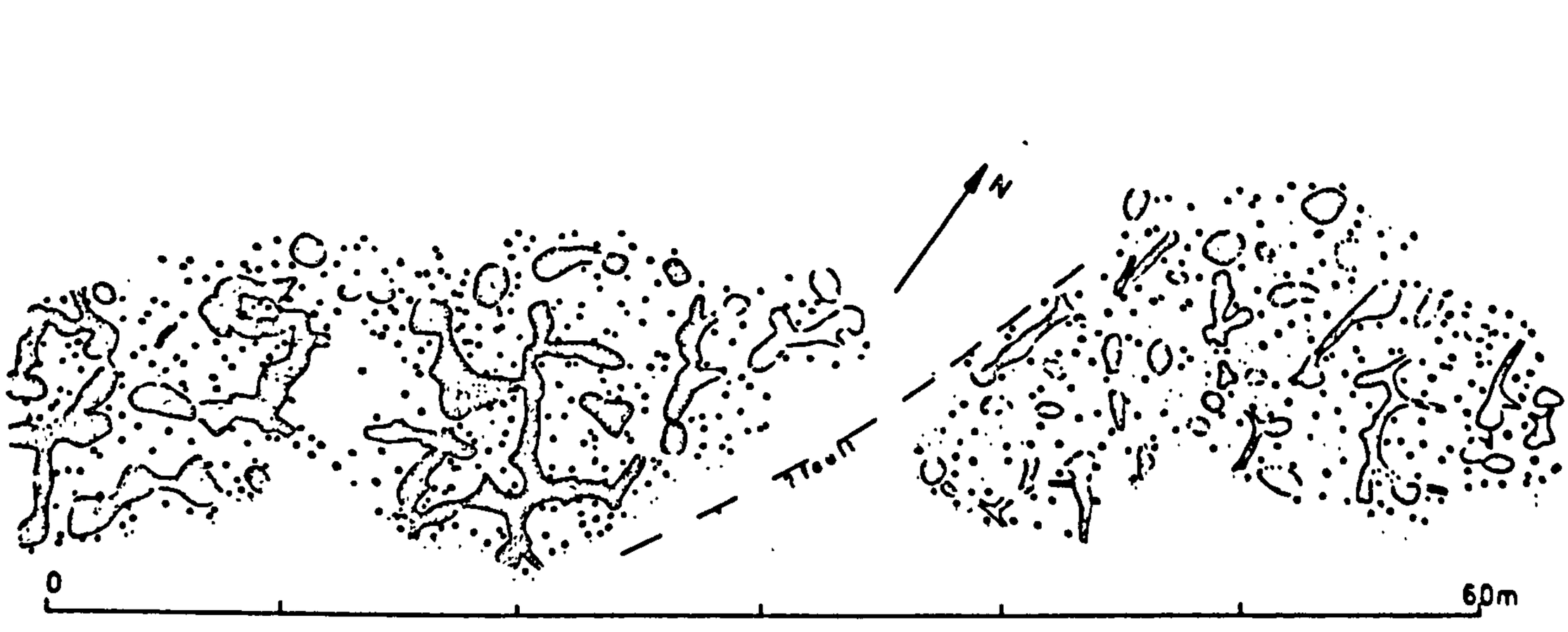


Figure 85. Diagrams to illustrate lithified polygonal sandstone wedges, a. on the upper surface of a diamictite, Precambrian Port Askaig Formation, Garvellach Islands, Scotland (from Eyles and Clark, 1985), and b. a similar network on a bedding plane surface within the Ulveso Formation, east Greenland (from Hambrey and Spencer, 1987). Compare these examples with the open network of cracks from a modern iceberg scour mark shown in Figure 13a.

Figure 86a. Double-sided feature with small, raised, parallel berms. Small surcharge pile (tape measure) truncates fine striations in trough behind. Note ridge in background (probably the berm of another feature) obliquely truncating the trough. This feature occurs on the Silurian transgression surface, above the Tamadjert Formation, Algerian Sahara, and is interpreted by Beuf *et al.* (1971) to have been formed by littoral sea ice. Taken from Figure 62 of Beuf *et al. op. cit.*

b. Soft-sediment, slumped ridges on a striated bedding plane surface, Ordovician Tamadjert Formation, Algerian Sahara (from Beuf *et al.* 1971, Plate 5). Discussion in text.

clastic material embedded in the sole of a moving glacier. However, they do note that curved striations may indicate scouring by floating ice. The flanks of the two prominent ridges in Figure 86b have slumped and appear to truncate adjacent fine striations. These features bear striking similarity to the one shown in Figure 84 from the Precambrian Kuibis Series quartzite of South Africa. Figure 87 shows ridges and grooves which change shape and transgress, reflecting dynamic change of irregularities in the bottom topography of the ice (see Chapter 3: Formation of ridge-and-groove microtopography). Also an unstriated, slightly raised margin is apparent on the left side. These elements, plus variations in striation orientation, that Beuf *et al.* (*op. cit.*) interpreted as possibly the result of local changes in glacial drainage patterns, although not conclusive by themselves are ones which define ice scour marks. Other mechanisms that create striated surfaces will be discussed later.

Upper Devonian

Clarke (1917) described small scale ridges and grooves from the Upper Devonian Portage Formation of New York. The features are developed on the upper surfaces of thin, sand shale beds, and are associated with flute marks and rarely with ripple marks. The ridges and grooves are always straight and are occasionally seen as cross-cutting sets. Hall (in Clarke, 1917) reasoned that the striae were formed when the sediments were soft because they are present throughout "a great thickness of strata". He also noted that at one stratigraphic level striations 32 km apart had the same orientation from which he concluded

Figure 87. Soft-sediment striations, Ordovician Tamadjert Formation, Algerian Sahara. Note unstriated margin on left side and gradual amplitude change and lateral migration of ridges across adjacent grooves, features characteristic of ridges and grooves formed at the trailing edge of scouring ice keels. Liftoff of the graving tools is implied where striations are developed on either side of, but not within, small (few cm wide) depressions along the left margin (from Beuf *et al.* 1971, frontispiece of Chapter 3).

that the grooving process operated "very uniformly over large surfaces".

Clarke (*op. cit.*) reasoned that the marks were made by "the dragging or shoving of irregular objects over the surface of the wet sand". He noted that the short, rod-like trace fossil *Fucoides graphica* was associated with the ridges and grooves resting on top of them at random orientations, and suggested that they were pseudomorphs after crystals of ice. Using the ice crystal pseudomorph interpretation to imply a cold environment he interpreted the ridges and grooves to have been formed by floating shore ice dragging across the bottom. The later observations of Udden (1918), Van der Meer *et al.* (1985), and experimental work of Allen (1926) and Mark (1932) showed that ice crystal marks form subaerially, and defined criteria for recognizing fossil ice crystal pseudomorphs. Ice crystal casts have been observed in association with the ice scour marks from Cobequid Bay (Figure 88).

Carboniferous/Permian

In the Dwyka Formation of South Africa 7 glacial and 2 interglacial units have been defined, and subaqueous outwash deposits indicate water depths ranged from 40 m to in excess of 250 m within the Karoo Basin where most sediments are found (Visser, 1989). Units 2 and 5 are interpreted as debris rain-out deposits from possible 'iceberg zones'. Soft-sediment grooved and striated pavements found throughout the Formation are almost always interpreted to have formed beneath ice sheets.

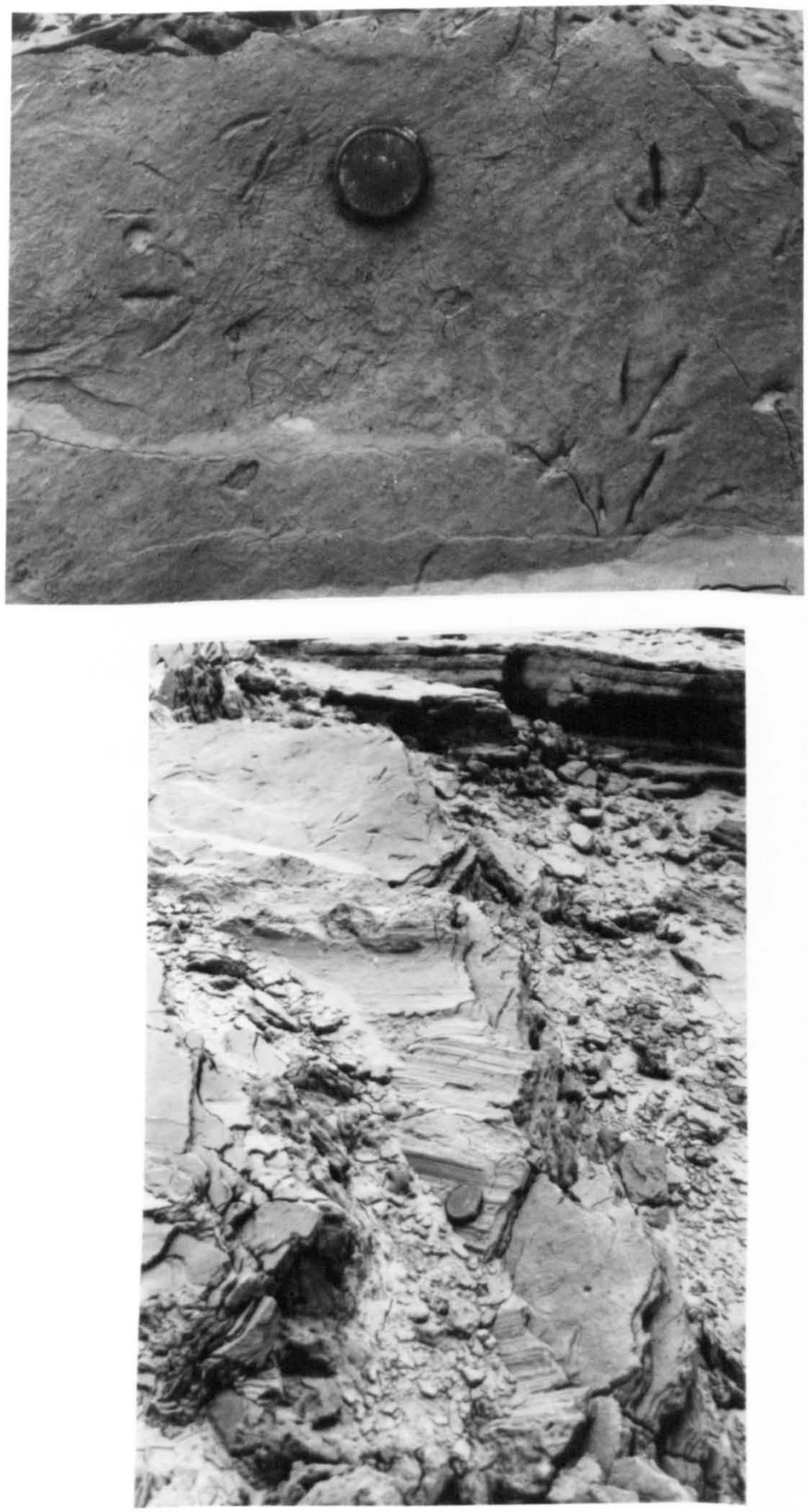


Figure 88a. Close-up view of the top portion of b. showing ice crystal pseudomorphs and bird footprints associated with striated surfaces (by camera lens cap in b.) of small-scale ice scour marks on an exhumed bedding surface of modern tidal flat sediments, Cobequid Bay. Note the different striation orientations.

Savage (1972) described grooves on bedding plane exposures of pebbly quartz sandstones. He noted that slumping of ridges across adjacent grooves, in a manner strikingly similar to the above examples from Beuf *et al.* (1971), indicated soft-sediment deformation immediately after the groove was formed (Figure 89). He acknowledged difficulty in explaining how the marks would be preserved if they were formed beneath an ice sheet. Visser (1990) described the same surface from a nearby location, and suggested that associated erosional troughs and channels could have been formed by scouring icebergs, although he preferring an interpretation of their origin due to subglacial meltwater flow. Commenting on soft-sediment grooves interpreted to have formed at the sole of a glacier, Visser and Hall (1984) noted that the preservation of these features "...suggest that pressure on the soft sediment was instantly relieved locally...". Near Kenhardt current ripples are oriented normal to soft-sediment sandstone grooves that have a disjunct orientation with respect to regional glacier flow (Visser, 1985). Such associations may be evidence of current-driven drift of scouring ice keels.

Permian

Iceberg scour features have been interpreted on bedding plane surfaces from the glacilacustrine Rio do Sul Formation (Itararé Subgroup) in Brazil (Rocha-Campos *et al.* 1990; Rocha-Campos, pers. comm. 1988; 1989; 1991; 1992; Paulo Santos, pers. comm. 1991). These authors describe sinuous, sub-parallel furrows with "V"-shaped or flat bottomed

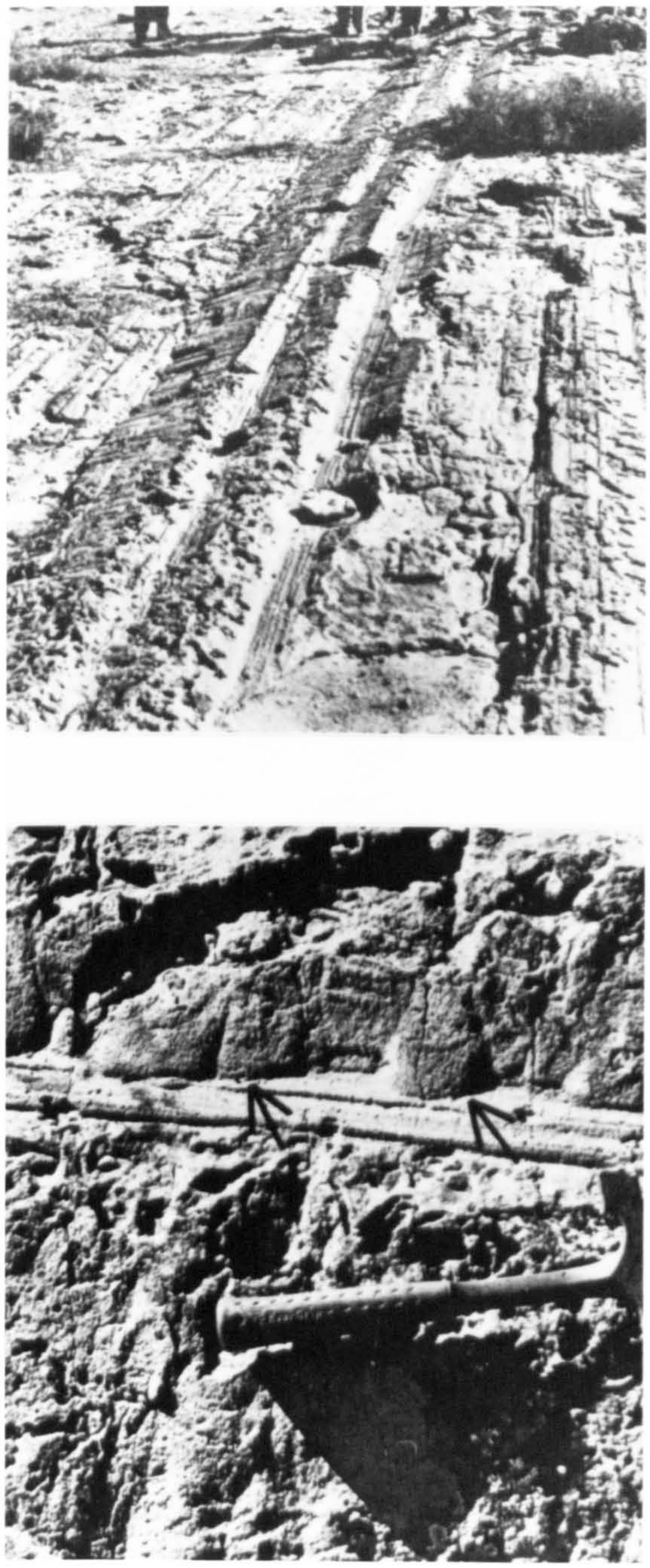


Figure 89a. Soft-sediment striations on a sandstone bedding surface of the Late Carboniferous Dwyka Formation, South Africa. Reproduced from Savage (1972) Figure 2.
b. Striations partially masked by material that has slumped (arrows) from an adjacent ridge. Reproduced from Savage (*op. cit.*) Figure 3.

striated troughs up to 50 cm wide, 20 cm deep and at least 80 m long. Cross-sectional views show downward-displaced varved bedding (Figure 90) "cut by small faults dipping towards the centre of the structures", and bear "striking similarity" to the Cobequid Bay scour marks (Paulo Santos, pers. comm. 1991). Small scale low angle reverse faults and recumbent folding occur on either side of the troughs.

Small-scale iceberg scour marks (< 1 m wide) have been described from bioturbated diamictites in the Pebbley Beach Formation by Powell and Gostin (1990). The A/B planes of boulders immediately beyond the scour mark margins dip towards the scour mark trough (R. Powell, pers. comm. 1991), suggesting sub-scour compaction during scour events was sufficient to locally re-orient clasts.

"Grooved and striated" surfaces marking sharp sedimentary contact within structureless diamictites have been described from the Pagoda Formation, Transantarctic Mountains by Miller (1989). One of these is illustrated developed above a winnowed diamictite (Figure 5c, Miller, *op. cit.*). Glacio-lacustrine conditions are interpreted to have existed during a series of glacial retreats.

"Striated and grooved pavements... clearly of direct glacial origin" are common in the lower part of the Buckeye Formation, also in the Transantarctic Mountains (Aitchison *et al.* 1988). However the one illustration of such a striated bedding surface shows an abrupt margin beyond which no striations are evident (Figure 91), and the possibility that striated

Figure 90. Downward-displaced varved bedding beneath a scour mark trough in the Permian Rio do Sul Formation, Parana Basin, Brazil. Note upwarping on either side. Compare similarity with scour marks from Cobequid Bay (Chapter 6). Photograph courtesy of A.C. Rocha-Campos, Universidade Sao Paulo.

Figure 91. Grooved and striated surface from the Permian Buckeye Formation, Transantarctic Mountains, Antarctica. Note the pronounced margin separating striated from non-striated surface: possibly the margin of an ice scour mark (Figure 5 of Aitchison *et al.* 1988).

pavements may originate from "the grounding of floating ice such as bottom scraping berg ice" is noted. Also dropstones occur in diamictite units with which the pavements are always associated, and hummocky stratification noted in parts of the sections indicates the presence of relatively shallow open water with sediments affected by storm wave action. These are all environmental indicators compatible with the presence of icebergs and sea ice.

CHAPTER 8

DISCUSSION AND GENERAL CONCLUSIONS

The keels of icebergs and of ice pressure ridges create typically curvilinear scour marks when they touch, penetrate and move through unlithified sediments. The most obvious effects of scour are seen on the seabed or lake bed that, for each scouring event, usually preserves a furrow with a berm of expelled material on either side (Chapter 3). Obscured from view in modern offshore or lacustrine areas are the effects of scour on sediments beneath the trough. Sub-scour deformation structures can be seen in excavated cross sections of ancient scour marks exposed on land and in smaller features exposed at high water on tidal flats (Chapters 5 & 6). With a set of identification criteria (Chapter 7) developed from unequivocal scour marks, it is possible to investigate the pre-Quaternary, lithified glacimarine and glacilacustrine record for scour marks. This may be a useful avenue of investigation in order to further define spatial variations in sub-scour deformation structures with variations in sediment type.

Ice scour in the rock record: engineering and stratigraphy

A major knowledge deficit area is in the quantity of data on sub-scour deformation from features formed in sediments of different grain size. This study has examined scour marks in fine-grained sediments only, with the exception of the scour marks on King William

an impenetrable barrier to excavation. It is likely that coarser-grained sediments and bimodal and polymodal sediments will behave differently during scour, developing and retaining different types of sub-scour deformation structures (e.g. Thomas and Connell, 1985; Eyles and Clark, 1988). In particular, fine-grained sediments are more likely to remain undrained during a scour event, and to develop deeply-penetrating slip surfaces. Conversely, coarse-grained sediments may experience some drainage, and intergranular friction will tend to inhibit, though not preclude, the development of deeply-penetrating slip surfaces. Scour marks in such a variety of sediment types do not exist in easily accessible unconsolidated sediments at the earth's surface. Instead a useful approach in quantifying the variations in style of deformation would be to examine ice scour marks in glacimarine and glacilacustrine sediments in the rock record that contain a variety of grain sizes. Such an analysis should produce quantifiable data on sub-scour deformation that have direct engineering applications to the modern-day problem of pipeline burial depth. A thorough examination of the glacimarine rocks discussed in Chapter 7 is thus appropriate on two counts: (1) the extension of recognition of ice scour turbate facies in a variety of sediment types, and (2) the engineering benefits.

Engineering applications of such a study include:

- Defining the zone of sediment deformation beneath scour marks from a variety of lithologies,

- Defining the types of deformation mechanisms that operate (such as bulk strain vs. discrete failure, bearing capacity failure and horizontal shear, for example) and

quantifying their effects (such as the amount of offset along faults and amount of compaction for example).

Observations of this kind made from the Lake Agassiz scour marks have provided very useful constraints in both the physical and mathematical modelling processes essential to pipeline design. The engineering value of the Lake Agassiz work was acknowledged by both oil and gas exploration companies and by the federal regulatory agency, Canada Oil and Gas Lands Administration, during a Workshop on Ice Scour and the Design of Arctic Pipelines held in Calgary in 1989 (Clark *et al.* 1990).

In the rock record a distinction between scour marks made by sea and lake ice and by icebergs will not be possible using the criteria for identification presented in Chapter 7. However, it may be possible to discriminate between the two types of ice (1) if water depths are accurately known: generally scouring by sea ice (and small icebergs) is restricted to about 60 m water depth in modern environments (Reimnitz *et al.* 1984), beyond this depth scouring is by glacial ice masses only, and (2) if the presence of either icebergs or pack ice (but not both) is known. For example in the Beaufort Sea, modern Lake Erie and northern Caspian Sea, scouring is by seasonal pack ice only (Lewis and Blasco, 1990; Grass, 1984; 1985; Koshechkin, 1958).

Ice-rafting

Ice-rafted sediment generally originates from glacial, colluvial, aeolian and littoral sources (Gilbert, 1990). Although not strictly a sediment source, a fifth origin is the post-scour rafting of sediment that has been incorporated in the keel of a scouring ice mass. Such mechanically incorporated debris will consist of a mix of "normal" marine or lacustrine sediment deposited from suspension or traction currents, ice-rafted sediment (from the other four sources) and previously scoured-and-rafted sediment. One of the consequences of prolonged exposure to this kind of rafting action will be the creation of sediments that contain a homogeneous mix of clasts from a variety of different original sources. Another consequence is that the mechanical processes of scouring-and-rafting may result in the creation of micro-features on individual grains that are similar to those characteristic of origin by glacial action. In any event it probably will be difficult to identify the proportion of a sediment that has been affected by the action of scouring-and-rafting.

Scouring-and-rafting may be the most important factor affecting sediments on the Canadian eastern continental shelf, and probably results in net removal of sediment beyond the continental shelf edge (see Chapter 3, Sedimentological effects). Additional removal may occur during the scouring process as fine-grained sediment is lifted into suspension and then winnowed by ocean currents (see Chapter 5, King William Island, Northwest Territories).

Ice scour: problems with preservation

A problem with the phenomenon of ice scour is that in an environmental setting conducive to either seasonal or annual scour, sediments are likely to be affected by numerous events so that the likelihood of finding individual scour marks in otherwise undisturbed sediments is low. Even in Lake Agassiz where the period of iceberg scouring was probably no greater than 1,200 years (see Chapter 5: Water depth and age of scour marks) undeformed layering is rarely preserved. Ice keel turbates are thus more likely to be preserved than discrete scour marks. However, discrete large scale scour marks have been documented by Rocha-Campos *et al.* (1990), Rocha-Campos (pers. comm. 1992) and Paulo Santos (pers. comm. 1991) from varved glacilacustrine Permian siltstones of Brazil, and small scale scour marks have been observed in Permian diamictites in Australia (Powell and Gostin, 1990). Discrete scour marks are similarly implied for certain striated surfaces described in Chapter 7.

In both the proximal and distal glacimarine environments (Eyles *et al.* 1985) ice scouring probably is common. Post-depositional downslope re-sedimentation is also an "exceedingly common process" to both environments because of the combination of high sedimentation rates and seabed relief (of as little as 0.5°) (Eyles *et al.*, *op. cit.*), thus possibly obliterating the traces of ice scour action and resulting in massive diamictites, often with intrafolial folds, faults and other soft-sediment deformation structures. However, massive diamictites can also be the combined product of iceberg rafting and scouring and these are

shown to have been the key processes in forming this facies on the east Greenland continental shelf (Dowdeswell, pers. comm. 1992). Despite considerable evidence for the presence of icebergs during deposition of the Yakataga Formation diamictites of southern Alaska (e.g. Eyles, 1988b), the effects of iceberg scouring have not been found probably because downslope re-sedimentation processes destroyed them (N. Eyles, pers. comm. 1991).

Striated pavements vs. scour marks

In Chapter 7 most of the features tentatively re-interpreted as scour marks are recognized largely based on soft-sediment striations on bedding plane exposures. Soft-sediment striations are perhaps the single most compelling diagnostic feature on which to base an initial interpretation of the presence of scour marks. However, nearly all reported striated pavements are interpreted to have been formed by the mechanical action of grounded or nearly neutrally buoyant, ice sheets (e.g. Beuf *et al.* 1971; Visser, 1989; Eyles, 1988b; Eyles and Lagoe, 1990).

Sub-glacial flutes

Striating and fluting mechanisms can operate at the sole of a glacier (e.g. Boulton, 1976) but there are notable differences between the morphologies and genesis of glacially- and iceberg-produced features. Glacial flutes originate subglacially on the lee sides of rigid obstructions, most commonly boulders, that project at least 0.3-0.5 m above the lodgement till surface (Boulton, *op. cit.*). Flutes, that may extend up to 1 km in length, are created when deformable subglacial sediment is intruded into cavities which open up in the base of the ice and propagate from the lee sides of obstructions (Boulton, *op. cit.*). In contrast, ridge (and groove) microtopography in a scour mark trough is produced by flow of seabed material into irregularities at the trailing edge of a scouring keel (Chapter 3), and although boulders have been observed at the start of ridges they are not a pre-requisite for ridge formation. Ridges-and-grooves generally have amplitudes up to 30 cm which is less than the height of boulder projection critical for glacial flute initiation. A lateral furrow is developed symmetrically on each side of individual glacial flutes below the level of the till surface (Boulton, *op. cit.*). In scour mark troughs ridges are generally closely spaced, and adjacent grooves exhibit variations in width, depth and elevation on either side of a ridge; they do not display the symmetry of flute-associated grooves. The crest lines of glacial flutes intersect the lee sides of initiating boulders in an upward-concave till wedge, so that the downstream height of the flute is always less than the height of the boulder; flute width is slightly less than boulder width (Boulton, *op.cit.*). These characteristics differ from scour mark ridge crest lines that are at the same elevation as the top of the boulder from the

point of initiation onward, and ridge width is the same as boulder width. In addition, ridge shape may mirror the cross-sectional shape of the initiating boulder (Chapter 3, Ridge-and groove microtopography). Glacial flutes are deflected around boulders in their path, explained by (Boulton, *op.cit.*) as the result of disturbance of ice flow lines. Such deflections are not seen in scour mark ridge-and-groove microtopography, and indeed are not expected because the microtopography, unlike glacial fluting, is an extrusion phenomenon generated at the same instant in time as it passes from beneath the scouring keel. Finally, striations generally are preserved on all ridge-and-groove surfaces in scour marks, but none have been described from glacial flutes.

Glacially-fluted surfaces are not always developed at the glacial sole and a fine example of a glacier with a marine terminus where flutes are absent is presented by Solheim (1991) who described seafloor features exposed between the surge moraine and the present marine terminus of the Bråsvellbreen glacier, Svalbard. The seafloor features were generated during the 1936-38 surge, and consist of a rhombohedral pattern of ridges, up to 5 m high, that have orientations sub-parallel and sub-perpendicular to the present ice margin, and also discontinuous arcuate ridges that are of similar height and with trends sub-parallel to the ice margin. The rhombohedral ridge pattern was formed by flow of seabed sediment into crevasses at the base of the glacier, and the arcuate ridges are small, annual push moraines (Solheim, 1991).

Ice shelf striations

A seabed- or lakebed-grazing buoyant ice sheet can be more easily envisaged producing ridges and grooves similar to those developed in scour mark troughs because irregularities in the ice sheet base will allow processes to function similar to those operating at the trailing edge of a scouring iceberg keel. Sediments deposited from rain out of basal material will characterize facies seaward of the grounding line of an ice shelf (Hambrey *et al.* 1989; Drewry and Cooper, 1981). Striated surfaces may be developed in these polymict sediments if the grounding line position has fluctuated. Striae in this zone will be different from scour mark striae because they should be regional in extent (no margins or berms) and orientation (e.g. Solheim *et al.* 1990).

Basal melting, and meltout deposition, usually takes place close to the grounding line of a floating ice shelf. As a consequence, sediments seaward of the shelf margin will probably receive very little rafted material because shelf icebergs contain far less englacial sediment than do icebergs calved from tidewater glaciers (Drewry and Cooper, 1981). Therefore striated surfaces associated with glacimarine sediments that are poor in rafted material are more likely to be the result of scouring icebergs which originated from an ice shelf. A key test in this situation is to look for margins and associated berms of striated surfaces. Variation in striation orientation is a less critical attribute for defining scour marks because there may be environmental influences that constrain the pattern of iceberg movement (e.g. Todd, 1984). However, the orientation of scour mark striations likely will

be variable and different from those of regional glacial flow (e.g. Solheim *et al.* 1990; Josenhans and Zevenhuizen, 1990), and directional indicators (such as boulders lodged at the start of a ridge [see Chapter 3, Formation of ridge-and-groove microtopography]) should show movement directions inconsistent with regional glacial flow.

Scour marks, ice keel turbates and the tillite problem

As is readily apparent in the preceding discussion and in the description of potential scour marks from the rock record in Chapter 7, the most easily recognized diagnostic features are those exposed on bedding plane surfaces. With the successful identification of scour marks from surface structures the sediment deformations associated with it in cross-section can be more confidently interpreted as scour-related, rather than as functions of other soft-sediment or tectonic deformation. This surface-feature kind of approach was used when initially interpreting scour marks from aerial photographs of King William Island and the glacial Lake Agassiz region (see Chapter 2, On-land studies, and Chapter 5, Introduction and summary).

Once familiarity with the association and nature of sub-scour deformation structures beneath striated surfaces is achieved an observer can progress to recognition of scour marks in cross-section alone. Identification of ice keel turbates is a good deal more problematical than of discrete ice scour marks because the physical appearance of structures in sediments

resulting from multiple scour events is not known. There are two approaches to resolving this problem.

The first is to examine sediments that contain discrete, recognizable scour marks, and then to work through the sequence into horizons that contain increasing numbers of scour marks that are complexly overprinted by subsequent scour events. Such an approach requires that scouring intensity must have been progressively increasing or decreasing with time, or that there must have been increasing or decreasing sediment deposition to ensure vertical separation of early from later events. A modern analogue where lateral (and possibly vertical) variation in sediment accumulation rates has resulted in preservation of both ice keel turbates and discrete scour marks is the Canadian Beaufort Sea. Here, annual sea ice scouring causes intense reworking of the seabed on the main shelf area where sediment accumulation rates are relatively low (<0.25 m/1000 years [Pelletier and Lewis, 1984]). If preserved, the lithified deposit would be an ice keel turbate. On the western margin of the shelf the Mackenzie river delta deposits large volumes of sediment at rates between 4-5 m/1000 yrs (Pelletier and Lewis *op. cit.*). Because accumulation rates are so high discrete buried scour marks are preserved in stratified sediments (S.M. Blasco, pers. comm. 1992).

The second approach is used when a gradation between discrete scour marks and an ice keel turbate does not occur, such as where there is an abrupt transition into "tillite" from previously- or subsequently-deposited sediments that may not contain any evidence of

scouring. In this case it is imperative first to become familiar with the variety of structures preserved in cross-section beneath lithified scour marks from other glacilacustrine or glacimarine sequences. Familiarity with the attributes of cross-sections is important because tillites are generally massive, unstratified deposits that have few internal bedding planes upon which scour mark surface features may be preserved. With this knowledge a "tillite" can be examined for scour mark elements that, even though not in discrete associations, may collectively help to define the unit as an ice keel turbate. It is possible that the lower, and more likely the upper, surface of an ice keel turbate unit may preserve a topography created by the last scouring ice keels. This surface may preserve a closer association of discrete scour mark elements than turbated sediments below such as, the shapes of *flat or dish-shaped troughs with defined margins, ridge-and-groove microtopography and striations, round berms defined by lag deposit on upper surface, berm blocks defined by sub-vertical cracks, ice dissolution voids* and *flat-topped mounds* (see Chapter 7).

Massive diamictites are often the product of distal glaciomarine sedimentation with significant input of iceberg-rafted debris (Eyles *et al.* 1985). Although the origin of massive and deformed diamicts interpreted by these authors probably is valid, alternative evidence from east Greenland indicates that massive diamictons may be the product of ice keel turbation and ice rafting (Dowdeswell, pers. comm. 1992). For example, the positive identification of small scale ice scour marks (< 1 m wide) in Permian bioturbated pebbly diamictites of New South Wales, Australia (Powell and Gostin, 1990; R. Powell, pers. comm. 1991) is an encouraging discovery. Using the observations and arguments presented above,

it is likely that some pre-Quaternary glacimarine and glacilacustrine diamictites ("tillites") record ice keel turbation.

Future work

In this work, criteria for identifying scour marks in pre-Quaternary glacimarine and glacilacustrine sediments are proposed, and a discussion of some likely candidate facies from the Proterozoic and Phanerozoic rock record is presented in the context of possible re-interpretation as ice-scoured facies (see Chapter 7). The identifying criteria must be verified or refuted by testing them against these possible examples from the rock record. This should be done for two key reasons, 1) there is a pressing, practical need to understand sub-scour deformation mechanisms from an analysis of deformation structures, because this has great potential benefit to designing and installing pipelines and other seabed facilities in modern environments where ice scour occurs. 2) Identification of scour marks and of ice keel turbates can assist in an interpretation of environment and water depth, and may assist in re-interpreting the origin of massive diamictites.

All of the interpretation of process has been based on combining the observations of surface morphology of modern scour marks from the eastern Canadian continental shelf, with those from detailed cross-sections of old, large features exposed in sediments of glacial Lake Agassiz (Chapter 5) and small, modern features on the tidal flats of Cobequid Bay and

the St. Lawrence estuary (Chapter 6). There are two deficiencies from this aspect of the work that need to be addressed, 1) descriptions should be obtained of long-sections and oblique-sections through both large and small scour marks because the appearance of scour-related structures in these planes is not known, and nature is not so kind as to ensure that every outcrop containing scour marks will expose them in perfect cross-section each time. 2) The scour marks described in this work are all developed in fine-grained sediments, no coarser than fine sand. The response to ice scour of coarse-grained, diamict and polymict sediments is yet unknown, and consequently so are the sub-scour structures.

Future work must consist of the following: 1) a rigorous testing to verify or refute the criteria for identifying scour marks in pre-Quaternary sediments, 2) detailed descriptions of long-sections and oblique-sections through known scour marks at a variety of scales, such as those in Manitoba and in Cobequid Bay, 3) an assessment of the variation in response to ice scour by sediments of various grain sizes and sorting. This may be possible only from an analysis of features in the rock record because scour marks of Quaternary age are not generally readily accessible in coarse-grained, poorly-sorted sediments.

APPENDIX

Direct-reading hand-vane tester

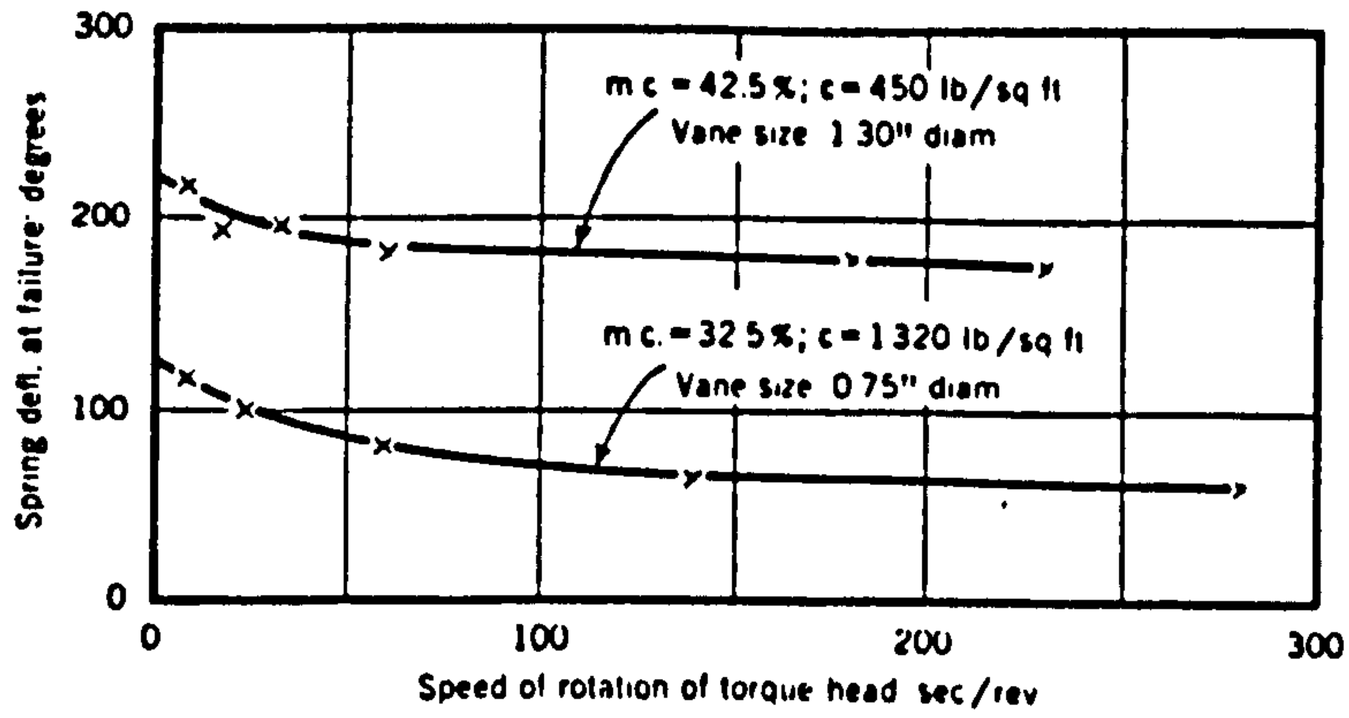
The vane used during the field study of tidal flat ice scour marks at Cobequid Bay and the St. Lawrence estuary was manufactured by Pilcon Engineering (now owned by English Drilling Company Ltd. of Huddersfield). There was no operating instruction manual for this machine, and based on advice from other colleagues who were familiar with its operation, the rate of application of torque was applied at approximately one 360° rotation in 10 seconds, a rate that would not allow pore pressure to dissipate, and thus giving a value of undrained shear strength. Later checking, during data analysis, shows that this rate is considerably faster than recommended by, for example, the American Society for Testing and Materials, who indicate a rate of torque application not exceeding one 360° rotation in 1 hour!

Serota and Jangle (1972) reviewed the operation of direct-reading pocket shear vanes for determining the undrained shear strength of saturated clay, and found that the best rate of application of torque was one 360° rotation in 60 seconds, but that this was not critical. These authors indicated that readings were reproducible with a deviation of less than 1% in two out of three readings. Additionally, the authors produced a table that showed the effect of rate of torque application on shear strength (as a function of deflection of the spring mechanism, in degrees), reproduced below. From this graph higher values of

measured shear strength are expected with fast rates of torque application (use the lower curve because it represents values obtained using a 19 mm-diameter [0.75"] vane, equivalent to the vane used in this study). Consequently, data collected during the two field studies overestimate the actual undrained shear strength of the sediments. However, overestimation of undrained shear strength is not critical to the results discussed in Chapter 6 for two reasons:

1. Shear vane measurements were obtained at similar rates of torque application during both studies, so that results are consistent and thus comparable.

2. Data were contoured, for purposes of comparison, in order to show variations in sediment properties across the cross-sectional profiles of scour marks.



Graph showing effect of rate of application of torque on shear strength, using a direct-reading pocket shear vane tester. Reproduced from Serota and Jangle (1972), figure 2.

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