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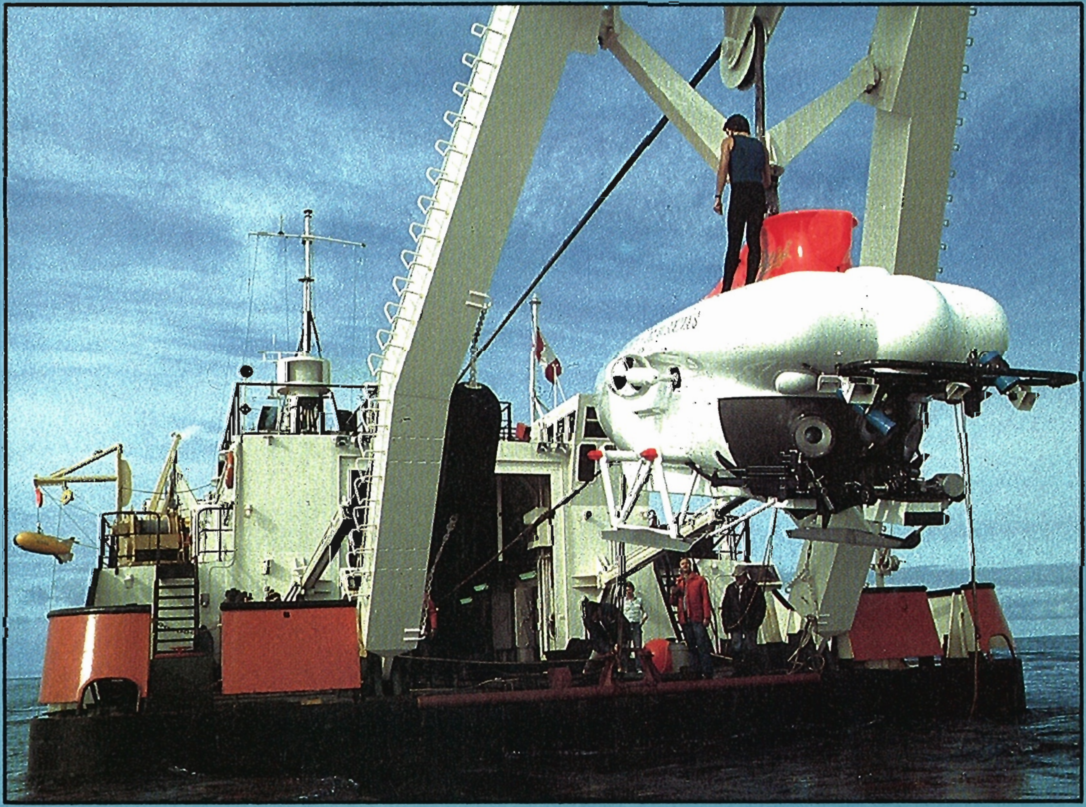
SUBMERSIBLE OBSERVATIONS OFF THE EAST COAST OF CANADA



EDITED BY
D.J.W. PIPER

1989

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Cover Photo

PISCES IV ready for launch

Critical Readers

R.Parrot
B. MacLean
P.R. Hill

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SOMMAIRE

Le Centre géoscientifique de l'Atlangique est la division de la Commission géologique du Canada chargée d'établir la géologie des zones marines au large des côtes est et arctiques du Canada. Ceci comprend la cartographie géologique, l'évaluation des ressources en hydrocarbures, et l'étude des processus qui régissent actuellement le modelé du fond marin. En 1981, on a réalisé un programme scientifique basé sur l'emploi d'un submersible, le PISCES IV, pour faire progresser ce type d'études. On a appliqué l'expérience gagnée au cours de ces recherches à l'élaboration d'un programme plus étendu en 1985.

Dans ce volume, sont présentés un résumé du programme et une bibliographie des résultats (dans l'article d'introduction), en même temps que des comptes rendus détaillés des cinq croisières à propos desquelles n'avait été publié nulle part de sommaire descriptif.

Résumé des objectifs scientifiques et du programme

En majeure partie, le programme d'observations réalisées en 1985 à partir d'un submersible avait été conçu pour examiner les problèmes en rapport avec l'exploration et la mise en valeur des ressources pétrolières et gazières au large des côtes est du Canada: dangers que présentent l'affouillement du fond par les icebergs, la sismicité, la rupture des sédiments, et la mobilité des sédiments du plateau continental. Le financement de ces croisières a surtout été assuré par le Groupe fédéral d'étude de la recherche et du développement énergétiques. Les autres croisières avaient pour objectifs des problèmes géologiques connexes. En général, on a sélectionné les détails durant le programme, après les avoir examinés à fond au moyen de levés par télédétection depuis un navire. Au cours de trois croisières, on a examiné les processus de sédimentation se déroulant sur les plateaux continentaux. On a examiné sur le plateau continental de Scotian la dynamique des rides d'avant-côte liées entre elles, le mouvement des structures de la surface du fond, et le processus suggéré de débordement. À l'emplacement des Grands bancs de Terre-Neuve, on a examiné les crêtes de sable et un vaste sillon résiduel creusé par un iceberg, dans le cadre d'un programme de cartographie régionale de surface. On a intégré la majeure partie des travaux réalisés sur le plateau continental du Labrador à l'expérience sur la dynamique de l'échouage des icebergs et de l'affouillement par ces icebergs (DIGS). Là où les icebergs spécifiquement surveillés durant les expériences DIGS avaient heurté le fond marin, on a examiné à partir du PISCES les traces d'affouillement produites. En outre, on a réalisé des observations sur la dégradation des marques d'affouillement. Les plongées réalisées dans ce but dans le détroit de Belle Isle avaient aussi pour objectif l'étude de la stabilité du fond marin à l'intérieur des sillons creusés pour la pose de câbles électriques sous-marins.

Au cours de plongées réalisées dans le fjords de l'île Baffin, on a examiné divers processus de sédimentation, en particulier la croissance des deltas et la seconde phase de sédimentation qui avaient été antérieurement étudiées par des procédés classiques durant l'expérience sur la sédimentologie des fjords arctiques (SAFE). On a organisé plusieurs plongées pour étudier plus en détail la nature et l'origine d'un suintement de pétrole survenu sur le fond marin dans la fosse de Scott au large de l'île Baffin. On a cité ailleurs dans leur totalité les résultats de ces deux croisières.

Durant l'une des croisières, on a examiné les phénomènes de rupture du fond marin le long du talus continental, causés par le séisme survenu en 1929 dans la région des Grands bancs sur le talus continental au large du banc de Saint-Pierre et de la partie supérieure du cône d'éboulis du chenal Laurentien. On a publié un rapport vidéo sur cette croisière dans les dossiers publics. En outre, durant deux plongées réalisées au-dessus du plateau continental du Labrador, on a examiné les processus modelant le bord de cette plate-forme le long du talus continental du Labrador. On a effectué deux courtes plongées expérimentales pour examiner les processus de sédimentation qui se déroulent dans la partie intérieure de la plate-forme au large de la Nouvelle-Ecosse. Une plongée effectuée dans le port a servi à vérifier les hypothèses déjà formulées sur la sédimentation pélitique à la suite d'observations faites auparavant dans le site du port. Grâce à une seconde plongée effectuée au large de Cole Harbour, immédiatement à l'est de Halifax, on a poursuivi des recherches détaillées sur la sédimentation de l'intérieur du plateau continental, et en particulier sur les facteurs qui influencent la mobilité des graviers ainsi que les caractéristiques et l'origine des grandes rides composées de graviers.

Dans ce volume, on présente les résultats donnés par quatre des croisières (celles qui se sont déroulées sur le plateau continental de Scotian, les Grands bancs, le cône d'éboulis du chenal Laurentien et du plateau continental du Labrador), ainsi que par la plongée effectuée au large du Cole Harbour en Nouvelle-Ecosse. Dans la bibliographie indiquée plus haut, sont cités les résultats des autres croisières de PISCES IV.

Le submersible PISCES IV

On a dirigé les plongées du submersibles PISCES IV à partir du navire MV PANDORA II. Le PISCES IV est un petit sous-marin commandé par moteur électrique, et pouvant plonger jusqu'à 2000 mètres de profondeur avec une vitesse de croisière de 1,5 kmh. Il est équipé de trois hublots permettant des observations à l'extérieur. La durée des plongées est surtout limitée par l'alimentation électrique. En raison des dangers que présente la récupération du submersible, on n'effectue pas de plongée si les vagues dépassent 2 mètres, si les vents dépassent 25 noeuds, ou si la visibilité en surface est inférieure à 2 km. Ces restrictions ont sérieusement limité le programme scientifique lors de plusieurs croisières, notamment lors des recherches organisées dans la région de Hibernia au-dessus des Grands bancs de Terre-Neuve.

Le PISCES IV transportait un pilote et deux observateurs. On a enregistré sur magnétophone les observations faites, et pris des photographies à travers les hublots avec des appareils tenus à la main, et prix des films avec une caméra-vidéo montée à l'extérieur du submersible. On a recueilli des échantillons avec les bras manipulateur et on les a rangés dans des compartiments pré-étiquetés dans un carrousel réunissant ces échantillons dans une collection à l'extérieur.

La navigation du PANDORA II est dirigée par ystème Loran C (si possible, on dispose de repères-radars) et par satellite TRANSIT. On a positionné le PISCES IV par rapport au navire d'attache au moyen d'un système de positionnement acoustique Honeywell à courte ligne de base. On a employé un système de navigation Syledis au-dessus du banc Makkovik. Si les observateurs notaient de façon détaillée dans le journal de bord le cap et la vitesse du submersible, et si l'on connaissant bien la position de lancement et de remontée de celui-ci, on pourrait reconstruire de façon suffisamment précise sa trajectoire. On pourrait aussi utiliser lors de certaines plongées des émetteurs d'impulsion pour assurer le radioguidage et la navigation sur le fond marin. On a effectué un grand nombre de plongées sur des cibles à l'emplacement desquelles on avait déjà obtenu des images par sonar à balayage latéral: les cibles ont aussi facilité les observations faites depuis le submersible en vue de psitionnement.

Résumé, perspectives

Le submersible a facilité sur place l'examen détaillé et même un échantillonnage précis des structures du fond marin trop petites pour être observées depuis un navire de surface. Le programme de 1985 nous a permis de bien mieux comprendre la nature du suintement de pétrole de la fosse de Scott, les caractères d'instabilité des régions d'avant-delta dans le fjords de l'île Baffin, et la dégradation du plateau continental du Labrador par l'affouillement dû aux icebergs, par exemple. On a pu ainsi interpréter avec plus de confiance les images transmises par le sonar à balayage latéral, et donc disposer d'un étalonnage quantitatif grandement nécessaire. Le principal inconvient du programme PISCES est qu'il dépend de conditions météorologiques adéquates. Certaines croisières se sont déroulées dans des conditions favorables, et ont rempli tous leurs objectifs: dans d'autres cas, la moitié ou même plus des plongées prévues ont été inefficaces, les meilleures conditions de navigabilité coincidant sur les Grands bancs avec les périodes de brouillard.

Lorsque se terminera le contrat conclu avec le PANDORA II, il sera beaucoup plus difficile de poursuivre les opérations de plongée avec le PISCES IV dans les régions du large. La Commission géologique du Canada considère les possibilités d'employer un véhicule téléguidé naviguant en eaux profondes (ROV) qui serait moins assujetti aux conditions météorologiques que le PISCIS. Le ROV sera plus flexible, dans la mesure ou il permettra de faire des observations pendant des périodes prolongées sans que l'on soit gêné par des vents modérés, par le brouillard, ou par le besoin de recharger les batteries. Il reste à voir si le ROV offrira immédiatement la même flexibilité qu'un submersible piloté grâce auquel on peut faire des découvertes scientifiques inespérées en observant le fond marin.

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The 1985 Atlantic Geoscience Centre PISCES IV Submersible program: Introduction

David J.W. Piper[1]

Piper, D.J.W., The 1985 Atlantic Geoscience Centre PISCES IV Submersible Program: Introduction; in Submersible observations off the East Coast of Canada, D.J.W. Piper, editor; Geological Survey of Canada, Paper 88-20, p. 3-7, 1989.

Abstract

In 1985, 65 dives of the submersible PISCES IV were made on geoscientific targets off the east coast of Canada. Dives were carried out principally to investigate sediment transport processes in fiords, on the continental shelf and on the continental slope and to address other issues related to oil and gas development, such as hazards posed by iceberg scour and seismicity. This volume describes the results of the diving programs that have not been reported in full elsewhere.

Résumé

En 1985, ont eu lieu 65 plongées du sbmersible PISCES IV à l'emplacement de cibles géoscientifiques au large de la côte est du Canada. Le but principal de ces prongées était l'étude des processus de transport sédiementaire dans les fjords, sur le plateau et le talus continentaux, et l'examen d'autres problèmes liés au développement des ressources pétrolières et gazières, par exemple les dangers que posent l'affouillement du fond par les icebergs et la sismicité du terrain. Dans ce rapport, on décrit les résultats des programmes de plongée qui n'ont pas été détaillés dans d'autres ouvrages.

INTRODUCTION

The Atlantic Geoscience Centre is the division of the Geological Survey of Canada responsible for the geology of the marine areas off the East and Arctic coasts of Canada. This work includes geological mapping, the evaluation of hydrocarbon resources, and the study of modern seabed processes. In 1981, a scientific submersible program was carried out using PISCES IV in support of these studies (Syvitski, et al., 1983). The experience gained from this work was applied to the development of a more comprehensive program in 1985.

This volume provides a summary of the program and a bibliography of results (in this introductory paper), together with detailed accounts of five cruises for which a descriptive summary has not been published elsewhere.

Acknowledgments

The work reported here would not have been possible without the enthusiastic cooperation of the PISCES pilots, the officers and crew of PANDORA II, and staff of Program Support Subdivision of the Atlantic Geoscience Centre and Ships Division of Bedford Institute of Oceanography. All the papers in this volume have been reviewed by D.R. Parrott, B. MacLean and P.R. Hill. G.B.J. Fader was interim editor during sabatical of D.J.W. Piper.

SCIENTIFIC OBJECTIVES AND PROGRAM SUMMARY

Most of the 1985 submersible program was designed to address issues related to the exploration for and development of oil and gas off eastern Canada: hazards posed by

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iceberg scour, seismicity and sediment failure, and shelf sediment mobility. Funding for these cruises came largely from the Federal Panel on Energy Research and Development. Other cruises addressed related geological problems. In general, the features studied during this program were selected after detailed investigation by ship-borne surveys using remote-sensing techniques.

Three cruises (Table 1.1) examined sedimentation processes on continental shelves. On the Scotian Shelf, the dynamics of shoreface connected ridges, movement of bedforms, and the proposed process of "spillover" were examined (Amos, 1988). Sand ridges and a large relict iceberg furrow were examined on the Grand Banks of Newfoundland (Fader, 1988) as part of the regional surficial mapping program. Most of the work on the Labrador Shelf was integrated with the Dynamics of Iceberg Grounding and Scour Experiment (DIGS) (Hodgson et al., 1988). Where specific icebergs monitored during the DIGS experiment had impacted the seabed, the resulting scours were investigated from PISCES (Josenhans and Barrie, 1988). In addition, observations of iceberg scour degradation were made. Dives made for this purpose in the Strait of Belle Isle also addressed the issue of seabed stability in a power cable trench (Zevenhuizen, 1986).

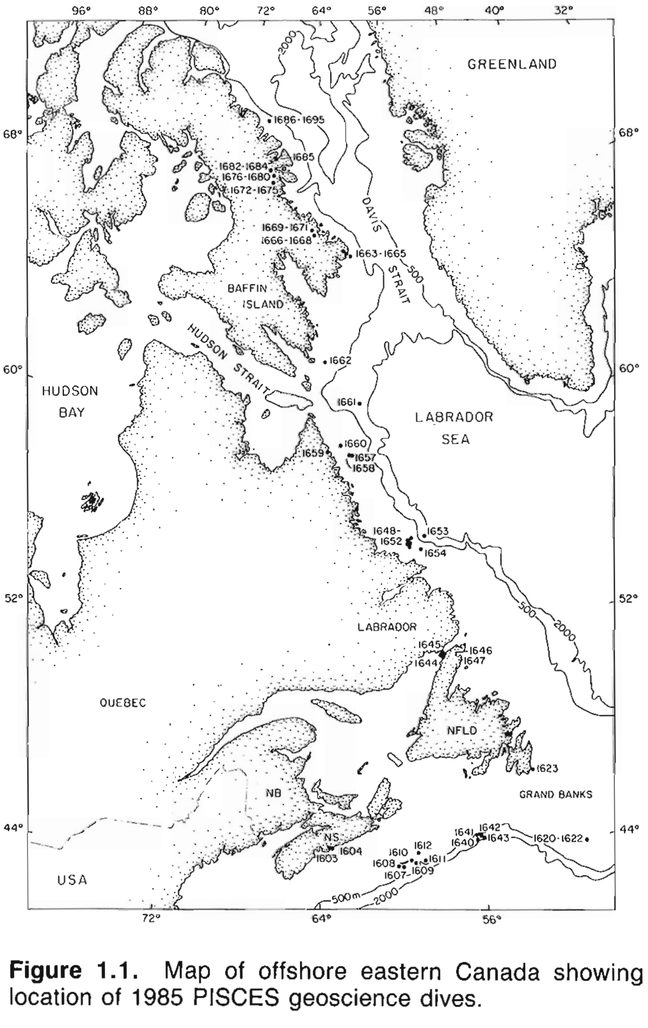

Figure 1.1. Map of offshore eastern Canada showing location of 1985 PISCES geoscience dives.

Dives in Baffin Island fiords (Schafer and Syvitski, 1985; Syvitski and Schafer, 1986; Syvitski et al., 1985; Syvitski, 1987) investigated a variety of sedimentary processes involving delta growth and resedimentation which had been previously studied by conventional methods during the Sedimentology of Arctic Fiords Experiment (SAFE). Several dives were directed to further investigations of the nature and origin of a seabed oil seep in Scott Trough off Baffin Island (Grant et al., 1986). The results of both these cruises are reported in full elsewhere.

One cruise examined seabed failures on the continental slope resulting from the 1929 Grand Banks earthquake on the continental slope off St Pierre Bank and the upper Laurentian Fan (Hughes Clarke et al., 1988). A video report on this cruise has been released on Open File (Hughes Clarke and Frobel, 1987). In addition, two dives on the Labrador Shelf cruise examined shelf edge processes on the Labrador continental slope (Josenhans et al., 1987; Josenhans and Woodward-Lynas, 1988).

Two short test dives were used to examine sedimentation processes on the inner shelf off Nova Scotia. One dive in Halifax Harbour (Piper, 1985) was designed to test hypotheses on mud sedimentation proposed as a result of previous monitoring of the harbour (de Iure, 1983; Piper et al., 1983). A second dive off Cole Harbour, just east of Halifax, continued detailed work on inner-shelf sedimentation (Forbes and Boyd, 1985, 1988), with particular attention to factors affecting gravel mobility and the characteristics and origin of large-scale gravel ripples (Forbes and Boyd, 1987).

This volume presents the results of four of the cruises (those to the Scotian Shelf, Grand Banks, Laurentian Fan and Labrador Shelf) and also the dive off Cole Harbour, Nova Scotia. The results of other PISCES IV cruises are reported in the references cited above.

THE SUBMERSIBLE PISCES IV

The submersible PISCES IV was operated from the support ship MV PANDORA II. Both vessels are described and illustrated by Syvitski et al. (1983) and only a summary is presented here. PISCES IV is a small electrically powered submarine that can operate to a depth of 2000 m with a cruising speed of 1.5 km/h. It has three ports for external observations. Dive duration is limited principally by available power. Because of the hazards during submersible recovery, dives are not carried out if waves exceed 2 m in height, winds exceed 25 knots, or surface visibility is less than 2 km. These restrictions seriously limited the scientific program on several cruises, notably planned work in the Hibernia region of the Grand Banks.

PISCES IV carried one pilot and two observers. Observations were voice recorded, and photographed using hand held cameras (through the viewing ports) and an externally mounted video camera. Samples were collected with the manipulator arm and stored in pre-labelled compartments in an external collection carousel.

Navigation of PANDORA II was by Loran C (where available, or else radar fixes) and transit satellite. PISCES

Table 1.1. Inventory of east coast PISCES IV dives with geoscientific objectives in 1985

Dive #	Latitute	Longitude	Location	Purpose/Target
Pandora 85-050: Halifax Harbour and approaches				
1603	44°36.2′N	63°33.1′W	Halifax Harbour	Outer harbour sediments; NFB film
1604	43°35.0′N	63°23.0′W	Cole Harbour	Inner-shelf processes
Pandora 85-054: C. Amos — Sable Island Bank and Banquereau				
1607	43°49.0′N 43°51.0′N	60°03.0′W 60°00.0′W	Sable Island Bank	Shoreface-connected ridges
1608	43°50.0′N 43°51.5′N	60°20.0′W 60°19.0′W	Sable Island Bank	Shoreface-connected ridges
1609	44°05.0′N 44°03.5′N	59°08.0′W 59°13.0′W	Sable Island Bank, Outer Gully	Canyon
1610	44°09.5′N	59°27.0′W	Sable Island Bank, Gully	Sediment spillover
1611	44°03.0′N 44°06.0′N	58°57.0′W 58°54.5′W	Southwest Banquereau	Megaripples
1612	44°18.0′N 44°18.0′N	59°09.0′W 59°04.5′W	The Gully	Megaflutes, megaripples
Pandora 85-057: G.B.J. Fader — Grand Banks				
1620	45°51.2′N 43°51.8′N	50°46.1′W 50°46.1′W	Tail of the Bank, Grand Bank, west of Southeast Shoal	Sand ridges, incised megaripples, gravel — ridge trough
1621	43°51.6′N 43°52.2′N	50°46.0′W 50°46.0′W	Tail of the Bank, Grand Bank, west of Southeast Shoal	Sand ridge, gravel — ridge trough
1622	43°51.6′N	50°45.8′W	Tail of the Bank, Grand Bank, west of Southeast Shoal	Sand ridge, gravel waves
1623	46°34.2′N	52°48.0′W	Avalon Channel	"Super" furrow, glacial till
Pandora 85-059: D.J.W. Piper — Laurentian Fan				
1640	44°32.2′N 44°32.7′N	56°00.8′W 56°09.8′W	Eastern Valley	Valley floor features
1641	44°43.9′N 44°47.4′N	56°09.6′W 56°11.6′W	Eastern Valley	Transect up Eastern Valley to slump scars
1642	44°42.7′N 44°44.5′N	55°55.8′W 55°51.2′W	St. Pierre Valley	Valley side features
1643	44°36.5′N 44°38.3′N	55°46.9′W 55°45.7′W	St. Pierre Slope	Rotational slumps, gully
Pandora 85-061: H.W. Josenhans — Labrador Shelf				
1644	51°16.19′N 50°17.33′N	56°57.76′W 57°58.60′W	Strait of Belle Isle	Boulder ridges, plow trench
1645	51°21.59′N	56°52.81′W	Strait of Belle Isle	Boulder ridges, shell hash
1646	51°21.54′N 51°22.20′N	56°45.95′W 56°47.45′W	Strait of Belle Isle	Cable trench, bedrock cliff
1647	51°12.20′N	56°48.50′W	St. Barbe's Bay, Strait of Belle Isle	Seafloor, Parks Canada film
1648	55°39.74′N 55°39.9′N	58°14.08′W 58°15.10′W	Makkovik Bank	"Bertha" site, 10 day old ice scour
1649	55°42.02′N 55°41.92′N	58°00.15′W 58°00.02′W	Makkovik Bank	"Anastasia" scour feature
1650	55°32.50′N 55°32.49′N	58°18.52′W 58°19.34′W	Makkovik Bank	Big scour: depth of disturbance experiment
1651	55°31.49′N 55°31.55′N	58°09.47′W 58°09.43′W	Makkovik Bank	Sandwaves, megaripples. Tracer experiment
1652	55°27.81′N 55°26.08′N	58°06.47′W 58°10.36′W	Makkovik Bank	Ground truth BRUTIV photo survey, sidescan
1653	55°45.91′N 55°45.46′W	57°05.33′W 57°06.76′W	Makkovik Bank off Continental Slope	Adlavik well site: upper slope debris flow
1654	55°18.50′N 55°19.81′N	57°25.80′W 57°27.93′W	Eastern Makkovik Bank	"Freda" site, boulder dumps, current scour
1655	55°32.28′N 55°32.57′N	58°18.16′W 58°18.76′W	Makkovik Bank	Big scour: depth of disturbance experiment
1656	55°26.81′N 55°26.57′N	58°10.39′N 58°13.17′N	Makkovik Bank	Megaripples, new scour and berm
1657	58°52.8′N 58°52.63′N	61°46.4′W 61°47.86′W	South edge Saglek Bank	Large cross cutting scours
1658	58°52.63′N 58°53.1′N	61°47.87′W 61°47.1′W	Edge Saglek Bank	Transition from relict to modern scours
1659	59°03.2′N	63°35′W	Nachvak Fiord	Moraine ridge sill
1660	59°21.0′N 59°20.4′N	62°34.3′W 62°34.4′W	Saglek Bank	"Caroline" site, fresh scour
1661	60°53.27′N 60°54.51′N	60°58.94′W 61°04.49′W	Upper continental slope off Hudson Strait	Seafloor grooves and whale feeding traces
1662	62°25.27′N	63°27.29′W	Southeast Baffin Shelf	Mud volcano
Pandora 86-062: J.P.M. Syvitski — Baffin Island Fiords				
1663	66°29.3′N	61°31.2′W	Sunneshine Fiord	Seabed with exposed till
1664	66°37.8′N	62°03.8′W	Sunneshine Fiord	Seafloor near sidewall talus
1665	66°35.9′N	62°04.8′W	Sunneshine Fiord	Side-entry glacier fan delta
1666	67°15.8′N	64°16.1′W	Coronation Fiord	Distal end of slide/slump
1667	67°12.5′N	64°46.0′W	Coronation Fiord	Hummocks
1668	67°14.6′N	64°36.2′W	Coronation Fiord	Facies transition
1669	67°19.5′N	64°31.9′W	Maktak Fiord	Determine seafloor acoustic properties
1670	67°21.2′N	64°46.8′W	Maktak Fiord	Channels on prodelta
1671	67°20.4′N	64°41.2′W	Maktak Fiord	Large scale soft-sediment folding
1672	69°06.2′N	68°53.8′W	Tingin Fiord	Slide/channel complex
1673	69°04.1′N	68°54.5′W	Tingin Fiord	Slide/channel complex
1674	68°59.6′N	68°57.6′W	Tingin Fiord	Crown of submarine channel
1675	69°01.7′N	68°56.7′W	Tingin Fiord	Turbidite "mega" channel
1676	69°16.2′N	69°15.0′W	Itirbilung Fiord	Channel features on prodelta slope
1677	69°16.4′N	69°14.5′W	Itirbilung Fiord	Foreslope of delta
1678	69°18.7′N	69°07.6′W	Itirbilung Fiord	Sediments from hanging glacier
1679	69°19.4′N	68°46.3′W	Itirbilung Fiord	400 m deep basin
1680	69°15.6′N	68°04.5′W	Itirbilung Fiord	Bedrock and sill features
1681	69°33.3′N	69°55.5′W	McBeth Fiord	Glide Block - not encountered
1682	69°33.4′N	69°38.4′W	McBeth Fiord	30 m slide failure face - not encountered
1683	69°33.1′N	69°33.9′W	McBeth Fiord	Sill
1684	69°31.3′N	69°19.0′W	McBeth Fiord	400 m deep basin
1685	70°12.9′N	68°37.7′W	Inugsuin Fiord	Western sill entrance
Pandora 85-063: E.M. Levy — Baffin Bay				
1686	71°23.7′N	70°09.2′W	Scott Inlet	Oil seeping from seafloor
1687	71°24.′N	70°09.′W	Scott Inlet	Oil seeping from seafloor
1688	71°24.′N	70°09.′W	Scott Inlet	Oil seeping from seafloor
1689	71°24.′N	70°09.′W	Scott Inlet	Oil seeping from seafloor
1693	71°24.′N	70°09.′W	Scott Inlet	Oil seeping from seafloor
1694	71°24.′N	70°09.′W	Scott Inlet	Oil seeping from seafloor
1695	71°24.′N	70°09.′W	Scott Inlet	Oil seeping from seafloor

IV was positioned with respect to the mother ship by a Honeywell short base line acoustic positioning system. A Syledis navigation system was used on Makkovik Bank. If the observers maintained a detailed log of submersible heading and speed, and launch and recovery position were well known, a reasonably accurate track could be reconstructed for the submersible. Pingers were also used on some dives for homing and seafloor navigation. Many of the dives were carried out on targets for which sidescan sonar images were already available: these also aided in positioning observations made from the submersible.

SUMMARY AND OUTLOOK FOR THE FUTURE

The submersible facilitated detailed site investigations, including precision sampling, of seabed features whose small size configuration made investigation from a surface ship very difficult or impossible. The 1985 program significantly improved our understanding of the Scott Trough oil seep, of prodelta instability features in Baffin fiords, and of iceberg scour degradation on the Labrador Shelf, for example. It increased confidence in the interpretation of sidescan sonar images, providing much needed quantitative calibration. The principal disadvantage of the PISCES program is its dependance on good weather conditions. Some cruises were fortunate, and met all their objectives: others lost half or more of the planned dives. The best sea conditions on the Grand Banks, for example, coincide with periods of fog.

With the termination of the contract for PANDORA II, future PISCES IV operations in offshore areas will be much more difficult. The Geological Survey of Canada is investigating use of a deep water remotely operated vehicle (ROV) as a less weather dependant substitute for PISCES. The ROV will be more flexible in allowing observations for extended periods of time without the constraints of moderate winds, fog or the need to recharge batteries. It remains to be seen whether the ROV will provide the immediate flexibility of a manned submersible in responding to unexpected scientific opportunities on the seafloor.

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Submersible observations of Quaternary sediments and bedforms on the Scotian Shelf

Carl L. Amos[1]

Amos, C.L., Submersible observations of Quaternary sediments and bedforms on the Scotian Shelf; in Submersible observations off the East Coast of Canada, D.J.W. Piper, editor; Geological Survey of Canada, Paper 88-20, p. 9-26, 1989.

Abstract

A complex sequence of unconsolidated sediments underlies much of the middle and outer Scotian Shelf, Canada. Parts of this sequence outcrop along the eroded bank edges. These were examined during dives in the submersible PISCES IV and resulting observations were compared with high-resolution seismic reflection profiles and side scan sonograms. Bedrock cliffs and terraces, postulated by Marlowe (1969) to occur on the west and northeast flanks of The Gully, were seen and corresponded with a seismic reflection discontinuity which has been traced under much of Sable Island Bank. The distribution and classification of shelf bedforms had been previously based largely on side scan sonograms and so their true nature and origin were in doubt. Observations of these bedforms verified interpretations of acoustic data. Bedform migration directions measured south of Sable Island support an eastward net transport of sand. The "spill-over" of this sand from eastern Sable Island Bank into The Gully was not apparent. However, sediment slumps and active grain flows were seen in Canyon 48, indicating a transfer of material to deeper water by the trapping of sand in canyon heads.

Resumé

Une séquence complexe de sédiments non consolidés occupe une grande partie du sous-sol des portions médiane et extérieure du plateau continental de Scotian au Canada. Des portions de cette séquence affleurent le long des bords érodés des hauts-fonds. On a examiné ceux-ci durant des plongées du submersible Pisces IV, et comparé les observations réalisées aux profils de sismique-réflexion de résolution élevée, et aux sonogrammes obtenus avec un sonar à balayage latéral. On a observé les falaises et terrasses constituées par la roche de fond, dont J.I. Marlowe avait postulé en 1969 l'existence sur les flancs ouest et nord-est du ravin (The Gully); ces structures correspondaient à une discontinuité de sismique-réflexion qui avait été suivie au-dessous d'une grande partie du banc de l'île de Sable. Autrefois, on avait largement basé la distribution et la classification des structures superficielles du plateau sur des sonogrammes obtenus avec un sonar à balayage latéral, de sorte que leurs vraies nature et origine étaient encore mal connues. On a pu vérifier l'interprétation des données acoustiques grâce aux observations réalisées des structures superficielles en question. Les mesures des directions de migration de ces structures au sud de l'île de Sable confirment un transport net du sable vers l'est. On n'a pas constaté de «débordement» de ce sable depuis le banc est de l'île de Sable dans le ravin. Toutefois, on a noté dans le canyon 48 des glissements de sédiment et des écoulements de grains, qui indiquent un transport des matériaux en eaux plus profondes, le sable ayant été piégé dans la partie amont du canyon.

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INTRODUCTION

Objectives

The lithostratigraphy and depositional history of the Quaternary geology on Sable Island Bank is largely unknown. Boyd et al. (1985) presented an acoustic sequence from this bank which correlates well with that seen on Banquereau, where lithology is known (Amos and Knoll, 1987). A number of the prominent seismic reflections mapped by Boyd outcrop along the flanks of Sable Island Bank. It is here that a correlation between these reflectors and lithology is possible. Six dives of the PISCES IV submersible were carried out primarily to examine these areas and to establish the correlations.

Physiography and Quaternary Geology

Sable Island Bank and Banquereau are bathymetric "highs" situated at the edge of the Scotian Shelf (Fig. 2.1). They are separated from the shoreline by the deeply dissected "coast-parallel marginal trough" of King (1967). They are the largest of a series of outer banks which extend along the entire Scotian Shelf. The outer banks are notable for their relatively flat surfaces which contrast with the irregular topography of the surrounding deeper shelf.

The Gully separates Sable Island Bank and Banquereau. Its irregular morphology and character are described in detail by Marlowe (1965) and Stanley et al. (1972). Near the shelf-edge, The Gully is straight and steep-sided and corresponds in form to a submarine canyon.

The Quaternary geology of the Scotian Shelf is described and reviewed by King and Fader (1986) and Piper et al. (in press). The distribution of bedforms, the nature of surface sediments and the major sedimentary processes are reviewed by Amos et al. (in press).

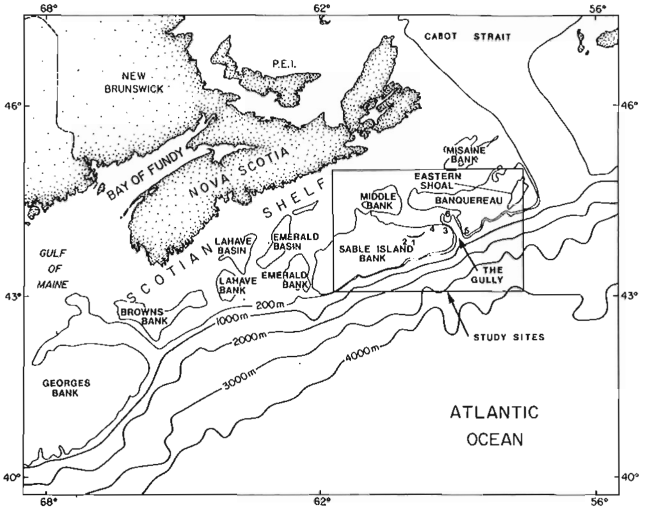


Figure 2.1. Location map of Sable Island Bank, The Gully and Banquereau, Scotian Shelf, Canada. The positions of the six PISCES IV dives reported in this paper are shown: (1) dive 1607; (2) dive 1608; (3) dive 1609; (4) dive 1610; (5) dive 1611; and (6) dive 1612.

Field methods

The observations reported herein were collected during six dives in the manned submersible PISCES IV. It was equipped with a manipulator arm for limited sampling and an external video camera. These dives were carried out during PANDORA II cruise 85-054 to Sable Island Bank and Banquereau during 20-26 May, 1985 (Amos, 1985a). The location of dives are shown in Figures 2.2 and 2.3. Table 2.1 summarizes the dives which varied in duration between 100 and 183 minutes and were carried out in depths ranging from 40 to 422 m.

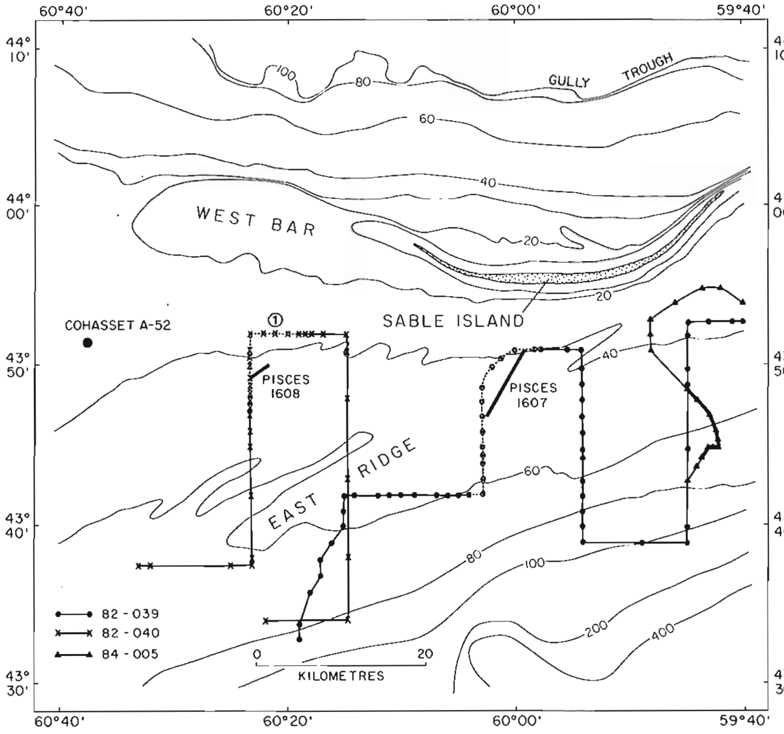


Figure 2.2. The locations of dive traverses 1607 and 1608 on the southwest shoreface of Sable Island (solid lines). The detailed bathymetry indicates the location of East Ridge and smaller shoreface-connected ridges inspected during these dives. The location of seismic profiles referred to in the text are also indicated. Each series of seismic profiles are referenced by cruise number.

Table 2.1. Location of seabed observations, PISCES IV, Scotian Shelf

Dive #	Date (D/M/Y)	Start		End		Heading (°T)	Water Depth (m)
		Lat (N)	Long (W)	Lat (N)	Long (W)		
1607	23/5/85	43°47′00″	60°02′50″	43°51′00″	59°59′30″	030	40 - 50
1608	23/5/85	43°49′20″	60°23′30″	43°50′00″	60°21′50″	030	40 - 50
1609	24/5/85	44°05′00″	59°08′00″	44°03′00″	59°13′00″	240	90 - 422
1610	24/5/85	44°09′00″	59°26′20″	44°06′40″	59°26′00″	180	90 - 240
1611	25/5/85	44°03′00″	58°53′30″	44°04′30″	58°51′50″	030	115 - 130
1612	25/5/85	44°17′40″	59°09′00″	44°18′50″	59°06′00″	090	170 - 230

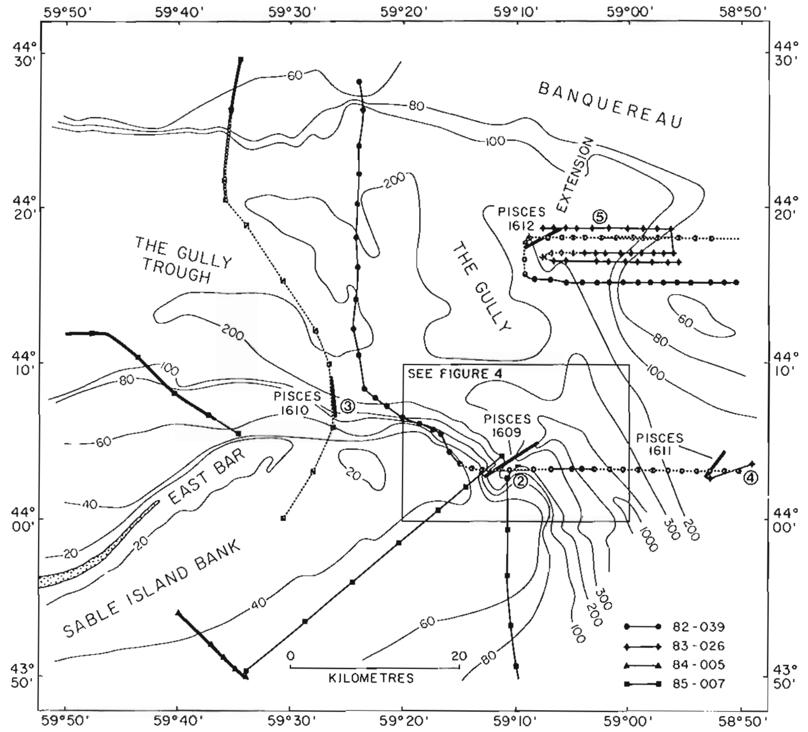


Figure 2.3. The locations of dive traverses 1609 to 1612 situated around the margins of The Gully. Seismic lines, used to plan dive sites, are referenced by cruise number; representative seismic profiles are given by numbers in circles.

Dive sites were selected on the basis of interpretations of high-resolution seismic reflection profiles and side scan sonograms collected on five surveys of Sable Island Bank and Banquereau. Details of these surveys and the geophysical systems used are given in a series of unpublished cruise reports (Amos, 1982; 1983; 1984; 1985a and 1985b).

Acknowledgments

I acknowledge and thank the support staff and pilots of PISCES IV and the crew of the tender ship M.V. PANDORA II. I also thank Odette Nadeau and Jim Dunn for support in the analysis of video tapes and 35 mm photographs; and G.B. Fader, B. MacLean and D. Scott for critical reviews of the manuscript.

DIVE SITE DESCRIPTIONS AND RESULTS

Shoreface-connected ridges, Sable Island Bank (Dives 1607 and 1608)

Location and purpose

Dives 1607 and 1608 were conducted on the south-west shoreface of Sable Island in water depths between 40 and 50 m (Fig. 2.2). The sites lie within the zone of shoreface-connected ridges described by Hoogendoorn and Dalrymple (1986). Seabed sediments contain up to 60% fines (Petro-Canada Resources Inc., 1986), whereas elsewhere around Sable Island the fines content is negligible. The spatially-averaged mean grain size of the sand fraction over the two sites is 0.20 mm. However, Hoogendoorn and Dalrymple (1986) have noted significant variations in size over individual sand ridges. Side scan sonograms illustrate sharp acoustic contrasts tentatively correlated with grain size and interpreted to be diagnostic of sand ridge migration. The objectives of these dives were to look for evidence of sand ridge migration and to establish a mechanism for the segregation of sediments.

Seismostratigraphy

A Huntec (DTS) seismic reflection profile and side scan sonogram collected over the dive site 1608 are shown in Figure 2.4. A sequence of unconsolidated sediment is interpreted to underlie the dive site. The sequence is approximately 100 m thick and rests on a strong seismic reflection discontinuity. The upper part of the section is characterized by strong eastward dipping reflections interpreted as tabular

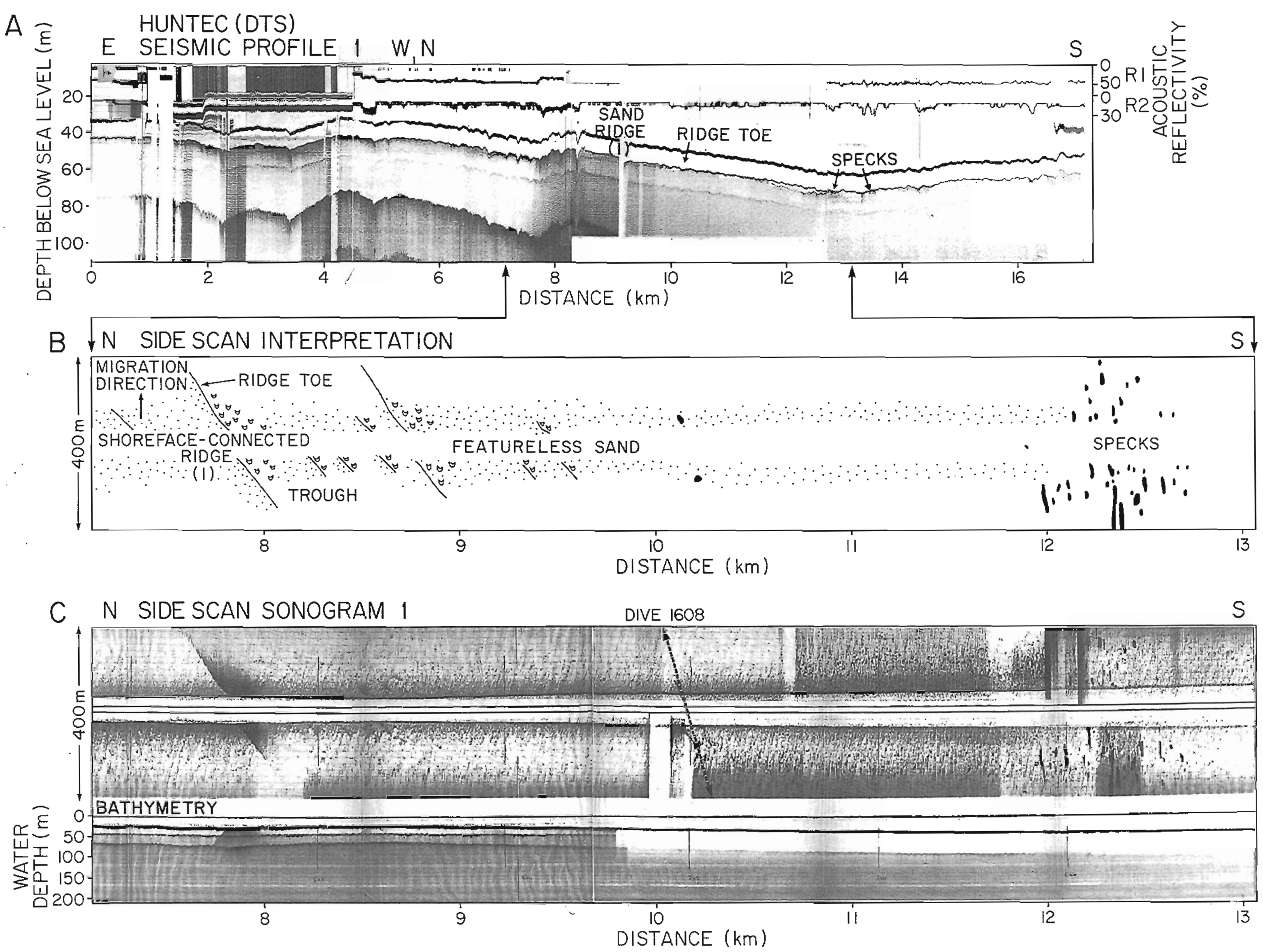


Figure 2.4. A seismic reflection profile from the vicinity of dive site 1608, Sable Island Bank. (A) shows Huntec (DTS) seismic profile through shoreface-connected ridges illustrating the presence of acoustic reflections considered to be lag gravel layers generated by the process of sand ridge migration. (B) and (C) show side scan sonogram and interpretation between 7 and 13 km on figure 2.4, illustrating the sharp changes in acoustic character diagnostic of changes in sediment texture, and the presence of "specks' (shell patches).

foresets which appear associated with the sand ridges illustrated in Figure 2.4a. Superimposed on the flanks of the sand ridges are circular and elongate features which produce strong acoustical backscattering on side scan sonograms (Fig. 2.4b and c). These were termed "specks" by Evans-Hamilton Inc. (1975) and occur over large areas of Sable Island Bank.

Visual observations: Dive 1607

The dive commenced on the western flank of East Ridge in a water depth of 50 m. The bottom water was at a temperature 4.5°C and was flowing to the southeast at a speed of approximately 0.2 m/s. Observations were made on a traverse oriented 030 T which passed into a sand ridge trough and then onto the eastern flank of an adjacent ridge. The seabed over the crest of the ridges was composed of clean, shelly sand that showed evidence of wave-rippling. The ridge troughs were composed of shell-rich gravel (similar to those in Figures 2.5a and b). Ripples superimposed a hummocky topography 50 mm in height, 0.5 m in chord-length and 1 m long. The ripples were modified by the sand dollar *Echinarachnus parma* which was locally abundant.

A circular patch of shell debris approximately 20 m in diameter was encountered on the west flank of East Ridge

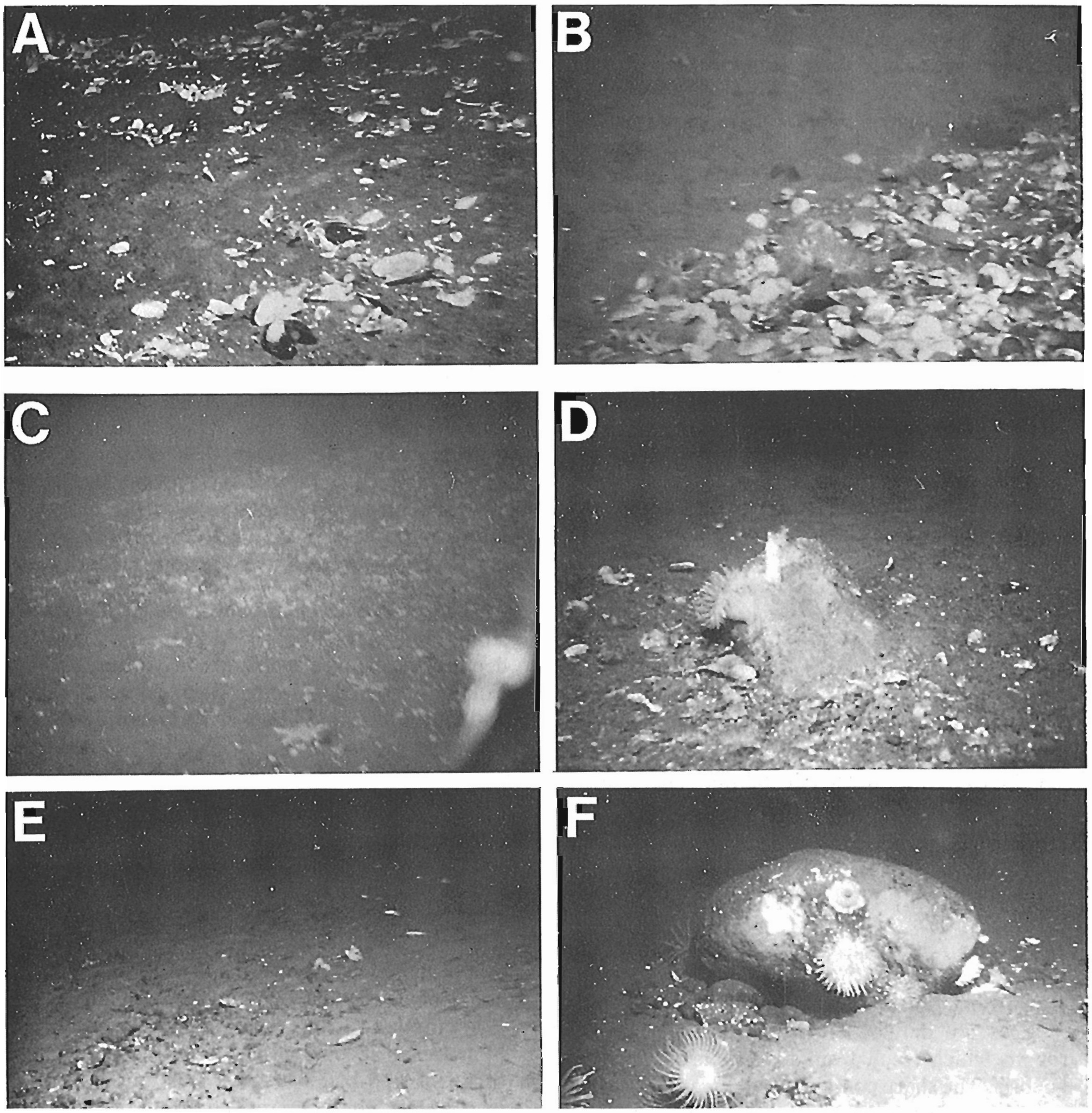


Figure 2.5. (A) shell debris in the trough of a shoreface-connected ridge, Sable Island Bank (dive 1608; see fig. 2.3); (B) the junction between the "pseudo-slip face" of the eastern (leading) flank of a shoreface-connected ridge and shelly material in the trough (dive 1608); (C) a circular patch of shell debris, referred to as "specks" on side scan sonograms (dive 1608); (D) the top of the wave-cut scarp on the southwest flank of Banquereau (dive 1611). Note the angular gravel in the foreground and the "zero-edge" of the Sable Island sand and gravel behind; (E) east to west oriented alternations of pebble-size gravel and sand seaward of the wave-cut scarp, Banquereau (dive 1611). They correspond to the acoustic patterns interpreted as 2-D megaripples in Figure 2.7; (F) Glacial till (Scotian Shelf drift) on the west flank of Banquereau extension (dive 1612).

(Fig. 2.5c). Shell material was disarticulated, worn and mixed with organic-rich sediment in a surface veneer: no live bivalves were seen. The boundary of the patch was sharply-defined.

The transition from the western flank of East Ridge to the trough was evident only by a gradual change in sediment from medium-size sand to a mixture of coarse sand and shells. By contrast, the contact between the eastward-dipping face of the adjacent ridge and the trough was sharp (Fig. 2.5b). This was due to the presence of a low-angle (3-5°), tabular face at the base of the ridge, which was composed of fine sand and which had partially buried shell debris in the adjacent trough. This shell debris was restricted to the sediment surface: clean medium-sized sand was found beneath this veneer. Sand ribbons, 0.5 m in chord length, were seen associated with hummocks and 2-D megaripples which were round-crested and approximately 10 m in wavelength. The megaripple troughs were oriented transverse to the ridge trough and were infilled with shell debris. No slip faces were evident and so the direction of megaripple migration could not be determined.

Visual observations: Dive 1608

The dive began in 55 m of water at the base of the eastern flank of a first-order shoreface-connected ridge (height 5 m; wavelength 1700 m; Hoogendoorn and Dalrymple, 1986). The bottom water was at a temperature of 1.6° C and was flowing to the southwest at 0.2 m/s. A traverse was made to the northeast and north; that is, parallel with the sand ridge trough. The seabed was composed of compact, clean fine sand which was highly bioturbated by *Echinarachnus parma*. Circular patches of shell debris, up to 20 m in diameter, were periodically observed. The packing of shell debris was variable. One patch was composed of tightly packed unbroken valves while others were degraded. The majority of valves were of the species *Arctica islandica*. The shell patches occurred in depressions of the seabed which were up to 0.5 m deep. All patches seen were sharply bound by fine sand. The sand appeared to have moved over part of the shelly patch. The shell debris was found only in a thin surface layer; beneath were found silt and fine sand. Wave-formed ripples were periodically seen, but no other bedforms were observed.

Interpretation

The acoustic patterns illustrated in Figure 2.4 (dive site 1608) are related to sand ridge morphology and seabed composition. The orientation and position of the shoreface-connected ridges are defined clearly by the acoustically "dark" troughs which result from acoustic backscattering from shell debris. The sharp contrast in backscattering at the western margin of the trough is the result of a similarly abrupt change in texture at the toe of the eastern flank of each sand ridge. This is the result of progradation of the eastern (leading) flank over shelly sand in the trough to produce low-angle foresets of fine sand. Thus the sand ridges show evidence of eastward progradation. This is in agreement with the direction inferred from eastward-dipping cross-bedding detected acoustically by Boyd (personal communication, 1985).

The circular and elongated specks seen on the sonograms in Figures 2.4b and c were verified as patches of reworked shell debris; no living specimens were seen. No evidence of gas venting was detected, such as "white slime" reported by Fader (1988), nor were any signs of seabed instability observed, so the origin of the features is still uncertain. Specks usually conformed with slight depressions of the seabed. They may therefore be the result of localized current scouring which exposes shell-rich lag layers, known to form in the process of sand ridge migration (Hoogendoorn and Dalrymple, 1986). Many of the specks were indeed elongated and aligned in the direction of current flow. Finally, the data reflected the otherwise acoustically featureless nature of the sand ridge.

Canyon 48, The Gully (dive 1609)

Location and purpose

Dive 1609 was carried out in a feeder canyon of The Gully (Fig. 2.3 and 2.6a). This canyon, termed "Canyon 48', is described in detail by Marlowe (1965, 1969). In particular, Marlowe proposed that rock ledges and submarine terraces were abundant in this canyon. Dredge samples were of freshly broken fragments of Tertiary mudstone and pebbles and boulders of granite, gneiss, quartzite, basalt, and Carboniferous carbonates presumed to be derived from compacted glacial till or outwash which were though to overlie Tertiary bedrock. Marlowe (1969), in reference to Canyon 48, also described slumps, evidence for slope failures and the existence of grain flows. The morphology and distribution of sediment at this site is complex. Stanley et al. (1972) correlated textural variations with depth below sea level which appeared to be controlled by reworking and transport of Tertiary and Quaternary material (Marlowe, 1969).

The objectives of this dive were firstly, to verify the stratigraphy proposed by Marlowe and to document the depth of occurrence and nature of Tertiary bedrock and glacial till. Secondly, to verify the documented sediment distribution and thirdly, to look for evidence of down-slope sand transport.

Seismostratigraphy

Interpretations of shallow seismic reflection profile lines shown in Figure 2.6 were used to locate dive targets. The stratigraphy interpreted from these profiles is shown schematically in Figures 2.6b and 2.7b. A strong acoustic reflection occurred throughout the area and appeared to crop out at depths of 300 m and greater in The Gully. This reflection is interpreted as the Tertiary bedrock surface. It is overlain by a unit of incoherent reflections characteristic of glacial till (King and Fader, 1986). This unit is covered in places by coherent, contorted reflections particularly on the steeper flanks of the canyon (Fig. 2.7c). The till appears to grade laterally into an acoustically stratified unit of coherent reflections which extend under Sable Island Bank so the till appears to be restricted to the margins of The Gully.

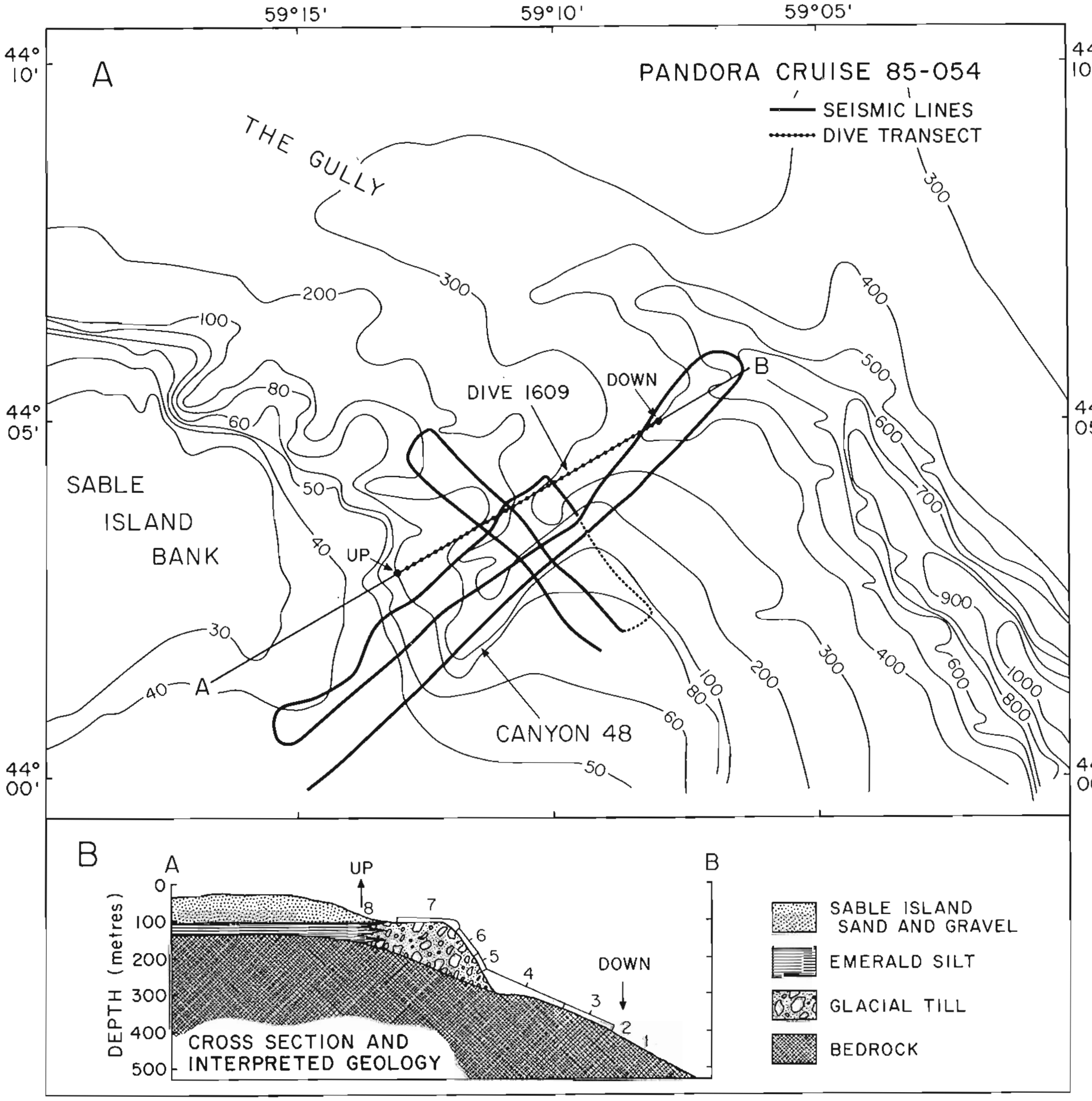


Figure 2.6. (A) Detailed location map of dive site 1609 situated in Canyon 48, The Gully. The figure shows the position of seismic profiles surveyed aboard PANDORA II prior to the dive. (B) A geologic section along the dive transect interpreted from the seismic reflection data. The seabed below 300 m appears to be underlain by Tertiary bedrock; between 120 and 300 m glacial till predominates; and above 120 m reworked sand is predominant.

Visual observations

Dive 1609 began in a water depth of 422 m. The water column was stratified and showed an increase in temperature with depth from 4 to 7.5° C. A near-bed current was flowing southward (out of The Gully) at a speed of approximately 0.1 m/s. The dive started at the mouth of Canyon 48 at its entry point into The Gully (Fig. 2.6a). The dive transect was classified into eight distinct zones on the basis of seabed character and depth (Fig. 2.6b). The following are brief descriptions of each of these zones:

Zone 1: 412 to 422 m; the seabed was composed of clean, well-sorted rippled, fine sand (Fig. 2.8d). Ripples were sharp-crested, asymmetric and had slip-faces that dipped to the south. These ripples were principally linguoid and lunate types and were superimposed on 2-D megaripples which were approximately 1 m in height, 30 m in wavelength, and which also showed a southward migration. Large, angular boulders of consolidated, stratified sediment protruded through the sand. Scoured moats approximately 1 m deep surrounded these boulders.

Zone 2: 400 to 412 m; this zone was characterized by a smooth vertical rock face which was seen immediately east of the site of descent. The base of the face is illustrated in Figures 2.8e and f. The rock was lithified and horizontally bedded. The base of the rock face showed evidence of undercutting.

Zone 3: 327 to 400 m; the seabed in this zone was morphologically featureless and at a constant slope of approximately 1:10. It was covered with a veneer of fine sand which showed an abundance of small-scale bioturbation structures and agglutinated worm tubes.

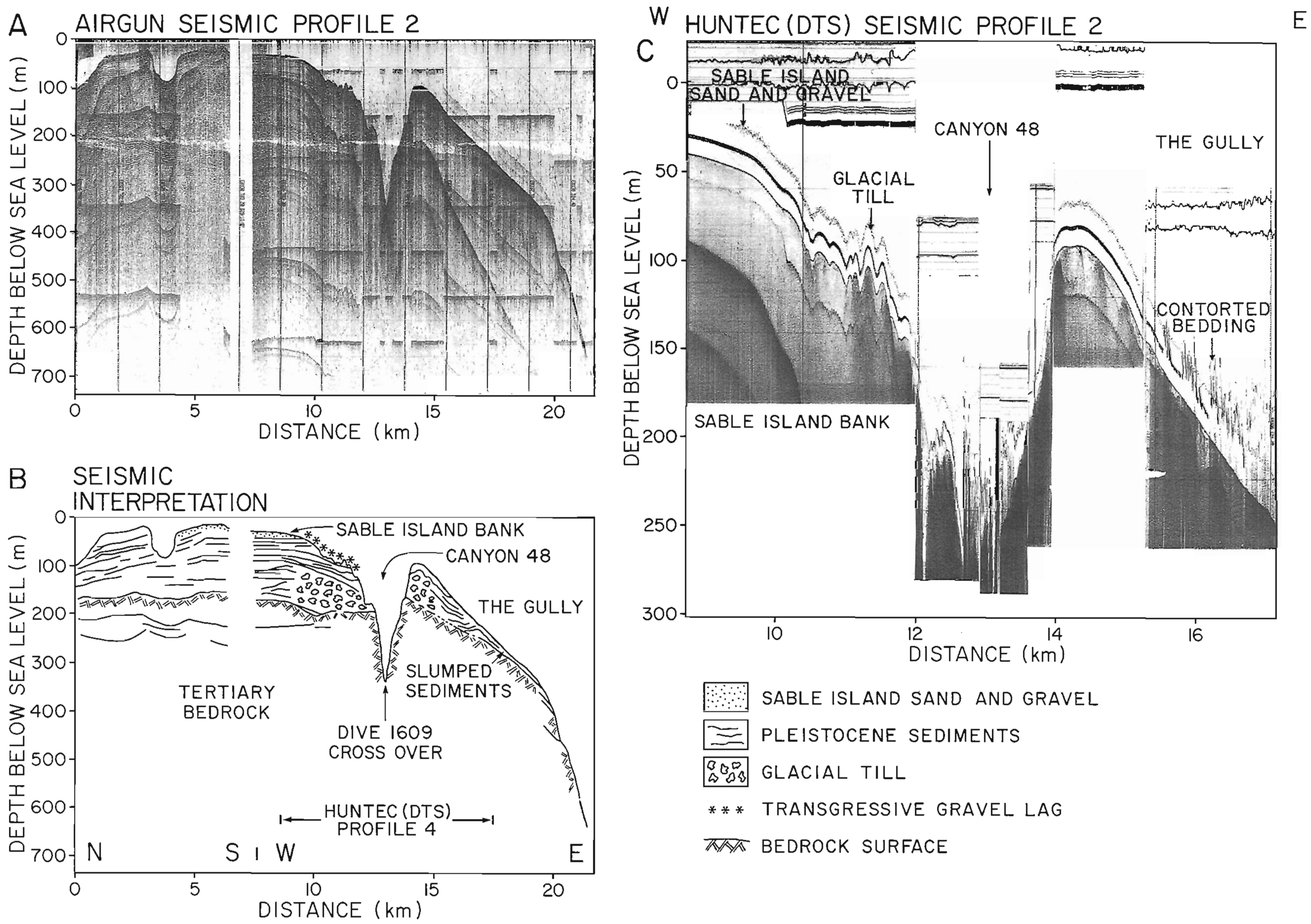


Figure 2.7. (A) Airgun seismic reflection profile which illustrates a cross-sectional view of Canyon 48. The data were collected during cruise 82-039 (Amos, 1982). (B) An interpretation of the seismic profile. Note that the irregular acoustic reflections diagnostic of glacial till are restricted to the region around Canyon 48. (C) A Huntec (DTS) seismic profile between 8 and 17 km in 7A, illustrating the presence of contorted reflections diagnostic of slumps (15 — 16 km), and an in irregular hummocky seabed (10 — 12 km) in regions underlain by glacial till and bedrock. Note that the slumps and the hummocks are morphologically distinct features.

Zone 4: 222 to 327 m; the dominant feature of this zone was a series of 15 m high hummocks. Each hummock was round-crested, steep-walled and spaced approximately 50-100 m apart. Surface material was composed of highly bioturbated, shelly silt or fine sand (Fig. 2.8a and b). The troughs separating crests were infilled with rippled sand. Active grain flows were observed on several of the hummocks. At 307 m, a 7-m-high rock face was encountered. The rock was sedimentary, bedded and consolidated. Four more hummocks were encountered between 220 and 290 m. Compacted, contorted sediment containing an abundance of gravel was seen at 230 m. The constituent material was partially covered by highly bioturbated shelly sand absent of bedforms.

Zone 5: 200 to 222 m; the seabed was characterized by highly bioturbated, fine-grained sediments which were absent of shell debris but supported an abundance of sea anemones (Fig. 2.9f). The seabed was morphologically featureless and had a slope of approximately 1:5. The current in this zone was lower than in zones 1-4.

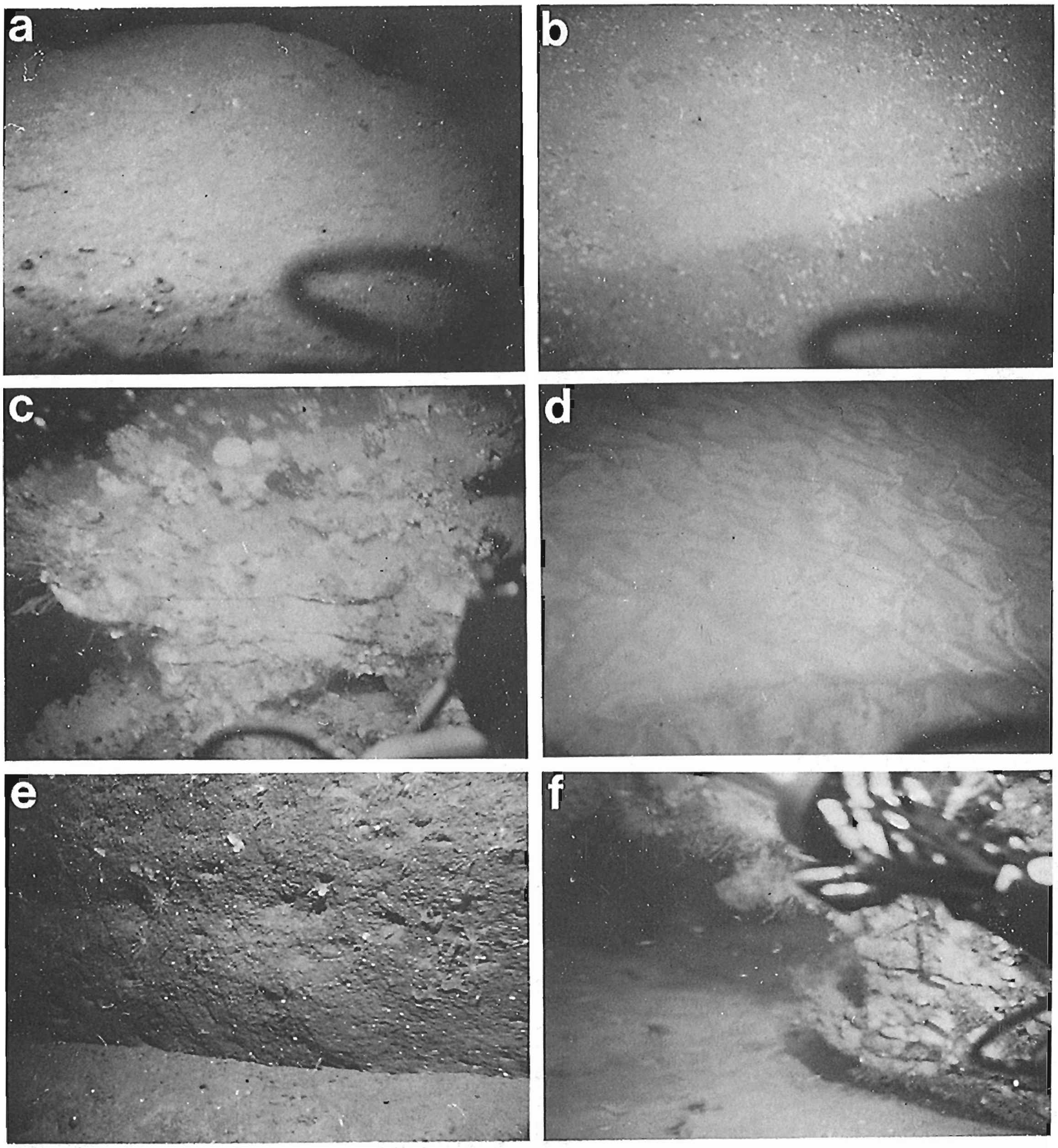


Figure 2.8. Sequential photographs of the seabed taken during dive 1609 in the lower part of Canyon 48, the Gully, which can be cross-referenced to geology in Figures 2.6 and 2.7. (A) the top of a hummock in zone 4; (B) featureless shelly sand characterising zone 4; (C) an eroded rock face in zone 2. Note the sub-horizontal bedding and the lithified appearance of the outcrop; (D) rippled sand in zone 1. The bedforms were active and were moving southward, out of the Gully; (E) a polished rock wall flanking zone 1 at the mouth of Canyon 48; (F) undercuts of the rock wall indicative of erosion through long-term sand movement.

Zone 6: 140 to 200 m; poorly-sorted sediment predominated with an abundance of angular gravel-size lithic fragments and worn shell debris. The morphology and slope of the seabed was similar to zone 5. No current was detected in this zone.

Zone 7: 100 to 140 m; the seabed consisted of compacted, gravelly sediment. The gravel was pebble-size and was both angular and rounded (Fig. 2.9a). Well-rounded boulders occurred in a band concentrated at the 110 m isobath (Fig. 2.9b and c) and most were surrounded by scour pits up to 0.5 m deep. Gravel comet marks (defined after Newton et al., 1973; Fig. 2.9d) were associated with many boulders and were oriented southward. The current in this zone was flowing at 0.2 m/s to the south.

Zone 8: less than 100 m; it was characterized by a slight increase in slope and a progressive increase in the occurrence of well-sorted, rippled medium-size sand. Horizontally-laminated, fine-grain beds occasionally outcropped through the sand, and the occasional boulder was seen with an associated comet mark oriented southward.

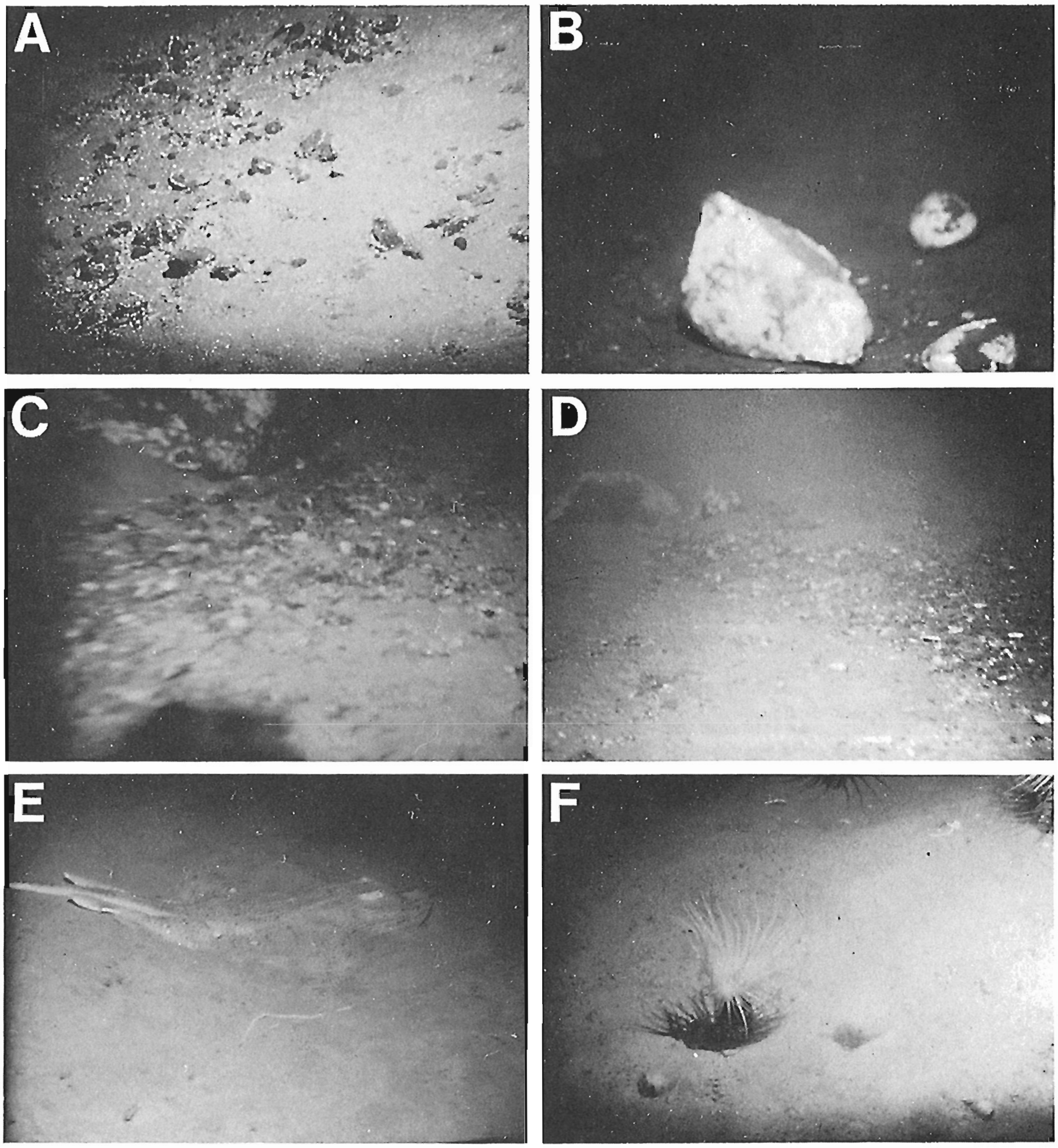


Figure 2.9. Sequential photographs of the seabed taken during dive 1609 in the upper part of Canyon 48, The Gully, which may be cross-referenced to geology in Figures 2.6 and 2.7. (A) compact, angular gravel found in zone 7. The photograph was taken at the top of the scarp above the 120-m terrace; (B) sub-rounded boulders found on the 120-m terrace; (C) and (D) south-oriented comet marks at the seaward edge of the 120 m terrace; (E) bioturbation resulting from resting skate; zone 5; (F) fine-grained sediment and sea anemones in zone 5.

Interpretation

Bedload transport of sand in the deeper parts of The Gully was verified. Transport was southward — towards the continental slope. Acoustic hyperbolae, coincident with the seabed on Huntec (DTS) profiles of the flanks of The Gully, were verified to be diagnostic of 2-D megaripples which were also active and oriented southward. The observed position of bedrock corresponded well with that inferred from the seismic reflection profiles shown in Figures 2.6 and 2.7. Consolidated bedrock crops out along the flanks and outer parts of Canyon 48 and underlies zones 1 to 4. The bedrock surface occurs at an approximate minimum water depth of 180 m. The hummocks observed in zone 4 (Fig. 2.6) are underlain by bedrock and are not produced by mass movement of surficial sediment. These features are more likely to be fluvial paleo-channels or possibly glacially-eroded, flute-like scours cut into the Tertiary sequence. This surface is overlain by a compacted, contorted diamicton which correlated with the contorted reflections on the seismic profile illustrated in Figure 2.7b. The sediment deformation appears to be the result of glacial loading (as opposed to slumping) in view of the compacted nature of the sediment. This sediment grades upwards into a boulder-rich material interpreted to be glacial till (Scotian Shelf Drift; King, 1970). The till was visible in zone 7 and corresponded to the scattered seismic reflections detected at the bank margins.

The bank-edge circulation model proposed by Galt (1971) appears to be applicable to this site. This is reflected in the contour-parallel currents at depth and an absence of significant currents between the bank and slope water masses (140-200 m; Houghton et al., 1978). Above 140 m and below 200 m sand is abundant: between these depths fines occur. It is proposed that 140 m represents the maximum depth to which sand is transported as bedload by hydraulic processes on Sable Island Bank. That is, it represents an hydraulic fence.

The seabed in zone 7 (100-140 m), immediately above the hydraulic fence, is interpreted to be a region of intensive sediment reworking. This is based on the presence of aligned, sub-rounded boulders, the absence of sand or fines and the predominance of compacted horizons of well-sorted gravel on a clearly definable terrace cut in glacial till. This zone corresponds in depth with the late Wisconsinan minimum stand of sea-level postulated by Milliman and Emery (1968). King (1970) proposed that the distribution of surficial sediments on the Scotian Shelf was the result of wave and current activity during the late Pleistocene low stand of sea level which took place approximately 15 000 years BP (King and Fader, 1986). Our observations made in zone 7 support this proposal. It is noted that features such as comet marks (after Newton et al., 1973) and the general absence of sand indicates that sediment reworking continues intermittantly in modern times. The orientation of comet marks indicates strong unidirectional flow to the south, parallel to the local isobaths.

Sediment spill-over, Sable Island Bank (dive 1610)

Site description

The northeastern flank of Sable Island Bank was inspected between water depths of 99 and 214 m (Fig. 2.3). This region was referred to as the site of "spill-over" by Stanley et al. (1972). Sediments are moderately well-sorted, have a mean grain size of 0.2 to 0.5 mm and contained an abundance of heavy minerals (James and Stanley, 1968). The region is devoid of any evidence of large-scale bedforms or slumping (Amos et al., in press).

The objectives of this dive were to look for evidence of the process of sand "spill-over" into The Gully and to define the sedimentary character of outcropping acoustic reflections.

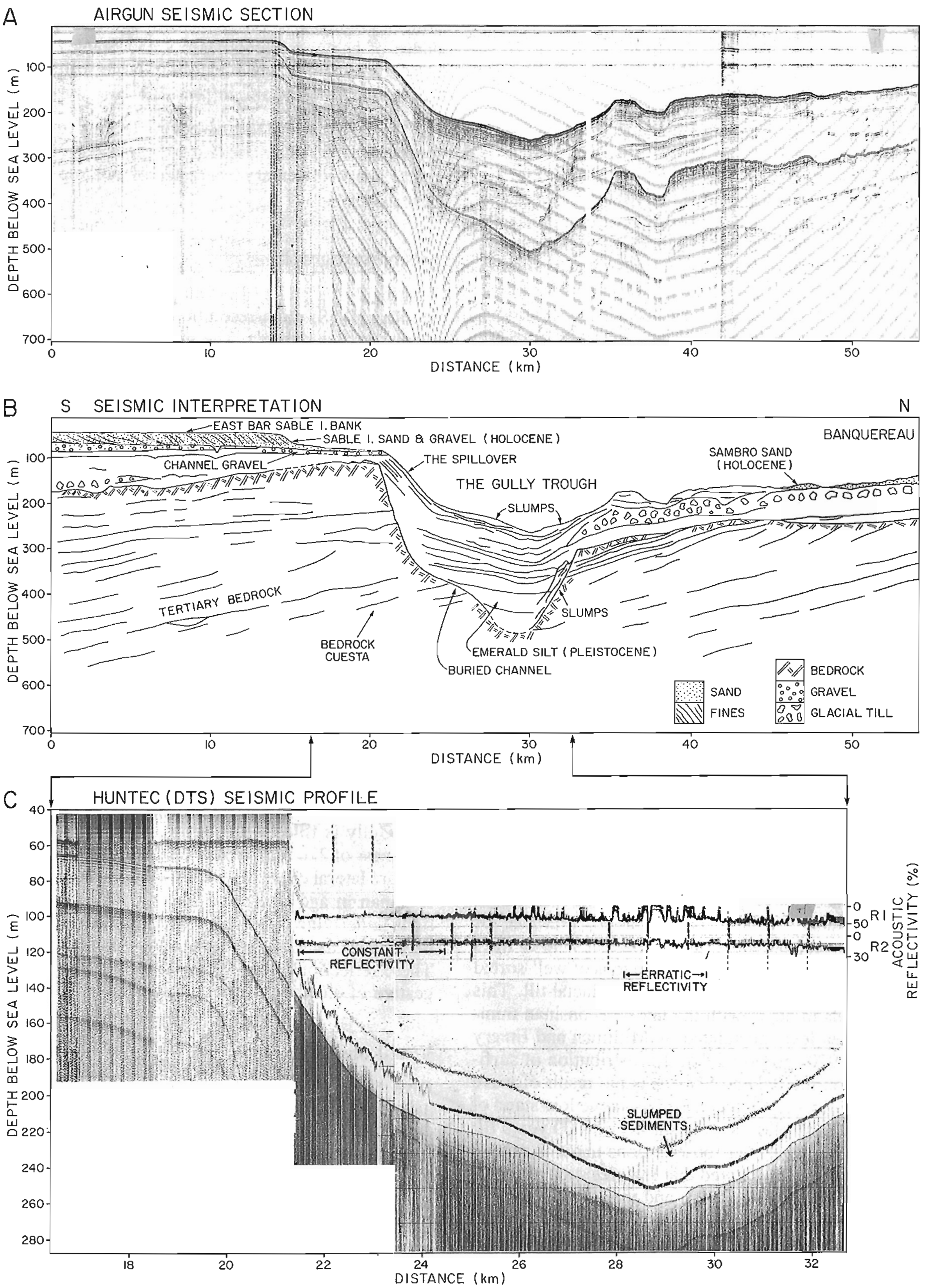
Seismostratigraphy

Figures 2.10a and c illustrate respectively an airgun and Huntec (DTS) high-resolution seismic profile collected along the dive transect. The interpretation shown in Figure 2.10b is based on a tentative correlation with the stratigraphy of Banquereau (Amos and Knoll, 1987) and from the basinal stratigraphy of King and Fader (1986). The sediments on the bank are thickest to the south (150 m) and become thinner to the north. North-dipping acoustic reflections within the upper 40 m of this unit indicated that East Bar has prograded in this direction; that is, in the direction of the "spill-over". An acoustic discontinuity occurs at a depth of 40 m beneath East Bar and outcrops near the top of the "spill-over" at the 120 m isobath. This horizon has been tentatively correlated with a dated equivalent on Banquereau (Amos and Knoll, 1987); a fluvial gravel-rich unit which separates reworked sand from underlying Pleistocene material of varying textures.

The most prominent acoustic reflection underlying the dive site is interpreted to be the Tertiary bedrock surface (correlated from dive site 1609) which is within 20 m of the seabed. To the north, within The Gully, the bedrock surface plunges steeply to a depth of 500 m to form a buried channel cut through Tertiary sediments (King and MacLean, 1976). The Gully is filled with stratified sediment to a maximum thickness of 220 m. The sediments underlying the dive transect are lateral equivalents of this unit and are probably Wisconsinan in age (King and Fader, 1986). Acoustic reflections underlying the dive site were traced above and below till tongues dated and interpreted by King and Fader (1986). These reflections were closely spaced and undeformed suggestive of slow, but continuous sedimentation.

Visual observations

Dive 1610 began at the base of the bank slope in a water depth of 214 m and terminated due south in a depth of 99 m (Fig. 2.10). A steady, near-bed current of 0.2 m/s was flowing to the east, yet no evidence of rippling was detected. The seabed was composed of organic-rich silt and was highly bioturbated. It was devoid of shell debris, sand or gravel. Sea anenomes were abundant and were surrounded by scour pits. Seabed depressions approximately 0.1 m deep and 0.5 m in diameter were also abundant. These depressions were excavated by resting skate (Fig. 2.9E); seabed sediment was suspended by slight motions of these fish and illustrated its unconsolidated nature. Farther upslope numerous burrows were seen which were approximately 0.5 m deep and 0.3 m wide. The current at this depth (193 m) was flowing to the east at an estimated speed of 0.5 m/s.

A
AIRGUN SEISMIC SECTION
DEPTH BELOW SEA LEVEL (m)
100
200
300
400
500
600
700
0
10
20
30
40
50
DISTANCE (km)
B
S
SEISMIC INTERPRETATION
N
EAST BAR SABLE I. BANK
SABLE I. SAND & GRAVEL (HOLOCENE)
BANQUEREAU
CHANNEL GRAVEL
THE SPILLOVER
SAMBRO SAND (HOLOCENE)
THE GULLY TROUGH
SLUMPS
TERTIARY BEDROCK
SLUMPS
BEDROCK CUESTA
EMERALD SILT (PLEISTOCENE)
BURIED CHANNEL
SAND
FINES
BEDROCK
GRAVEL
GLACIAL TILL
DEPTH BELOW SEA LEVEL (m)
DISTANCE (km)
C
HUNTEC (DTS) SEISMIC PROFILE
DEPTH BELOW SEA LEVEL (m)
40
60
80
100
120
140
160
180
200
220
240
260
280
CONSTANT REFLECTIVITY
ERRATIC REFLECTIVITY
SLUMPED SEDIMENTS
R1
R2
0
50
0
30
ACOUSTIC REFLECTIVITY (%)
18
20
22
24
26
28
30
32
DISTANCE (km)

Between depths of 180 and 160 m an abundance of reworked wood fragments was encountered. These fragments occurred at the transition of sediment type to a sandy texture. Between depths of 130 and 120 m a notable increase in shell debris was detected, the sand dollar *Echinarachnius parma* appeared and small-scale rippling of the bed was detected. The current speed here was no greater than 0.2 m/s. At 116 m, we observed the presence of well-rounded granules and pebbles which were composed of varying lithologies. At 107 m, there was a sharp increase in the seabed slope associated with a return to a predominantly sandy seabed.

Interpretation

The observations made during this dive support the concept that sedimentation on the north flank of Sable Island Bank has been slow but continuous. Clean sand and debris of the bivalve *Arctica islandica*, which proliferate on the banks, are restricted to depths less than 120 m. The observed currents and linearities in scour patterns suggest a prevailing transport of material to the east: that is, out of The Gully. The zone of wood debris at 160 m is interpreted to be diagnostic of the "hydraulic fence" noted in dive 1609.

The abundance of well-rounded, gravel-size clasts at 116 m correlated with the outcrop of the acoustic reflection referred to as the Channel Gravel in Figure 2.10b. The gravel-rich character of this unit is similar to a Channel Gravel unit sampled in cores from Banquereau (Amos and Knoll, 1987) and which is the base of the reworked sequence.

There was no evidence for "spill-over" of sand into The Gully, postulated by Stanley et al. (1972). The scale and abundance of bioturbation favours low sedimentation rates and a stable seabed.

Figure 2.10. (A) An airgun seismic reflection profile along dive transect 1610. The section is oriented north-south and extends from Sable Island Bank and across The Gully. The profile illustrates well-developed acoustic reflections underlying the dive site; one of which outcrops along the dive transect; (B) the interpretation of the seismic profile showing a complex sequence of Quaternary sediments resting on a dissected Tertiary surface. The site of the spill-over of Stanley et al. (1972) is also shown. Reflections under this site appear conformable with those in the deeper part of The Gully; (C) a Huntec (DTS) seismic profile in the area of the spill-over showing contorted reflections indicative of downslope sediment movement.

Southwest Banquereau (dive 1611)

Location and purpose

The region covered by dive 1611 lies near the shelf-edge on the southwest flank of Banquereau in water depths that range from 110 to 120 m (Fig. 2.3). A 5-m-high scarp occurs at a depth of 110 m and is parallel with local isobaths. This scarp is presumed to be wave-cut during a late Pleistocene low-stand of sea level (King, 1970). Bedforms were detected near the scarp (Amos and King, 1984), though their relationship to the scarp remain unclear.

The purpose of this dive was to examine the bedforms near the wave-cut scarp in order to determine their origin, direction of migration and conditions under which they were active.

Seismostratigraphy

A high-resolution, seismic reflection profile and side scan sonogram along the dive site are illustrated respectively in Figures 2.11a and c. The figures show the interpreted stratigraphy at the dive site and the distribution of bedforms (Fig. 2.11b). A major acoustic discontinuity, interpreted as Tertiary bedrock (Amos and Knoll, 1987) occurs approximately 100 m beneath the seabed. It is overlain by a complex acoustic sequence of which only the top 5 m are seen in Figure 2.11a. The seabed at the dive site is underlain by an acoustic unit devoid of coherent reflections. This unit is up to 3 m thick and though to be Holocene sand. It is underlain by an horizon of scattered reflections which reaches the seabed at the wave-cut scarp. This horizon is a lateral equivalent of the Channel Gravel of Amos and Knoll (1987).

Figure 2.11c is a side scan sonogram across the scarp which shows acoustically contrasting bands thought to be moribund 2-D megaripples (Amos and King, 1984). Below 115 m, the seabed is acoustically featureless.

Visual observations

The water column at the dive site was thermally stratified: the water temperature was 4.5°C at the surface and 9.5°C near the bed. The thermocline occurred at a depth of approximately 40 m. A near-bed current was flowing to the northwest at a speed of approximately 0.2 m/s.

The seabed at the point of descent was composed of fine sand devoid of primary sedimentary structures. Bioturbation was abundant; mounds were typically 20 to 30 mm in height. An angular boulder surrounded by a halo of shell debris was encountered at a depth of 130 m (Fig. 2.5d). The halo was elongated to the west. Patches of gravel were seen beneath a veneer of sand at the 120 m isobath. The gravel comprised well-sorted granules which were 10 to 20 mm in diameter and which were composed of a variety of lithologies. The gravel unit was compact, but was only one clast thick and sat on fine-grained sediment. At 110 m, linear,

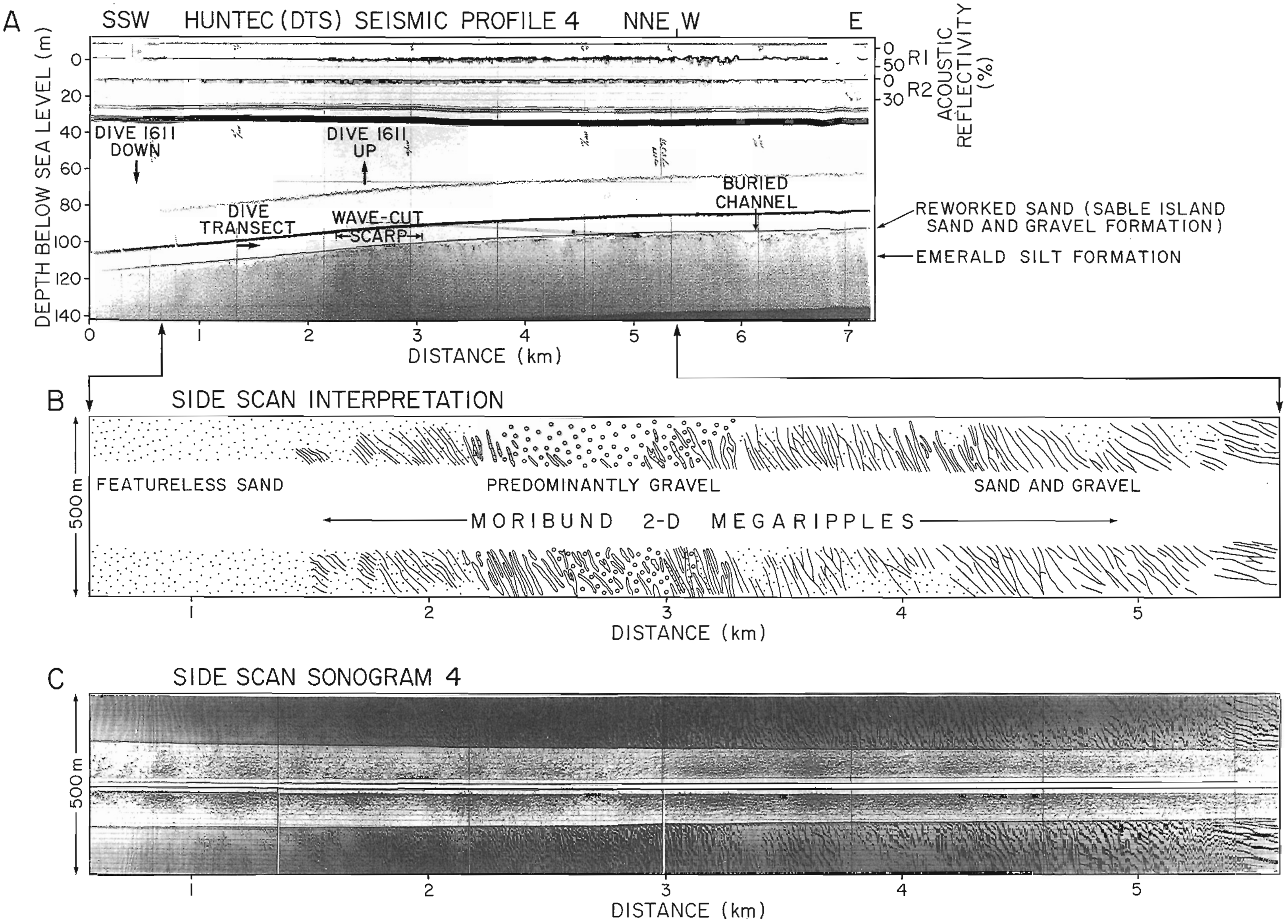


Figure 2.11. A seismic profile along dive transect 1611. The section is oriented SSW to NNE and is on the southwest flank of Banquereau. (A) Huntec (DTS) seismic record illustrating that the seabed is covered by a thin veneer of sand. Underlying material crops out at the wave-cut scarp; (B) and (C) a side scan sonogram of the dive transect and interpretation. The acoustic patterns either side of the scarp are interpreted to signify moribund 2-D megaripples. These features are oriented parallel to the local isobaths.

gravel patches alternated with sand. The axes of the patches were oriented east-west (parallel with the isobaths) and were approximately 20 m wide. As the sand patches barely covered the gravel, little relief was apparent. The boundary between sand and gravel was sharp (Fig. 2.5e) and showed evidence of a small slip-face dipping to the north.

Sediment motion was not observed, nor was the seabed rippled.

Interpretation

The observations correlated with the interpretations of the side scan sonograms illustrated in Figure 2.11b. The bioturbated, featureless sand correlated with acoustically featureless areas. The region of high reflectivity on the Huntec profile (Fig. 2.11a; 2-6 km) corresponded to the region underlain by compacted, well-sorted gravel. This lithology is similar to that of the Channel Gravel and to that observed at a similar depth in dive 1610.

The observed alternations of sand and gravel corresponded with the distribution of moribund 2-D megaripples. The mini-slip face to the north favours bed form migration in that direction which is at right angles to local isobaths and the prevailing flow, and indicates a transport of sand to the top of the bank, that is, in the opposite direction to that proposed by the ''spill-over'' mechanism. However, the well-defined nature of the bedforms suggests that they were formed by modern processes.

There appear to be two possible mechanisms for sediment transport at this site: firstly, the southwestward flowing, contour-parallel currents reported by Hill and Bowen (1983). Scour pits elongated in the direction of this current provide evidence of intermittent sand transport by this process; secondly, currents generated by the propagation of internal waves measured by Sandstrom and Elliott (1984) in this region. Karl et al. (1986), and Heathershaw and Codd (1985) describe shelf-edge sand waves with crests parallel to the local isobaths. They ascribed the pattern of bedforms to the action of internal waves which impinge on the shelf. It is therefore proposed that the 2-D megaripples are generated by this process. The wavelengths of the bedforms and the measured internal waves (20 m and 300 m respectively) differ markedly. This is problematic as previous authors suggest they should be equal.

The Banquereau extension: (dive 1612)

Site description

Dive 1612 was located adjacent to the western flank of Banquereau in the north part of The Gully (Fig. 2.3). The dive was carried out over a finger-like extension of Banquereau (the Banquereau extension). Many similar features exist around the edges of the outer banks of the Scotian Shelf. Quaternary sequences on the Scotian Shelf have been generalized into basin types (King and Fader, 1986) and bank types (Amos and Knoll, 1987). The stratigraphy and sedimentary character of these sequences are different and are considered to interdigitate on the flanks of the banks. The stratigraphy in this ''transition zone'' is not known due to lack of sampling and the degraded nature of seismic profiles on the relatively steep bank margins.

The purpose of this dive was to document the stratigraphy on the western flank of Banquereau extension and to examine the conditions under which the suite of bedforms developed.

Seismostratigraphy

Airgun and Huntec (DTS) seismic reflection profiles through dive site 1612 are shown respectively in Figures 2.12a and b. Also shown is a side scan sonogram of the margin of Banquereau (Fig. 2.12c). The profiles illustrate a high-intensity acoustic reflection underlying Banquereau extension which crops out on its western flank at a depth of 160 m. It is overlain by a unit of incoherent acoustic reflections interpreted by MacLean and King (1971) to be glacial till. The upper surface and eastern flank of Banquereau extension appears to be underlain by an acoustically transparent unit 10 m thick which is interpreted to be reworked sand. The side scan sonogram (Fig. 2.12c) indicates that this sand is reworked into active bedforms on the flank of Banquereau.

Visual observations

Dive 1612 began in 220 m of water on the west side of Banquereau extension. A traverse was made from west to east over the crest of this feature. A near-bed current flowed at a speed of 0.5 m/s to the south. Visibility was low (4-5 m) due to the presence of particulate matter in the water column. The water temperature was 4° C. The seabed at the start of the dive was composed of well-sorted, fine sand that was moulded into southward-migrating ripples. Sand ribbons and comet marks in gravel were seen periodically and were oriented parallel to the prevailing flow. In shallower water (200 m) well-rounded, multimineralic granules and pebbles replaced the sand and were interspersed with scattered, well-rounded boulders. The boulders were associated with gravel comet marks which were in all cases oriented to the south. Immediately beyond the boulders, we encountered an extremely irregular bed that was dominated by large boulders (greater than 1 m in diameter) intercalated with rippled sand. The seabed at this site sloped at approximately 10° and rose in a series of steps. Boulders were covered with biota and showed no evidence of recent motion. At 160 m depth we encountered a well-defined trench cut into the seabed which was approximately 1 m wide and 0.4 m deep.

The generally boulder-strewn character of the seabed prevailed to a depth of 150 m. Above this depth a thin layer of sand covered a substrate of well-sorted gravel on a relatively flat seabed. The current was slower (0.2 m/s) but continued to flow to the south. The crest of Banquereau extension was encountered at a depth of 137 m. It was characterized by well-sorted, wave-formed rippled sand but was devoid of any detectable current. The uppermost part of the eastern flank of Banquereau extension was covered

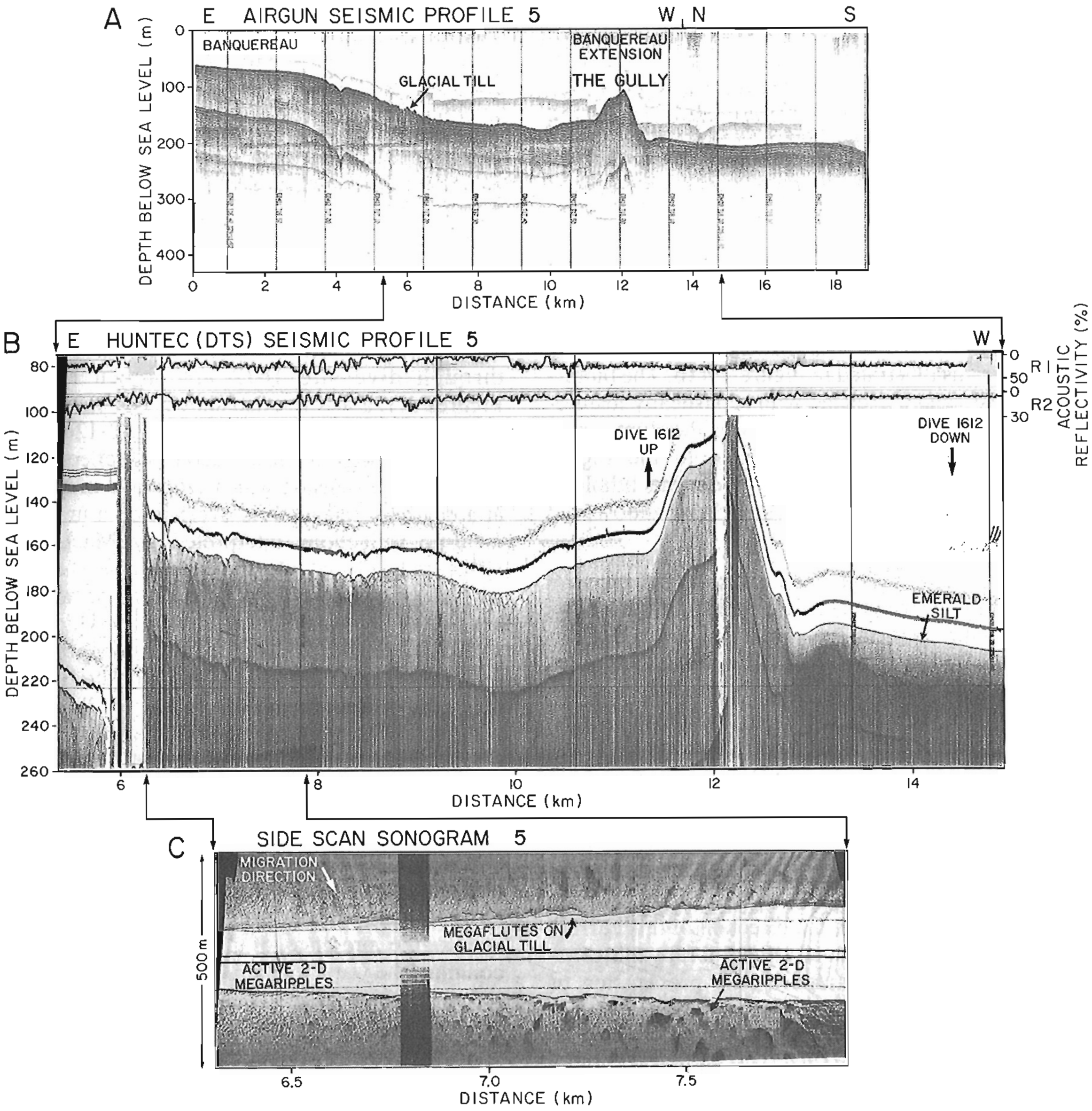


Figure 2.12. A seismic profile along dive transect 1612. The section is oriented east-west and extends from western Banquereau through the Banquereau extension. (A) Airgun seismic profile of the transect. A strong acoustic reflection outcrops on the west flank of Banquereau extension. This is interpreted to be the surface of Tertiary bedrock. MacLean and King (1971) proposed that much of the seabed is underlain by glacial till. Much of this material has been reworked into active bedforms such as those illustrated in (C). These bedforms appear to be 2-D megaripples and megaflutes.

by well-sorted, fine to medium shelly sand moulded into lunate and linguoid ripples. These ripples had slip faces oriented to the east. Between 150 and 160 m, silty-sand predominated; for the first time in the dive, sand was seen moving as a result of the near-bed current. To 170 or 180 m the water temperature increased to 8.1° C. An increase in bioturbation and the appearance of sea anemones occurred at the thermocline. Sediment was clearly seen moving to the south as bed load and scour pits were evident at the bases of sea anemones. The local current was strong (approximately 0.5 m/s) and was associated with an increase in the scale of the bedforms. At the termination of the dive, small, active 2-D megaripples were seen oriented to the south.

Interpretation

The PISCES IV observations correlated only in part with the seismic reflections shown in Figures 2.12a and b. The observed terraces at the base of the west flank are interpreted to be formed by Tertiary strata; however no bedrock was seen. The irregular nature of the seabed and the prevalence of boulders supports the presence of glacial till originally mapped by MacLean and King (1971) though the nature of the strong acoustic reflection beneath the till was not resolved. At the top of Banquereau extension, till had been reworked into clean sand (Fig. 2.12b).

The correlation between bioturbation, sediment texture and the location of the thermocline below 150 m is significant and corresponded with observations of the hydraulic fence made in dives 1609 and 1610. It appears that thermal stratification of the water mass in The Gully is a prevailing phenomenon that has a significant influence on the nature of the seabed. This is best demonstrated by reference to the eastern flank of Banquereau extension. It is covered by a continuous veneer of sand which shows an abrupt increase in bedform size and concomitant biological activity immediately below the thermocline. The colder water mass above is, by contrast, relatively quiescent yet the seabed showed signs of periodic reworking. Ripples appear moribund and are oriented with slip faces to the east; that is in the direction of the prevailing sand transport on Banquereau (Amos and Knoll, 1987). The water-mass below is associated with prevailing conditions of baroclinic shelf circulation. Within this lower water mass, bedforms, where present, are active and well-developed. The progression of bedforms on the eastern flank of Banquereau extension reflect this circulation. The sequence is: small-scale, wave-formed ripples; the hydraulic fence; small-scale current ripples; large-scale current ripples; 2-D megaripples (Fig. 2.12c) and 3-D megaripples. All bedforms on the lower part of this flank show a net transport to the south. In this lower water mass, it is noted that the prevailing sediment transport is parallel to the regional isobaths, in the upper water mass, this was not the case.

SUMMARY AND CONCLUSIONS

This paper attempts to verify previous interpretations of the lithology and dynamics of Quaternary sediments on Sable Island Bank and Banquereau, Scotian Shelf. The six PISCES IV dives, carried out around The Gully, Scotian Shelf, have provided useful visual information on the nature of the Quaternary lithostratigraphy and the transport paths of sand reworked from this sequence. The following are the major findings and conclusions of this study.

1. Large-scale bedforms southwest of Sable Island are confirmed as sand ridges, not sand waves. These ridges show evidence of migration to the east. This direction is opposite to that proposed by Stanley et al. (1972) and indicates that a clockwise circulation of sand around Sable Island does not take place.

2. Specks, areas of high acoustic backscatter first identified by Evans-Hamilton Inc. (1975), are circular to lenticular concentration of disarticulated shell debris. They appear to be formed by current scouring of the seabed.

3. Tertiary bedrock, documented by Marlowe (1969), was verified to outcrop in the flanks of Canyon 48, The Gully. It is lithified and showed evidence of polishing of erosional walls and scouring of the upper surface. The bedrock surface correlates with a regional acoustic discontinuity that can be traced under much of Eastern Sable Island Bank.

4. Glacial till was seen to overlie Tertiary bedrock in Canyon 48 and Banquereau extension. The surface of the till underlying Sable Island Bank has been extensively reworked between depths of 100 and 140 m.

5. No evidence for the process of sand ''spill-over', documented by Stanley et al. (1972), was seen. Instead, sand was found restricted to depths principally above 140 m and below 200 m. The depth range where sand is absent is proposed to be controlled by an ''hydraulic fence''. This ''fence'' is situated at the change in slope at the bank-edge or at the pycnocline and prevents sand from moving off the banks as bed load.

6. The gravel-rich unit which separates Pleistocene and reworked younger sediments (Amos and Knoll, 1987) was seen to outcrop at a wave-cut scarp on Banquereau. It was also seen on the north flank of Sable Island Bank where it outcropped at a depth of 120 m. This unit correlated with a strong acoustic reflection that can be traced under much of Sable Island Bank at depths beneath the seabed typically less than 40 m.

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Submersible observations of iceberg furrows and sand ridges, Grand Banks of Newfoundland

G.B.J. Fader[1]

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Abstract

Iceberg furrows and sand ridges at the seabed on the Grand Banks of Newfoundland have been studied to better understand processes which modify surficial Quaternary sediments. Observations were made from the submersible PISCES IV. Iceberg furrows and pits, exhibiting relief of up to 12.5 m, cover the seabed of the Avalon Channel and appear to be relict and coeval. They are developed within glacial till of the Grand Banks Drift formation. Postglacial ice-rafting appears to play a minor role as a sedimentation mechanism. The troughs of the iceberg furrows consist of well-sorted, pebble- to cobble-sized, angular clasts, in contrast to the flanking berms which are composed entirely of boulders.

Sand ridges of the Grand Banks Sand and Gravel formation occur across most of the surface of Grand Bank. Complex, broad sinuous areas of megarippled coarse sand and fine gravel are incised and eroding into the ridge surfaces. The ridges overlie a basal gravel lag deposit which outcrops in the troughs of the sand ridges. This gravel consists of pebble- to large boulder-sized material, most of which is subrounded to rounded. The distribution and shape of the gravel within the ridge troughs implies that the gravel originated principally through the action of glaciers that extended across the entire Grand Banks of Newfoundland and not through ice-rafting.

Resumé

On a étudié les sillons creusés par les icebergs et les crêtes de sable présents sur le fond marin des Grands bancs de Terre-Neuve, pour mieux comprendre les processus modifiant les sédiments quaternaires de surface. Ona réalisé les observations à partir du submersible Pisces IV. Les sillons et cavités creusés par les icebergs, qui montrent un relief de 12,5 mètres au maximum, recouvrent le fond marin du chenal d'Avalon, et semblent être des structures reliques et contemporaines les unes des autres. Elles se sont formées à l'intérieur du till de la formation morainique des Grands bancs. Il semble que la dérive des glaces pendant la période post-glaciaire ait joué un rôle mineur du point de vus des mécanismes de sédimentation. Le fond des sillons creusés par les icebergs se compose de clastes angulaires, bien triés, de dimensions comprises entre celles de cailloux et de galets, contrairement aux gradins latéraux qui sont entièrement composés de gros blocs.

Dans la formation sablo-graveleuse des Grands bancs, les crêtes de sable traversent la majeure partie de la surface de ces derniers. Dans la surface des crêtes, ont été incisés de vastes secteurs complexes couverts de grandes rides de sable grossier et de gravier fin, que l'érosion continue à creuser à la surface des crêtes. Les crêtes recouvrent un pavage de gravier basal qui affleure dans les dépressions traversant les crêtes de sable. Ce gravier se compose de matériaux de dimensions comprises entres celles de cailloux et de gros blocs, dont la plupart sont subarrondis à arrondis. La distribution et la configuration des graviers à l'intérieur de ces dépressions suggèrent qu'initialement, l'existence de ces graviers a été due à l'action des glaciers qui s'étendaient sur l'ensemble des Grands bancs de Terre-Neuve, et non à leur dépôt pendant la dérive des glaces qui les transportaient.

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INTRODUCTION

A two-week submersible investigation was undertaken with the PISCES IV submersible as part of a larger program to study the regional surficial and shallow bedrock geology of the Grand Banks of Newfoundland. The objectives of the PISCES IV submersible investigation were to ground truth interpretations previously made on the basis of geophysical data.

The program objectives were: (1) to determine the maximum extension of the last (Wisconsinan) and earlier glaciations across the Grand Banks of Newfoundland and the characteristics of the sediments deposited by the glaciers; (2) to map the distribution, morphology and characteristics of sand ridges, sand waves, sand ribbons, and sand ripples; (3) to determine the late-glacial sea level history of the area; (4) to map the regional distribution of relict and modern iceberg furrows and to deduce their relationship to seabed materials; and (5) to understand and delineate the Holocene transgression history of the Grand Banks by seeking evidence for subaerial channelling, the formation of terraces, the presence of unconformities, and the nature of overconsolidated and desiccated sediment.

Dives were undertaken in an iceberg-furrowed area of Avalon Channel and in a sand ridge field of the central area of Grand Bank (Fig. 3.1). High resolution sidescan sonograms were collected from the M.V. PANDORA II across shell beds on Southeast Shoal, iceberg furrows and pits, a glory hole (a man-made depression at the seabed to protect seabed facilities from damage) and sedimentary bedforms in the Hibernia region of northeast Grand Bank. Submersible dives were prevented in the Hibernia region and on Southeast Shoal by poor weather conditions.

The following is a description of the geological setting of the two dive locations, the observations made from the PISCES IV submersible, and a discussion and interpretation of the observations.

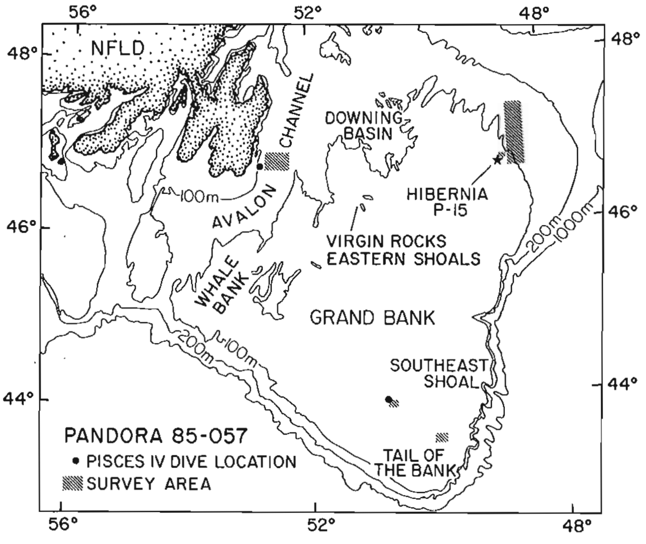

Figure 3.1. Index for the study area showing the locations of the PISCES IV dive sites and the geophysical surveys conducted from the M.V. PANDORA II.

Acknowledgments

I thank the Captain, Officers and crew of M.V. PANDORA II and Chief Pilot Frank Chambers and pilots of the PISCES IV submersible. T. Lambert of the Atlantic Oceanographic Laboratory, P. Hale of Mineral Policy Sector and R. Parrott provided valuable observations and discussions. Field technical support was provided by W.A. Boyce and R.O. Miller assisted in the laboratory analysis. The manuscript was reviewed and improved by C.L. Amos and C.F.M. Lewis who provided helpful suggestions.

AVALON CHANNEL ICE SCOUR

Regional setting

"Super furrow" is a large iceberg furrow developed in till (Grand Banks Drift; Fader and Miller, 1986). The feature is known from an interpretation of geophysical profiles (Fig. 3.2) to be over 500 m wide, and 12.5 m deep; it extends for at least 3 km along the Avalon Channel oriented subparallel to the bathymetry in 200 m water depth. The seabed surrounding "super furrow" (Fig. 3.3) has been completely ice-scoured and iceberg furrows and pits are common.

The iceberg that formed "super furrow" appears to have eroded through the overlying till to the bedrock surface, a broad regional unconformity on Cambrian-Devonian fine-grained siltstones and mudstones (King and Fader, 1976; King et al., 1986). The ice-scoured surficial sediments in the Avalon Channel are mainly till, less than 3 m in thickness with occasional thicknesses up to 15 m. To the southeast of the "super furrow" site, the till is interbedded with glaciomarine sediments in the form of till tongues (King and Fader, 1986).

The region of iceberg furrows covers the entire Avalon Channel area and broadens to the north to include the inner Grand Banks of Newfoundland. The location of this dive was chosen to establish a type area for iceberg scouring of till for the Grand Banks of Newfoundland.

Submersible program

The objectives of the program to study "super furrow" were: (1) to accurately measure the height of the berms and the slopes of the inner and outer furrow surfaces to compare with measurements from geophysical data; (2) to sample the seabed materials in the trough, berms and adjacent seabed; (3) to observe cross-cutting relationships with adjacent furrows to determine relative ages; (4) to observe textural characteristics of till; (5) to determine roughness (morphology) of the furrow trough; (6) to assess the degree of post-formational current winnowing; (7) to observe benthic communities at the seabed; and (8) to compare observations with conventional bottom photographs and sediment samples previously obtained in the area.

Observations

Dive 1635 began to the south of "super furrow" on a northwest heading intended to cross the large scour feature. The initial part of the seabed transect was in an area adjacent to

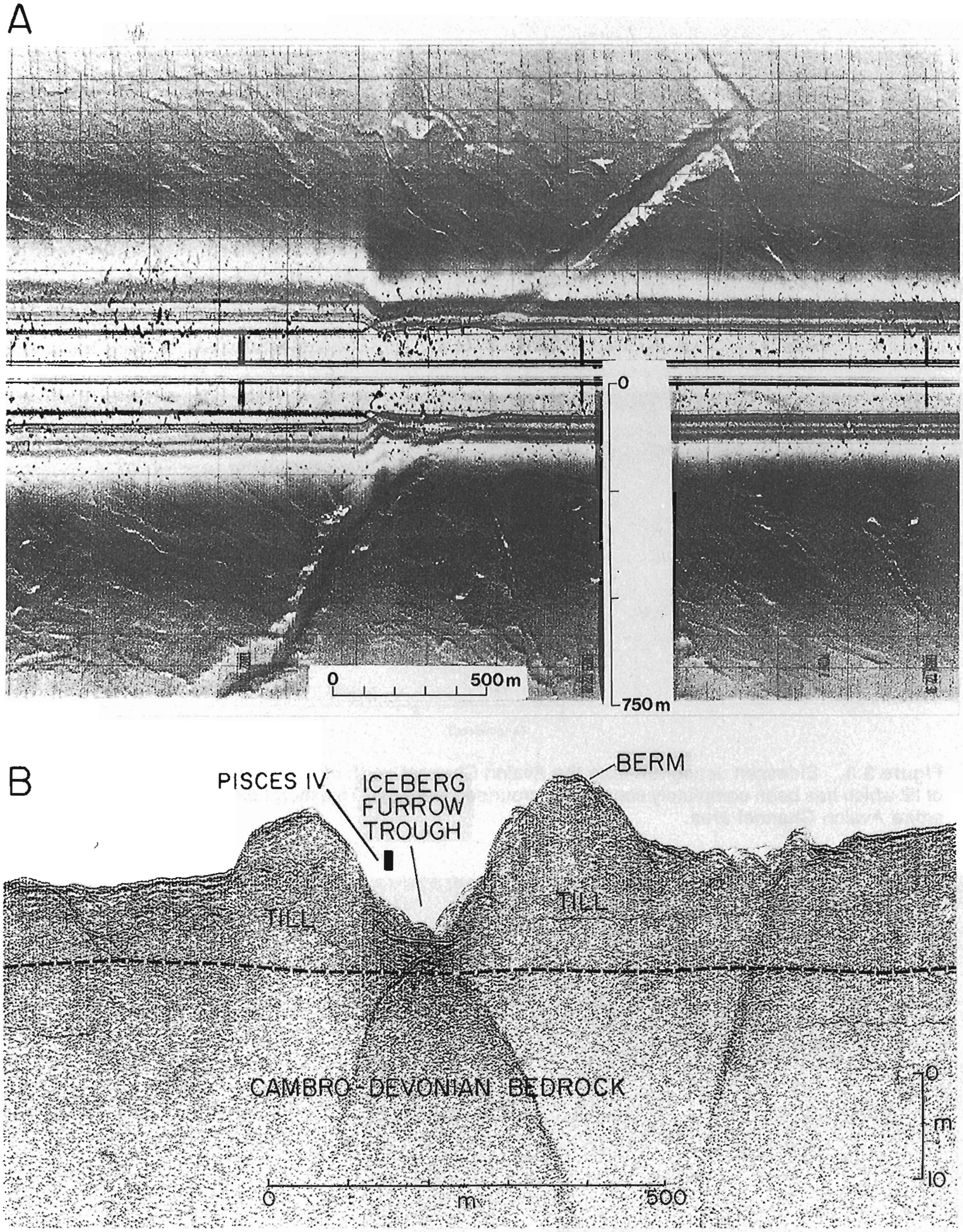

Figure 3.2. Sidescan sonogram and Huntec DTS profile across "super furrow" Avalon Channel. This iceberg furrow is the largest on the Grand Banks of Newfoundland. The berms consist of large boulders some of which are 5 m in diameter whereas the trough is flat and composed of small angular cobble-sized clasts. (Sonogram courtesy of C.F.M. Lewis).

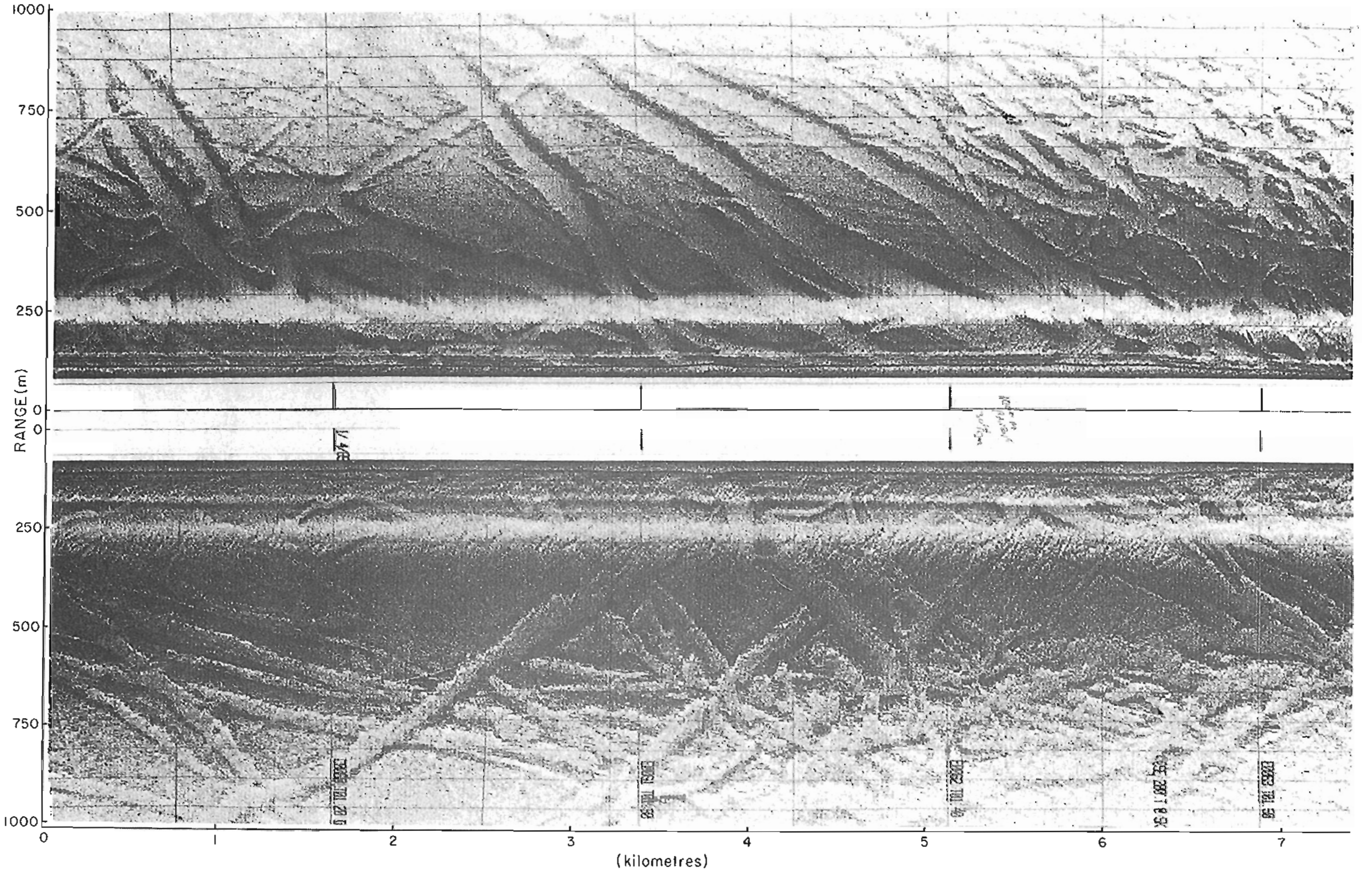

Figure 3.3. Sidescan sonogram from the Avalon Channel north of "super furrow" showing a seabed of till which has been completely scoured by grounded icebergs. This morphology is characteristic of the entire Avalon Channel area.

Figure 3.4. Bottom photograph collected from the PISCES IV submersible showing boulders in the berm of "super furrow".

''super furrow'' where smaller iceberg furrows occur up to 3 m in depth. The berms (linear ridges flanking the central furrow depression) consistently were composed of boulders (Fig. 3.4) and the troughs or central furrow depressions were generally flat, cobbled surfaces of angular uniformly-sized fragments. One of the most conspicuous aspects of the troughs of the furrows was the lack of apparently ice-rafted boulders or large clasts.

''Super furrow'' was located on the sonar of the PISCES IV submersible and appeared as a very large linear feature. The morphology of the seabed within the trough of ''super furrow'' was similar to the troughs of other adjacent small furrows. It was generally flat with relief in the trough varying by only 3 m. Boulders, 5 m in diameter (Fig. 3.4) were seen at the base of the inside edge of the berm. These were the largest boulders encountered in all of the berms observed during the dive outside of ''super furrow''. The boulders decreased in size to 1-2 m toward the top of the berm. The inside wall was very steep, in places up to 40°. Several small terraced areas were encountered where the slope decreased to 20°. Most boulders in the berm were dark in colour making observations of composition difficult. The height of the berm (as measured from the base of the trough to the berm top) was 12.5 m.

Interpretation and discussion

The distribution of boulders, which appear confined to the berm areas of the iceberg furrows, and of the boulder-free uniformly-sized, pebble-cobble areas of the iceberg furrow troughs suggests that ice-rafting is not important as a significant sediment transport process in this area of the Grand Banks. Similar interpretations have been proposed for areas of the shelf off Trinity and Conception Bay investigated with the PISCES IV submersible in 1981 (Syvitski et al., 1982).

From a study of sidescan sonograms, cross-cutting among iceberg furrows is clearly evident (Fig. 3.3). These relationships provide relative ages for individual furrows. However, no morphological, textural or other evidence was found during the submersible investigations to identify different ages for the iceberg furrows. This suggests that they are all of one population representing one scouring episode. Josenhans (1985) has documented modern and relict iceberg scour features in similar sediments from the Labrador Shelf. The characteristics of modern furrows, such as sediment molding, extrusion, fracturing and the presence of silt, clay and sand sized matrix were not observed across the Avalon Channel study area and support a relict interpretation. The larger size of the sponges on the boulders of the furrow berms of ''super furrow'' may indicate an older relative age, but this could also be explained by preferential growth due to local oceanographic conditions associated with such a large morphologic feature.

Most bottom photographs of the ice scoured till of the Avalon Channel previously collected with ship-deployed systems depicted the seafloor of the area as consisting of angular, well-sorted, cobble-pebble sized material free of sand, silt and clay matrix (Fig. 3.5). It was difficult to explain the consistent size of the angular material seen in the photographs, as the area is well below the 100-m, late glacial interpreted low sea level stand (Fader and King, 1981) and a mechanism for such a high degree of sorting was not readily apparent. The submersible transect provided an explanation for the sorting. The troughs of the iceberg furrows consisted of well-sorted, cobble-sized, angular fragments while the adjacent berms were piles of large boulders. In addition, the trough areas occupied the largest amount of seabed, up to 80%. It would appear that through the mechanism of iceberg furrowing, boulders are pushed aside to form the berms or into the substrate. The uniform seafloor of the iceberg trough might result from a process of sediment sorting, or possibly by crushing of boulders to cobble and pebble size.

Figure 3.5. Ship deployed bottom photograph in the Avalon Channel collected on HUDSON cruise 77-011. The angular, well-sorted, cobble-pebble seabed as seen in this photograph is typical of most ship-deployed bottom camera stations in the area. These textural consistencies are now known to represent the troughs of iceberg furrows which cover over 80% of the seabed in furrowed terrains.

SAND RIDGES, GRAND BANK

Regional setting

Perhaps the most dominant characteristic of the surficial sediment distribution across the eastern Grand Banks of Newfoundland is a sand ridge field which covers most of the seabed on Grand Bank. Sand ridges range in height to a maximum of 12 m, the average being 5 m, and have wavelengths of over 4 km (Fader and Miller, 1986). They appear to be developed across lag gravel pavements (Fig. 3.6) largely developed on the surface of Tertiary bedrock across most of the eastern Grand Banks. The sand ridges occur as solitary features, as isolated features grouped in fields, or as coalesced features in which it is difficult to determine where one sand ridge ends and another begins (Fig. 3.7).

The surfaces of the sand ridges as defined on high resolution seismic reflection and sidescan sonar data show zones of complex sinuous depressions up to 3 m deep (Fig. 3.6). Within these depressions, megaripples with heights of 0.5 to 1 m and wavelengths up to 3 m occur. In some areas, two and three different direction patterns of megaripples can be seen superimposed on a primary set.

Submersible program

A typical sand ridge area was chosen from geophysical data to the west of Southeast Shoal in 60 m water depth where the sand ridges ranged in height from 10-12 m. The objectives of the submersible program were: (1) to transect a sand ridge from the trough to the crest along a line of previously collected high resolution seismic reflection and sidescan

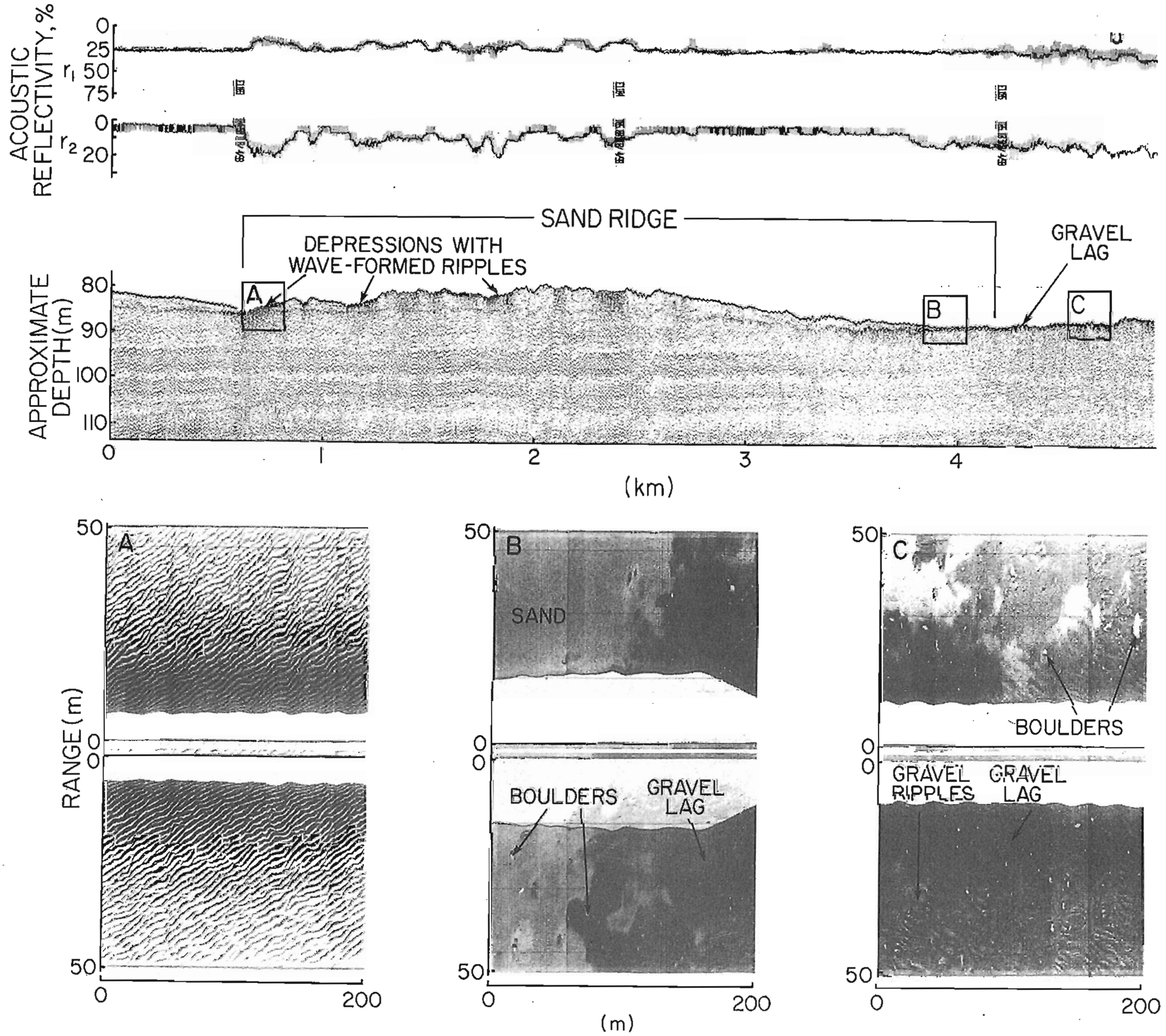

Figure 3.6. Huntec DTS profile and sidescan sonogram across the sand ridge investigated with the PISCES IV submersible. The upper surface of the sand ridge is incised with zones of wave-formed ripples. The trough areas of the sand ridges are gravel lag deposits with boulders and ripples formed on gravel.

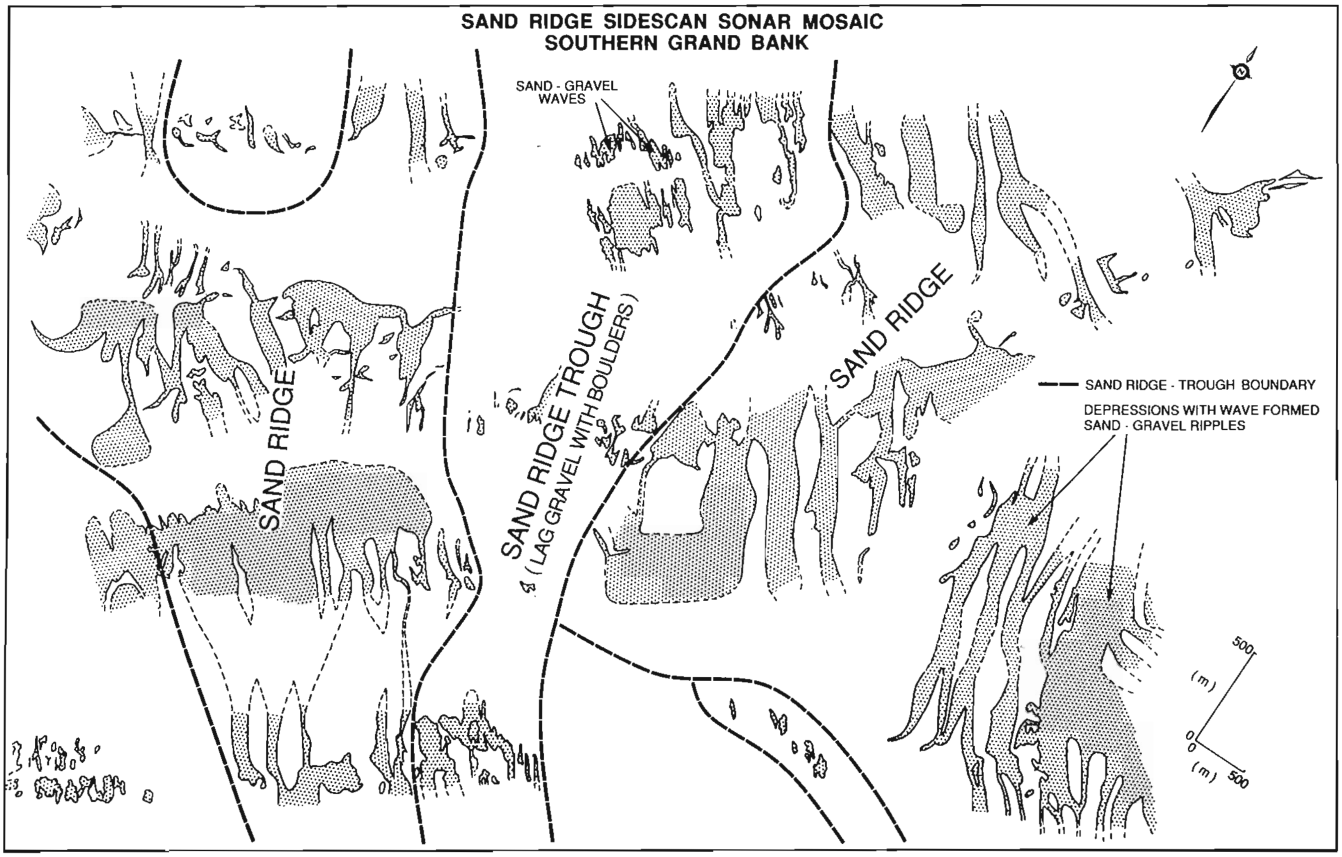

Figure 3.7. Sidescan sonar mosaic of the area investigated with the PISCES IV submersible. The orientation of the sand ridges could not be determined because of their large size.

data; (2) to determine the nature and morphology of gravel lag and possible Tertiary bedrock outcropping in the sand ridge trough area; (3) to collect samples of gravel in the trough for lithologic provenance studies; (4) to observe and sample entrenched rippled areas near the crests of the sand ridges; and (5) to sample and observe other flat featureless surfaces of sand ridges.

Observations

Three dives were completed across the sand ridge area (dives 1632, 1633, and 1634). The surface of the sand ridge is a flat featureless seabed of fine-medium sand (Fig. 3.8). Shells and shell fragments were randomly distributed across the seabed. Small current ripples were not observed on the ridge surface, however, the surface appeared dimpled by 5-10 cm depressions. Large incised rippled areas of the ridges were defined by abrupt, straight escarpments which descended 2-3 m to the rippled surface. These ripples consisted of straight, symmetric, sharp-crested bedforms with amplitudes of 0.5-1 m and wavelengths of 2-3 m (Fig. 3.9). The sand-size sediment in the rippled areas is coarser than the sand outside the incised areas and the troughs of the bedforms contain fine gravel and broken shell debris.

In the trough areas between sand ridges, the seabed consisted of boulder-strewn gravel lag with areas of gravel ripples, small sand patches, and broken shell debris (Fig. 3.10). The gravel was poorly sorted and consisted of a wide variety of sizes. The largest boulders were up to 4 m in diameter and generally subrounded in shape although some were angular. They were heavily covered with a dense marine growth that prevented lithologic description. Several of the boulders had recently been dragged across the seabed, possibly by fishing trawlers, as evidenced by 1 m wide × 0.5 m deep furrows leading up to the boulders and the destruction or absence of marine growth on some of them. Many large boulders were observed only slightly protruding from the seabed. These would not be easily identified on sidescan sonograms. No areas of outcropping Tertiary bedrock were identified within the sand ridge troughs.

During the dives in the sand ridge trough areas, large patches (up to 4 m^2) of white filamentous material were seen around the boulders and covering sandy patches at the seabed (Fig. 3.11). The term "white slime" has been proposed for these types of deposits (Bright and Rezak, 1977) and have been identified as bacterial mats. They may be feeding on hydrocarbon gases seeping from the subsurface bedrock. The airgun seismic reflection profiles in the subsurface show acoustic anomalies at approximately 300 m depth that may represent gas charged sediments (bright spots) (Fader and Miller, 1986).

Interpretation and discussion

The incised channel-like depressions on the surfaces of the sand ridges containing large ripples are similar to features

Figure 3.8. Bottom photograph of the surface of a sand ridge from PISCES IV. The sediment is medium-fine, well-sorted sand with fine gravel and shell debris: note the absence of ripples. The only surface relief was a slight 5 cm dimpling of the seabed, which is attributed to biological activity.

Figure 3.9. Bottom photograph of ripples in a large incised depression on the surface of a sand ridge. The features are 0.5 m in height and have wavelengths up to 3 m. The sidescan sonogram (Fig. 3.6) is collected from this area of ripples.

reported by Cacchione et al. (1984) for the continental shelf off California. They interpreted the channel-like depressions to form under storm-generated bottom currents associated with coastal downwelling, and the straight-crested ripples to form by large-amplitude, long-period surface waves generated by winter storms. Samples and submersible observations of the rippled areas from the Grand Banks, indicate that they are composed of both gravel and sand-sized material and are coarser than the sand outside the incised areas. These textural and morphological characteristics suggest that the rippled areas represent residual coarse sediments which resulted from erosion and winnowing of parts of the sand ridges.

Within the troughs of the sand ridges, the sediments consist of lag gravels of pebble-cobble sized clasts, boulders and rippled areas of fine gravel. The boulders range to 4 m in size and most are subrounded to rounded in shape with the smaller boulders sometimes being well-rounded. Near the contact between the sand ridge and the trough gravel lag (Fig. 3.6b), large boulders protrude through the sand of the ridge edge. Surrounding the boulders, scour depressions are common and can extend in diameter to over five times the size of the boulders they surround. These scour depressions attest to the occurrence of strong currents which erode the sand.

The dominant rounded to subrounded shape of the boulders and cobbles within the troughs provide evidence for an interpretation of the late-glacial to postglacial sea level history and the extent of glaciers across the Grand Banks of Newfoundland. Regional studies of the adjacent Scotian Shelf (King and Fader, 1986) and the northern Grand Banks (Fader and King, 1981; Fader et al., 1985; Fader and Miller, 1986) provide a wide variety of geological evidence to support a late Pleistocene low sea level stand of 100-110 m. The rounded shape of the boulders in the sand ridge troughs and an absence of silt- and clay-sized sediment sug-

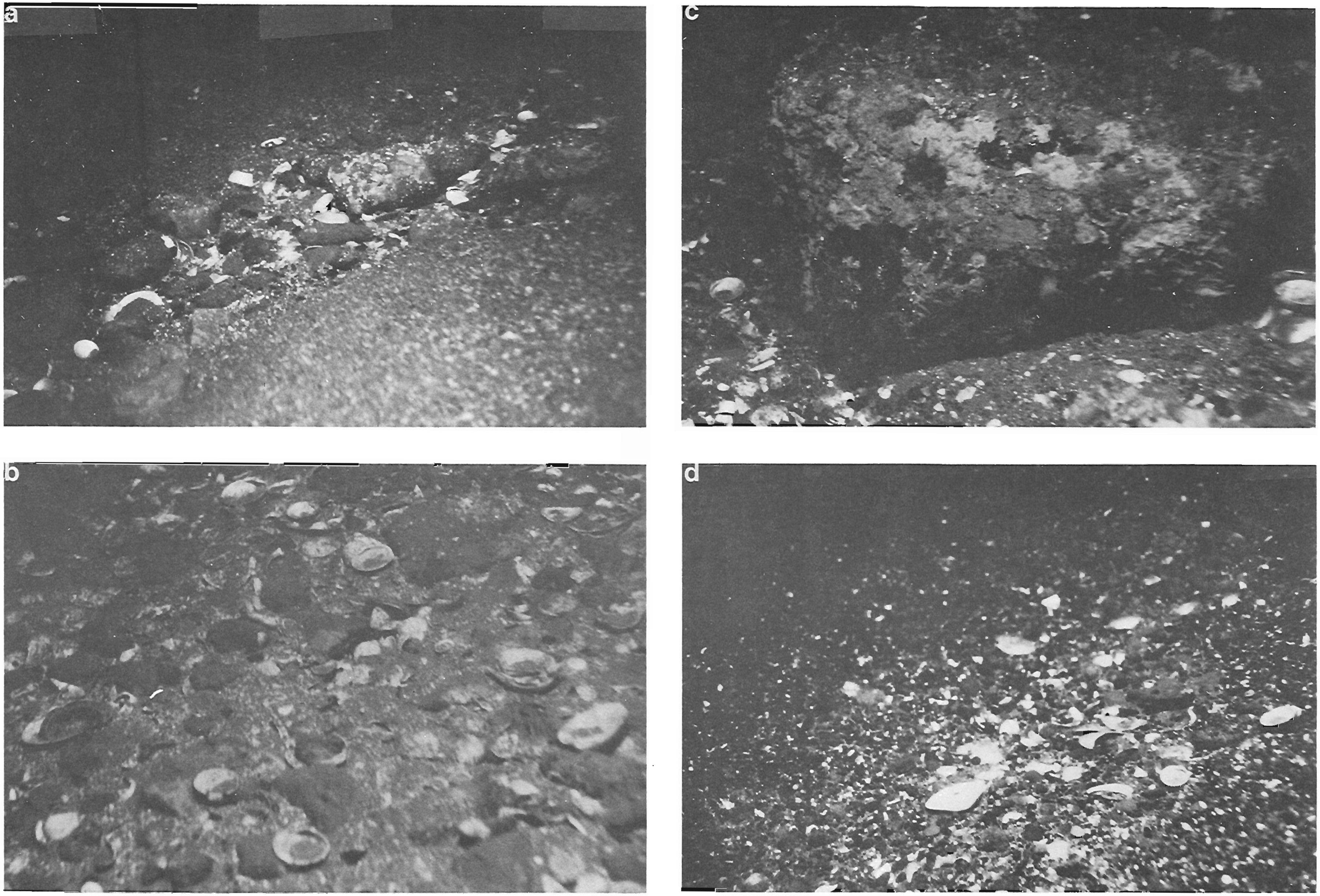

Figure 3.10. Composite of bottom photographs from PISCES IV in a trough between sand ridges: (a) a seabed of gravel, boulders, and sand patches; (b) a gravel/cobble lag with shell debris; (c) a large boulder at the seabed; (d) a small gravel ripple composed of fine gravel and shell debris.

Figure 3.11. Bottom photograph from PISCES IV showing a large patch of "white slime" at the seabed. The "white slime" is a filamentous mat of bacteria interpreted as occurring at the seabed in areas of venting hydrocarbons. This would suggest that the source of the hydrocarbon is the Tertiary bedrock in the subsurface.

gest that the area has been eroded by passage through a transgressing beach zone. This indicates that the boulders were present on the shelf before the last transgression, and were not deposited by Holocene and recent icebergs floating across the area. Fader and Miller (1986) studied the lithology of clasts obtained from the trough areas of the sand ridges at the dive locations and concluded that Cambrian-Devonian sediments of the inner shelf were the source. This suggests that glaciers extended across the southeastern part of the Grand Banks and provided the transport mechanism for the numerous boulders and cobbles found beneath the sand ridge field. The shallow underlying Tertiary bedrock, which regionally consists of mudstones, sandstones and siltstones, could not have provided a source for the large amount of gravel which occurs beneath the sand ridge field.

Sidescan sonar study

Sidescan sonograms were collected in a number of other areas while poor weather conditions prevented the use of the submersible. Acoustic anomalies interpreted as "shell beds" in the Southeast Shoal area of Grand Bank were investigated (Fig. 3.12). The patches exist in a wide variety of circular-lenticular zones of high acoustic scatter. Similar features (specks) have been identified from the Scotian Shelf (Evans-Hamilton Inc., 1975).

Several high quality sidescan sonar surveys were conducted around a large iceberg pit, 100 m in diameter located at 46°43.36'N and 48°37.74'W near the Mara M-54 wellsite on northeast Grand Bank. Figure 3.13 is the sidescan sonogram from the seabed over the feature together with an interpretation. Sidescan data was also collected at the Hibernia B-08 wellsite where a glory hole was dredged at the seabed. The feature is clearly shown on the sidescan sonogram and has not been obliterated by infill since its creation in 1980. The location of a reported sunken ship (Canadian Hydrographic Service, chart L/C 8014) was surveyed at 46°42'N, 48°45'W, but no ship was located. Instead, a bedform termed "W" (Fader and Miller, 1986) which consists of gravel ripples surrounded by a W-shaped sand body was mapped at the plotted location for the ship.

CONCLUSIONS

In the ice furrowed area of the Avalon Channel: (1) all of the iceberg furrows appear to be of the same population, i.e. no differences in relative age were observed; (2) the geophysical profiles previously collected characterized accurately the furrow dimensions as measured from the submersible; (3) ice rafting as a mechanism for sedimentation plays a minor role in this area of the Grand Banks; (4) post-formational winnowing has removed most of the sand, silt and clay-sized sediment from the furrowed seabed; and (5) boulders are confined to the furrow berms and the troughs consist of well-sorted, pebble-cobble sized angular clasts.

In the sand ridge area of south-central Grand Bank: (1) sand ridges overlie gravel lags; (2) with the exception of the incised rippled areas, the surfaces of the sand ridges are flat and featureless, composed of fine sand; (3) incised rippled areas occur on the upper surfaces of the sand ridges and consist of medium-coarse sand with gravel and shell debris; (4) boulders are common in the sand ridge trough areas; (5) most boulders are subrounded to rounded in shape suggesting that they were deposited before the late Pleistocene-Holocene transgression of the Grand Banks and not from post transgressional icebergs. This supports the theory that large glaciers covered the Grand Banks area and transported large clasts from the inner shelf area; and (6) bacteria mats are common in the sand ridge trough areas and may be associated with venting hydrocarbon gases originating in the subsurface bedrock of the southern area of Grand Bank.

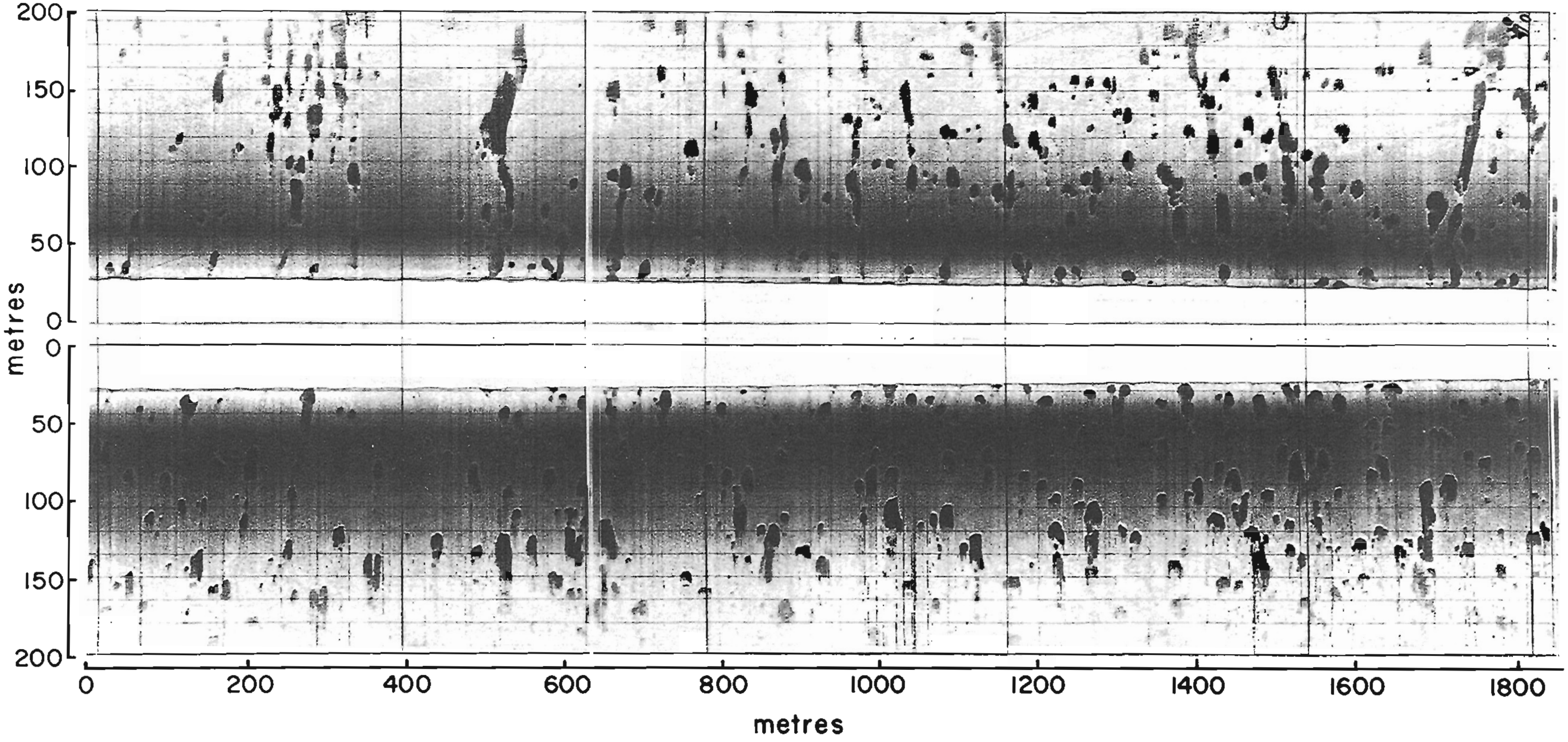

Figure 3.12. Sidescan sonogram of interpreted shell beds at the seabed on Southeast Shoal. The shell beds appear as circular to linear, dark, highly reflective acoustic anomalies across a flat sand seabed. Epibenthic sled tows across this area collected large quantities of dead and broken shellfish as well as sea cucumbers.

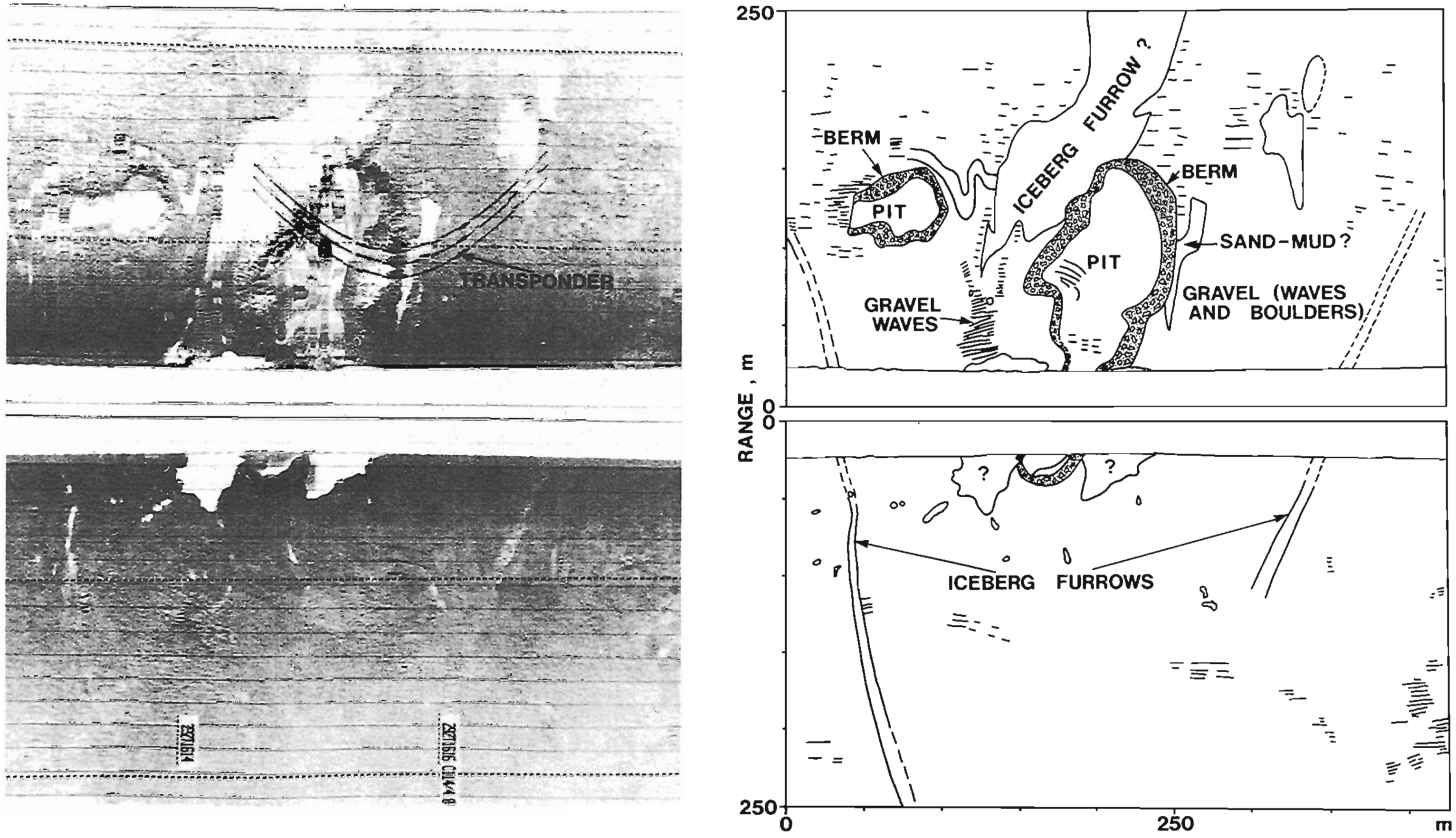

Figure 3.13. Sidescan sonogram and interpretation of a large iceberg pit and the surrounding seabed near the Hibernia region of northeast Grand Bank. The iceberg pit is interpreted as forming through a combination of vertical loading associated with iceberg roll and increased iceberg draught, and of horizontal loading due to current or wave-induced forces causing passive seabed failure (Barrie et al., 1986).

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Submersible observations on the Labrador Shelf, Hudson Strait and Baffin Shelf

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Josenhans, H.W. and Barrie, J.V., Submersible observations on the Labrador Shelf and Hudson Strait; in Submersible observations off the East Coast of Canada, D.J.W. Piper, editor; Geological Survey of Canada Paper 88-20, p. 41-56, 1989.

Abstract

Observations were made from 19 submersible dives on the Labrador and southern Baffin Shelves. The dives document three newly formed iceberg scour marks in different sediment types and allow for interpretations of scour mark formation. One of these scour marks was investigated only 10 days after the grounded iceberg drifted off the impact site. Rates of seabed change over time are estimated by documenting features of known age: a cable trench one year after it was ploughed, an iceberg scour mark 10 days after formation and another iceberg scour mark six years after its formation. The rate of iceberg scour mark erosion is estimated at one locality where the six year old scour had been crosscut by another scour, which, based on the lack of biogenic colonization and fresh appearance is believed to have formed within weeks of our inspection. One metre of berm erosion in six years was measured. All dives on the shelf areas indicate frequent and substantial reworking by the iceberg scouring process and subsequent rapid erosion by a combination of biogenic reworking and removal of the fine sediments by local bottom currents. Evidence on the bank tops in water depth less than 150 m indicates a dominatley erosional setting.

One dive completed at the upper slope of the central Labrador Shelf between a depth of 1000 and 650 m indicated modern mass wasting and a recently formed debris flow. Some of the slope failure was triggered by ice-rafted debris. A dive off Hudson Strait between 1000 and 750 m (below the maximum depth of iceberg scouring) indicated furrowing and raking of the seabed in a contour parallel direction by some mechanism which is not understood at this time.

Resumé

On a réalisé des observations durant 19 plongées d'un submersible au-dessus des plateaux continentaux du Labrador et du sud de la terre de Baffin. Ces plongées ont permis d'établir l'existence de traces d'affouillement nouvellement formées par des icebergs dans divers types de sédiments; on peut aussi interpréter la formation de ces marques d'affouillement. On a étudié l'une d'entre elles 10 jours seulement après que l'iceberg échoué eut dérivé au large du site d'impact. On a estimé les vitesses de modification du fond marin en tenant compte des structures que l'on peut dater: le sillon d'un câble installé depuis un an, une marque d'affouillement formée par un iceberg 10 jours auparavant, et une autre trace de ce type, formée 6 ans auparavant. On a estimé la vitesse d'érosion des marques d'affouillement par les icebergs en un lieu où la marque d'affouillement âgée de 6 ans avait été recoupée par une autre (dont on estime qu'elle s'est formée quelques semaines après notre inspection), d'après son absence de colonisation par des organismes et la fraîcheur de son aspect. On a évalué par des mesures que l'érosion des

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gradins était d'un mètre en 6 ans. Toutes les plongées effectuées sur les zones des plates-formes indiquent que le substrat est fréquemment et substantiellement remanié d'abord par l'affouillement qu'exercent les icebergs, ensuite par l'érosion rapide que causent simultanément le travail des organismes marins et l'entraînement des sédiments fins par les courants de fond locaux. Les détails notés au sommet des bancs, dans une profondeur d'eau inférieure à 150 m, indiquent que le milieu est soumis en grande partie à l'érosion.

Une plongée effectuée à la partie supérieure du talus du plateau continental central du Labrador, entre 1000 et 650 mètres de profondeur, a indiqué qu'un mouvement en masse était survenu à l'époque moderne, et qu'une coulée de débris s'était récemment formée. En partie, l'effondrement du talus a été provoqué par la chute de débris que transportaient les glaces. Une plongée effectuée au large du détroit d'Hudson entre 1000 et 750 m (au-dessous de la profondeur maximum d'affouillement par les icebergs) a indiqué que le fond marin était traversé par des sillons et cannelures suivant une direction parallèle aux contours, suivant un mécanisme que l'on ne comprend pas encore.

INTRODUCTION

Objectives

The objective of the 19 submersible studies on the Labrador Shelf, Hudson Strait and southern Baffin Shelf (Fig. 4.1) was primarily to provide visual observations and detailed samples in areas that had been previously investigated by acoustic methods such as sidescan sonar and high resolution seismic reflection systems (Huntec DTS boomer). The main scientific problems concerned the mechanisms of iceberg scour mark formation; determining the rate of scour destruction by sedimentary and erosive processes; documenting seabed dynamics on the bank tops of the shelf and investigating the processes operating at the shelf edge in 1000-m water depth.

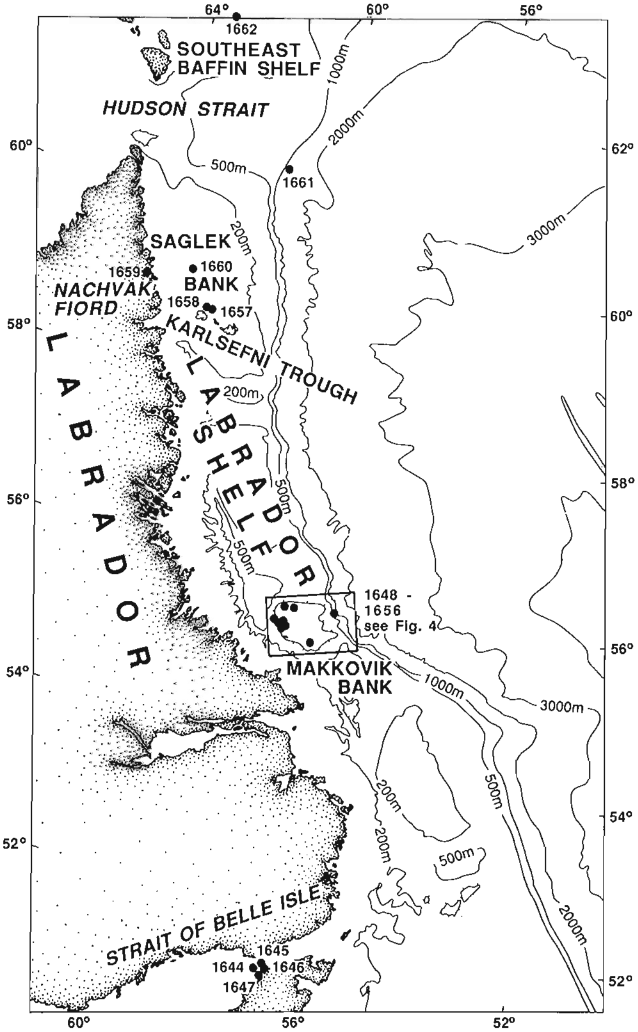


Figure 4.1 Location of dives on the Labrador Shelf and adjacent areas.

Methods

Acoustic equipment deployed from the M/V PANDORA II in support of the PISCES IV dive program included 100 khz sidescan, 12 khz echo sounder and a Huntec surface towed boomer. Navigation on Makkovik Bank was by Syledis short baseline system giving an accuracy within ± 5 m. Navigation farther north was entirely based on satellite navigation and frequently had errors in excess of 300 m. Seafloor sampling was done by Leheigh corer deployed from PANDORA II and by the manipulator arm of the submersible. In all cases PISCES dives were made in areas which had previously been surveyed with sidescan sonar. In some cases this sidescan data consisted of 50 khz or 75 khz and our experience on this cruise has shown that only the 100 khz systems have sufficient resolution for optimum comparison with the direct visual observations. This was most clearly shown by the dives where only SeaMARC I 30 khz mosaics were available; there visual observations could not be directly related to what was seen on the mosaics.

Acknowledgments

We thank the officers and crew of the submersible tender M.V. PANDORA, and particularly the diving team for getting us to our targets. We thank Chris Woodworth-Lynas for helpful discussions and participation in many of the dives. The paper was reviewed by G.B. Fader and D.J.W. Piper.

STRAIT OF BELLE ISLE (dives 1644-1647)

These dives were intended to visually inspect a 60-cm-deep cable trench, which had been ploughed one year earlier, in order to assess rates of sediment transport and seabed change. Dives 1644 and 1646 succeeded in locating and following the trench (Fig. 4.2); the trench had little relief but could be clearly recognized by the lack of biogenic cover on the overturned pebbles and boulders (Fig. 4.3). The only benthic life colonizing these overturned fragments were basket stars, brittle stars and occasional barnacles. These observations have helped to determine the rate of biogenic colonization within these environments and allow us to use the amount of colonization as a guide to determining the age of other trenches on the seafloor such as iceberg scour marks. Determining the state of preservation of the trench was also of value to the Newfoundland and Labrador Hydro Company, which is investigating the possibilities of burying a power cable in such a trench. Details of the Strait of Belle Isle dives are reported in Zevenhuizen, (1986).

MAKKOVIK BANK DIVES

''Bertha'' scour pits (dive 1648)

This dive surveyed a scour mark at 110-m water depth which had been formed only two weeks earlier by the grounding of the iceberg code-named ''Bertha'' (Fig. 4.5). The seabed around the grounding site had a well developed gravelly sand lag surface with considerable and varied biogenic cover. In some areas localised symmetrical sand and gravel ripples were also present. These bedforms and the well developed lag surface indicate a dynamic current regime.

The iceberg ''Bertha'' had been instrumented with a motion sensor (six degrees of freedom) which monitored the iceberg motion while grounded and following refloatation (Hodgson et al., 1988). The grounding produced four aligned but separate impact marks which could clearly be seen on the 100 khz sidescan data (Fig. 4.5). Linear grooves and ridges were characteristic of the troughs of the last three impact marks. The initial pit had well developed berms up to 1.5 m in height on all but one side which could be seen both visually and on the sidescan sonograms. Wallowing of the stationary berg caused the underlying glacial till (Unit 3b) (Josenhans et al., 1986) to be squeezed from below the keel to form the berms. There had been considerable erosion of these berms and scour troughs by the local bottom currents in the two weeks after their formation. Within the pit, a boulder was found surrounded by ice. When disturbed by the manipulator arm of PISCES the ice floated to the surface, confirming its origin as a broken piece from the iceberg. The sediments in the initial pit were remoulded and compacted. After forming the initial pit, the berg lifted and moved westwards producing three aligned but separate pits rather than one linear scour mark. These observations on scour character might be explained by aligned pits being produced by unconstrained and unstable floating bergs, whereas the continuous linear scour marks may be produced by icebergs frozen into and driven by sea ice preventing them from rolling or chattering over the seabed.

''Anastasia'' scour feature (dive 1649)

This dive was intended to investigate another iceberg scour, produced by the iceberg named ''Anastasia'' (Hodgson et al., 1988). Water depth at this site was 118 m (Fig 4.4), approximately 10 m deeper than the ''Bertha'' site. The seafloor at this site was dominantly a silty pebbly clay, with less gravel than at the ''Bertha'' site. Sand and gravel waves were also present and there was considerably more biogenic colonization and reworking than at the shallower site. The dive did not encounter any obvious fresh impact features and appears to have missed the fresh scour.

The visual survey did reveal an older pit with well developed berms approximately 1.5 m high made of consolidated silty clay. These berms were heavily encrusted and reworked by biogenic organisms. Biogenic dissaggregation of the cohesive clays had allowed the local bottom currents to remove the fine-grained sediment. Even a very strong current acting for a long time could not erode these consolidated sediments without the prior disaggregation by biogenic reworking.

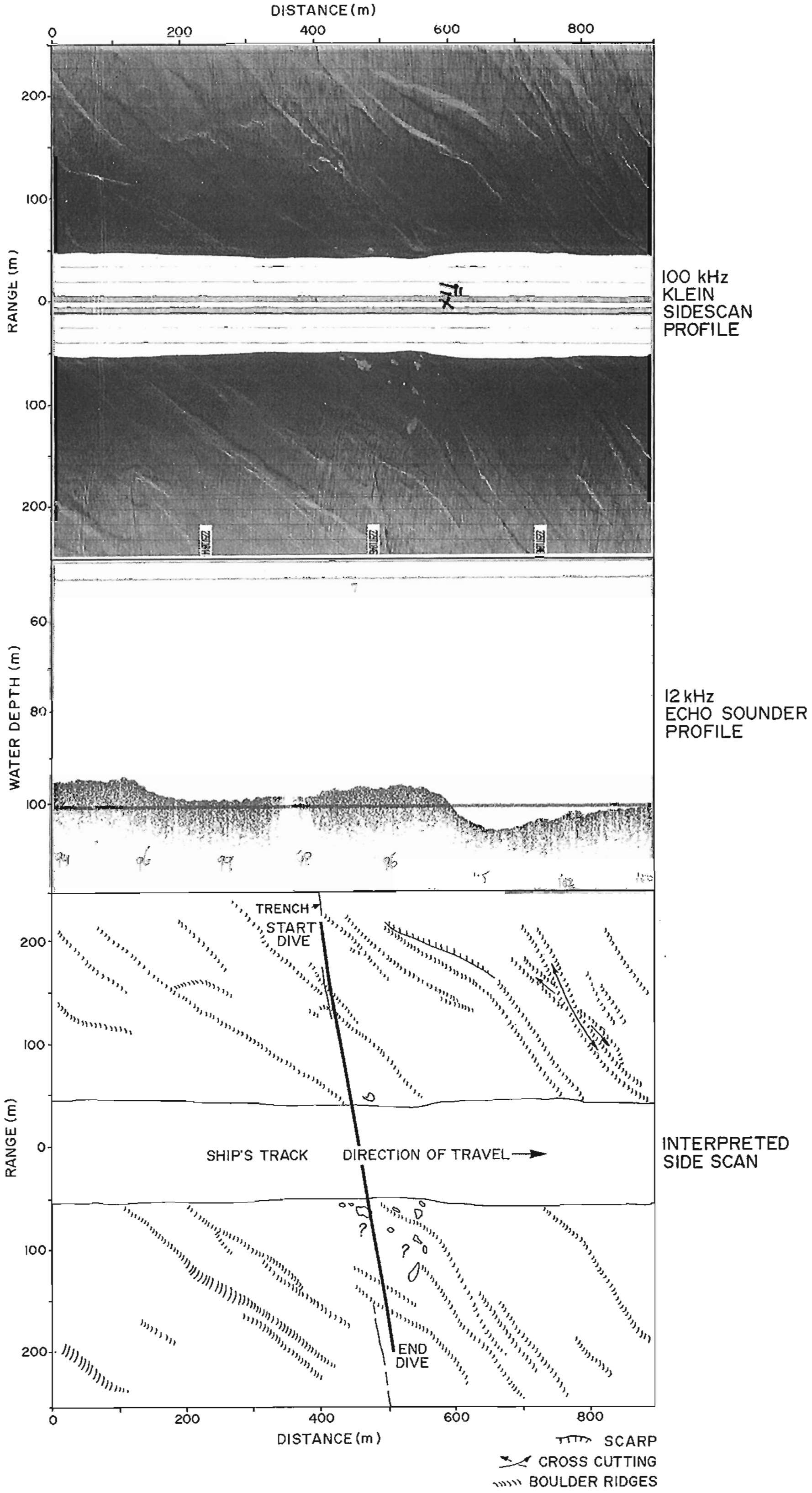
Depth of disturbance experiment on large scour (dives 1650, 1655)

Dive 1650 in 150 m water depth (Fig. 4.4) traversed a scour mark which had been surveyed acoustically two weeks earlier and appeared as a fresh feature on the 100 khz sidescan record. The seabed surrounding the scour mark consisted of a well developed gravel lag with occasional patches of sand. Underlying this lag deposit were normally consolidated silty pebbly clays. As predicted from the sidescan data, the scour had steep berms of material which had been extruded by the iceberg scouring action. Linear grooves and ridges parallel to the berms were seen in the trough. Moats surrounding boulders within the trough were interpreted as resulting from dissolution of ice that had once surrounded the boulder as seen at the ''Bertha'' site. Although the scour berms and sediment blocks showed clear evidence of erosion and disintegration causing reduced berm height, there was no evidence of infill within the scour trough.

One of the initially unexplained features of this scour were isolated mounds approximately one to two cubic metres in volume outside the scour berms. These mounds had exposures of pebbles and cobbles protruding from the silty clay matrix, suggesting that some erosion had occured. The origin of these mounds remained unexplained until a later dive (1656), on what appeared as a fresher scour, showed similar but less eroded mounds of sediment outside the scour berm. These mounds were angular, massive sediment blocks which were clearly distinguishable from the surrounding seabed and could be confidently associated with material that had been extruded from the iceberg scour trough. We interpret that this sediment was extruded from below the berg, forming an unsupported mass beyond the berm crest which finally fractured under gravity effects to form isolated blocks one to three metres from the berm crest. The mounds of sediment seen on dive 1650 may be similar features that are more degraded.

In order to determine the rate of erosion or sedimentation within this scour mark at dive site 1650, three depth of disturbance rods were deployed. Two rods were deployed on the berm crest and one was deployed in the scour trough. Future visual inspection either by manned submersible or

Figure 4.2 Interpreted sidescan sonar and bathymetry record showing the trench and area surveyed in the Strait of Belle Isle.



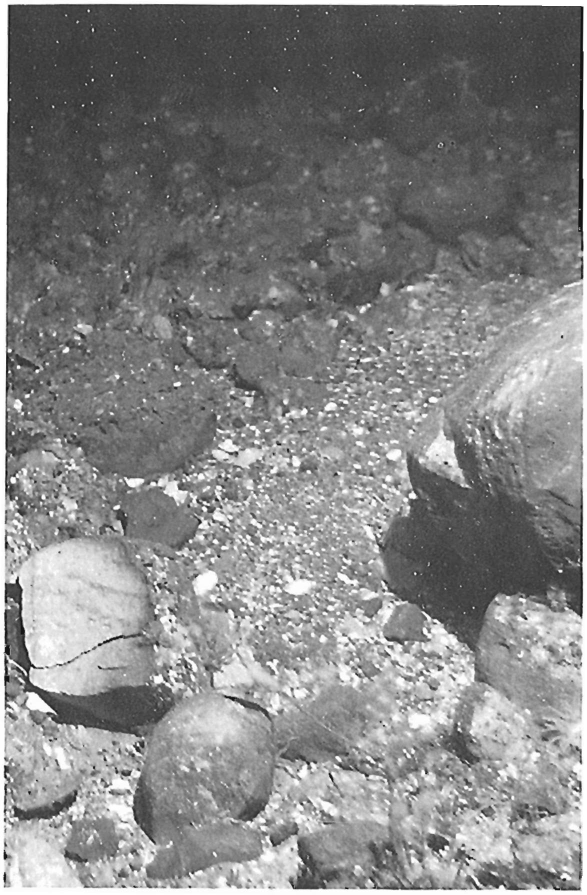


Figure 4.3 A bottom photograph of trench in the Strait of Belle Isle one year after it was cut. Notice the uncolonised area of the boulder which has been overturned by the plow. Base of photograph is approximately Im.

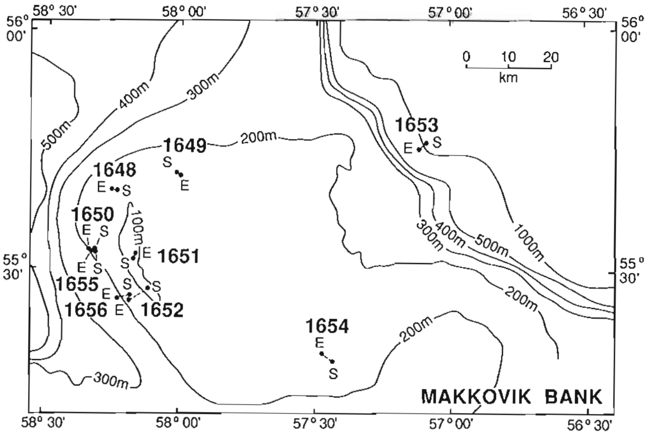


Figure 4.4 Detailed bathymetry map of Makkovik Bank, central Labrador Shelf, showing the areas covered by dive transects.

remotely operated vehicle should allow determination of the amount of erosion or infill since deployment.

Features seen from PISCES such as the linear grooves in the bottom of the scour were compared with features on the 100 khz sidescan record. This showed that features as small as 10 cm in height and 5 cm in width could be resolved by the sidescan system and related directly to the visual observations.

Tracer experiment, western Makkovik Bank (dive 1651)

A current meter was deployed at 108 m on the shoalest part of Makkovik Bank along with 10 kg of pollucite [cesium aluminosilicate ($CsAlSi_2O_2$)] tracer sand. It was intended to sample the site two weeks after it was deployed in order to see how much dispersal or transport of tracer had taken place.

The dive site (Fig. 4.4) was on a smooth fine sandy seafloor with abundant shells and worm tubes. Occasional boulder mounds interpreted to be boulder dumps of iceberg-rafted material (Josenhans and Barrie, 1982a) were found. Extensive fields of coarse-grained megaripples were observed with wavelengths up to 3 m, amplitudes of 0.5 m and crest orientations of 130°-220°. The ripples were located in linear to oval-shaped groups cut into the seafloor and surrounded by flat unrippled areas. The current meter was located sitting on smooth fine sand with no evidence of the fresh sharp crested bedforms that had been observed only a few hundred metres away in the same water depth. No scour or bedforms were observed around the current meter mooring.

The pollucite tracer sand site was located adjacent to the current meter and was sampled at five locations, 50 m apart, with the suction sampler on the PISCES IV. The subsea float deployed to mark the tracer was not located. Results of the tracer analysis suggest that transport was along a southwest-northeast axis. Too few samples were collected to derive accurate direction and total sediment transport for the two week period. However, peak semi-diurnal and diurnal tidal flows over the same period were determined to be to the southwest.

West edge of Makkovik Bank (dives 1652, 1656)

Dive 1652 was intended to traverse and provide visual ground truth of a 75 khz sidescan mosaic obtained three years earlier, which extended over the shoalest part (85 m) of the western edge of Makkovik Bank and into deeper water (154 m) where a fresh scour mark had been observed on seafloor (Brutiv) photographs. An additional objective was to search for evidence of relict beach ridges or other features that might indicate the influence of a lowered stand of sea level and subsequent transgression. The dive began on a gravelly, bouldery lag with occasional smooth patches of fine sand 100 to 200 m wide, with extensive biogenic reworking. Within these fine sand patches were fields of coarse megaripples, with wave lengths of 60 to 80 cm and crest heights of 20 to 30 cm. In cross section individual waves were symmetrical with flat crest slopes. Although the megaripples varied considerably in grain size they were consistently coarser than the surrounding fine sand into which they were cut. The megaripple fields were generally oval in planform, with lengths of 60 to 100 m and widths of 20 to 40 m. The surfaces of these bedforms were devoid

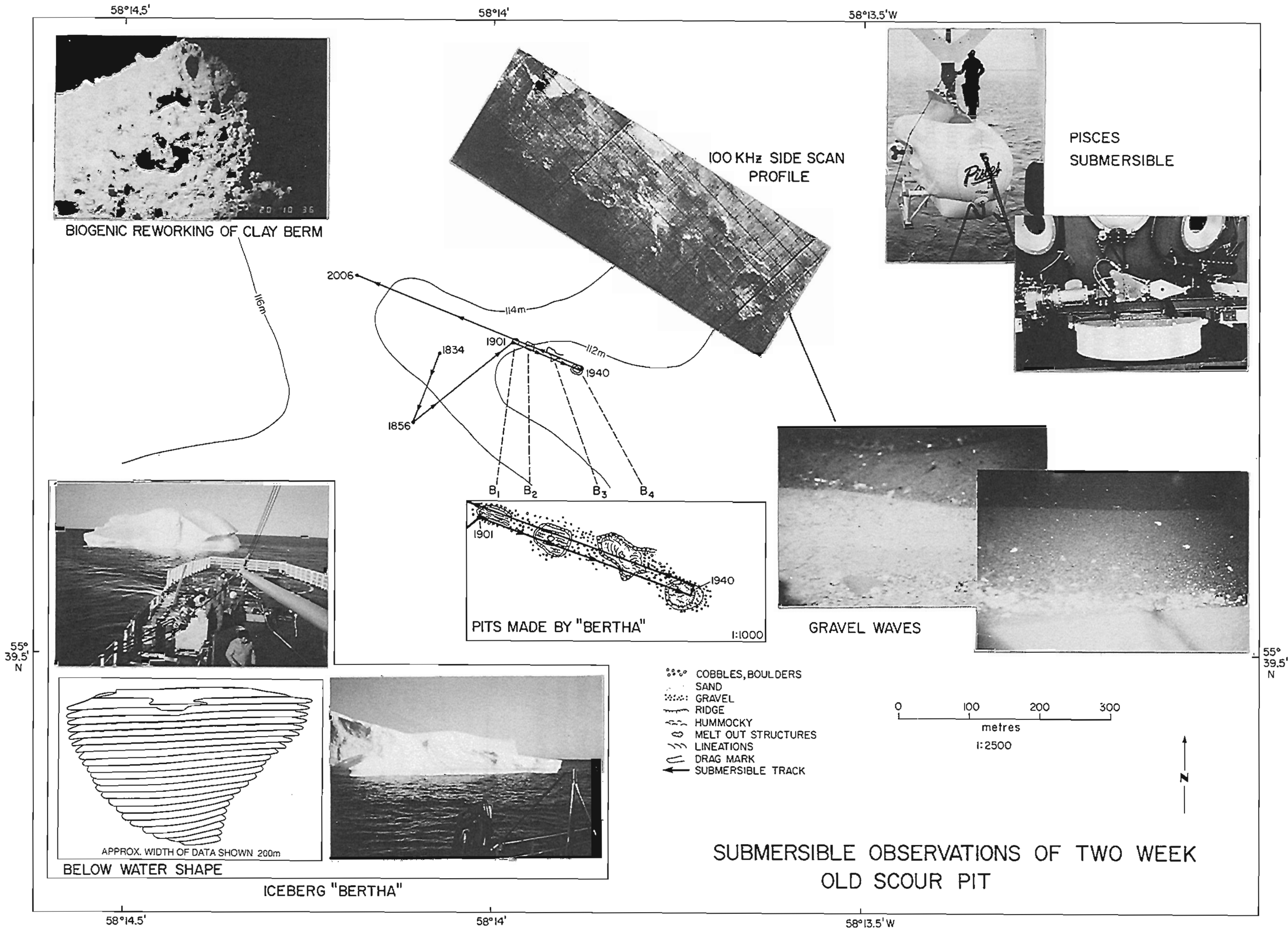


Figure 4.5 Composite diagram showing a sidescan profile, bottom photographs and an interpretation of the "Bertha" grounding site. Also shown are the above-and below-water profile of the iceberg "Bertha" which made the pits and a front and rear view of the submersible PISCES IV.

of benthic organisms and had extremely sharp crests. Considering the high rate of bottom reworking by bottom dwellers observed in this area we conclude that these features were formed within a few days of our visual inspection. The patchy distribution and erosional nature of these megaripple fields is not understood. Perhaps the smooth fine sand surrounding the megaripple fields is not eroded because of the bonding effect of biogenic cement.

The traverse over the bank top in areas shallower than the suggested Late Wisconsinan low stand of sea level at −110 m (Fader, 1988) did not look appreciably different than the deeper areas; boulders and gravels were subrounded to subangular; there were no relict beach ridges and the local current regime appeared strong enough to explain the sorted sediment features seen. On the western margin of the bank at 115 m, the surface veneer of fine sand increased in thickness and areal extent; this may be an area of deposition of fine sand that is winnowed from the bank top.

Seabed relief on the bank top is smooth; iceberg scour ridges are rare and can only be recognized by linear mounds of isolated pebbles and cobbles protruding a few centimetres above the surrounding gravel lag. The lack of relief on the bank tops is attributed to the consolidated nature of the underlying (Lower) till (Silva et. al. 1986) which is not readily incised or remoulded by the scouring process. The dive investigated one area of exposed stiff pebbly clay devoid of the usual gravel lag, which may have been an area of iceberg impact. However, no berms were visible and the inferred seabed impact only removed the gravel lag without affecting the stiff underlying material. Despite its low relief, this feature could be resolved by the sidescan because of the difference in reflectivity between gravel and clay. Although the surface veneer did not change in character, scour berms were better developed in the deeper areas where the seabed is underlain by the less consolidated Upper Till (Josenhans et. al., 1986). Dive 1652 terminated in 123 m depth in an area of numerous eroded scour marks, some of which had berm slopes up to 20-30°.

Dive 1656, a continuation of the mosaic transect, began in 109 m water depth over a field of coarse megaripples with wave lengths of 1.5 m-2 m and heights 30-40 cm. Bottom currents were less than 12 cm/s and flowing in a northerly direction. From the beginning of the dive until a depth of 125 m was reached, the dive traversed areas of coarse megaripples which were eroded into larger patches of fine sand. Seabed relief was essentially flat. Subdued scour ridges first become apparent at 125 m depth and rapidly increased in height and frequency toward the deeper water. A fresh asymmetric scour mark heading along slope was seen at 138 m, with no berm on the upslope side and a 6-m high berm with slopes of up to 45° on the downslope side. The transition from surrounding seabed to the upslope scour margin could be recognized by a marked textural change, with a smooth lineated clay surface within the scour and the typical lag gravel marking the undisturbed seabed. On the upslope side, the scour feature was cut into the gravel lag by less than 5 cm. On the downslope, outer margin of the berms, were angular blocks of sediment, similar in colour to those found in the scour trough, indicating that this material had originated from within the scour. The origin of these blocks by extrusion beneath the berg has been discussed in the report on dive 1650.

The berm crest was traversed for 200 m, with variations in berm height of between 1 and 6 m. The lack of biogenic cover and the angularity of the sediment blocks outside the scour mark suggest that it is a fresh feature, probably cut within the last year. It must have been less than 3 years old since the same area was surveyed with sidescan sonar and Brutiv camera sled in 1983 and no fresh scour mark was seen at that time.

We interpret this asymmetric scour as cut by an asymmetric ice keel with more draft in deeper water. The ice keel essentially conformed to the seabed slope although it must have been slightly deeper than the seabed on the downslope side in order to excavate enough material to plough up a 6-m high berm. This suggests that berg keels are eroded as they impact the seabed and will gradually conform to the seabed shape.

The dives provided ground truth for the 75 khz sidescan mosaic and demonstrated that this sidescan system does resolve such large scale features as iceberg scour marks and textural differences such as sand patches. However the 75 kHz sytem failed to resolve the megaripples which were seen on both the 100 khz sidescan data and in the submersible observations.

Continental Slope off Makkovik Bank (dive 1653)

This dive was planned to survey the upper slope to bank top from a depth of 1000 m to approximately 500 m. The area had been surveyed previously with the SeaMARC I midrange sidescan (Fig. 4.6). A large valley trending downslope at a heading of 210° had been identified as the prime target for visual observations. The submersible was deployed over the valley axis but landed on the south wall due to 1.5 km lateral drift during submergence. The submersible landed at 977 m depth on a seafloor comprising fine silty clay with numerous pebbles, cobbles and occasional boulders as large as the submersible. The seafloor was heavily encrusted with and reworked by a diverse biogenic cover. Seabed slopes were estimated to range between 20-60° and in one area a vertical undercut cliff was observed (Fig. 4.7). Slumping on a variety of scales was the most dominant process on these steep slopes (Josenhans et. al., 1987). Slump scarps displacing one to two cubic metres were common and thought to be triggered by ice-rafted boulders impacting the seafloor. Larger scale slumps displacing hundreds of cubic metres appeared to account for the undulating relief and sharp scarp faces encountered during the earlier part of the dive. Some of the soil failure appears to be enhanced by the disaggregation of the substrate by the bottom fauna. Also soil creep following biogenic disaggregation accounts for some of the mass wasting within this steep setting. Creep of ice rafted boulders was also noted on numerous occasions by the presence of a furrow or trough on the upslope side of the boulders. On one occasion at the upper slope, in 700 m, a crab had been overridden and killed by one such boulder slide, thus indicating that this sliding can be quite rapid.

The most dramatic feature of this dive was observed in the valley axis at a depth of 971 m. Here, an apparent debris

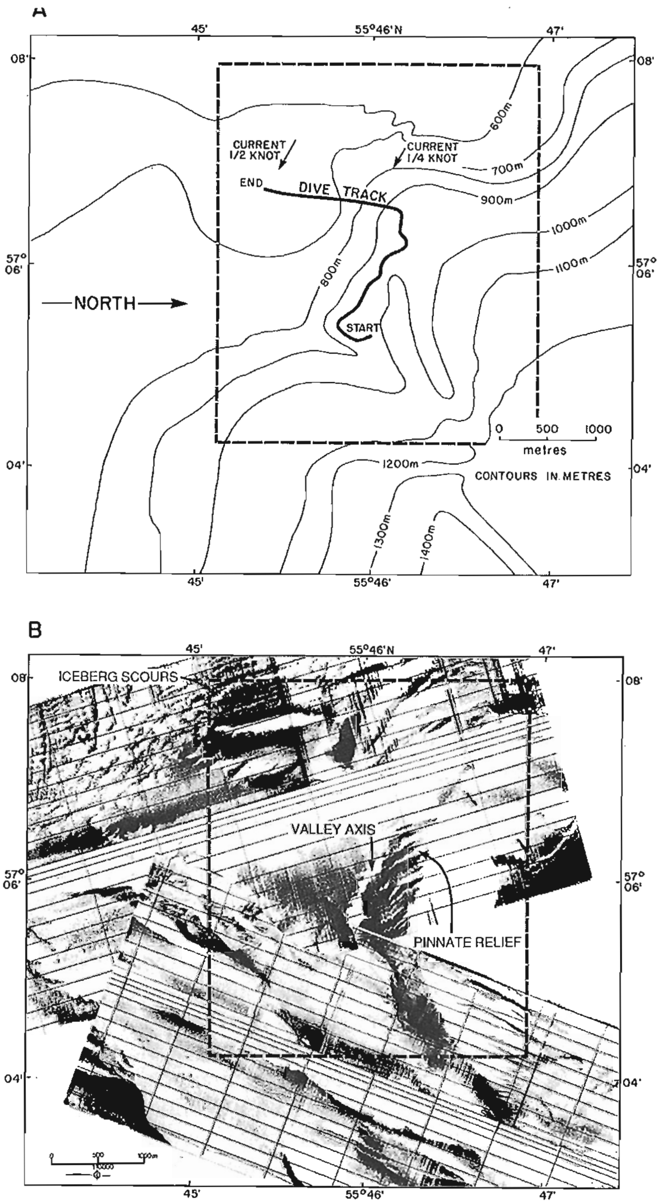


Figure 4.6 Location map for dive 1653. The figure shows the bathymetry on the upper continental slope off Makkovik Bank and a SeaMARC I Mosaic from the same area (after Josenhans et al., 1987).

flow had flowed down the valley axis and substantially downcut the valley floor. At the side walls, the debris flow had undercut the local consolidated massive clay substrate. Observations of the debris flow showed a surface composed of boulders and cobbles which had much less biogenic cover than the surrounding seafloor adjacent to the debris flow. The transition between debris flow and surrounding seafloor was marked by the conspicuous vertical, and in places undercut, wall of massive clay. The height of this wall was measured to be at least 3 m and could have been considerably higher but this was out of range from the submersible viewports. The vertical wall was completely encrusted with a diverse biogenic cover except at the transition between the wall and the debris flow. Here the light grey massive clay was exposed and individual fine laminations could still be recognized. The undercut area was approximately one metre in height and cut 30-50 cm into the wall. On the surface of the undercut area were numerous tool marks of cobble size which are believed to have been formed by cobbles bouncing along the rapidly moving debris flow surface hitting the valley walls. Such marks were seen up to 1.5 m above the present debris flow surface. This could indicate down cutting and subsequent lowering of the debris flow surface, reduction in debris flow thickness towards the trailing edge, or compaction and reduction in volume following still stand of the feature. The lack of biogenic cover on the undercut walls and over the debris flow surface suggests that it was a recent event. The debris flow was followed up valley along its edge for approximately 100 m and the undercut wall diminished in height up valley until there was no noticeable change in relief between debris flow and adjacent seabed, the only criteria for differentiation was on the basis of texture with the debris flow surface having a coarser texture. Following inspection of the debris flow, the traverse continued up a steep slope until a depth of 750 m was reached. From 750 m to 666 m, where the dive was terminated, seabed slopes were lower and the influence of a strong southerly flowing current was apparent in the form of current scour pits around boulders and by a coarse gravel-boulder lag. Numerous eroded (relict) scour berms in the form of boulder ridges were evident in water shallower than 750 m. Isolated boulder dumps of ice-rafted debris and localised impact marks of ice-rafted boulders were also seen. Even at these lower slopes many of the ice-rafted boulders had slid downslope and all that was remaining were impact marks or grooves about 15 cm in width trending down slope. Current strength at the termination of the dive was 0.25 m/s in a southerly direction. The dive demonstrated steep slopes at the shelf edge interpreted to be beyond their angle of repose as well as evidence of recent debris flow activity.

Eastern Makkovik Bank (dive 1654)

This dive began in 140 m depth near the eastern edge of Makkovik Bank. The seafloor consists of fine sand with abundant shell debris and worm tubes and has little relief. The dive encountered one train of ice-rafted boulders which had no biogenic cover and appeared fresh. They may have been deposited by the iceberg ''Freda'' which was observed to have rolled and deposited a large dump of supraglacial debris from its surface only days before. The area is actively current scoured as seen by the current pits that surround the isolated boulders. The dive terminated in 141 m depth.

SAGLEK BANK AND KARLSEFNI TROUGH

Southern edge of Saglek Bank (dives 1657, 1658)

These two dives were intended to provide ground truth for a BIO 75 khz sidescan mosaic and high resolution Huntec DTS seismic data, covering the area between the bottom of Karlsefni Trough and the top of North Saglek Bank. Two acoustic stratigraphic units occur within this area. A weakly stratified mud (Unit 5a of Josenhans et. al., 1986) outcrops

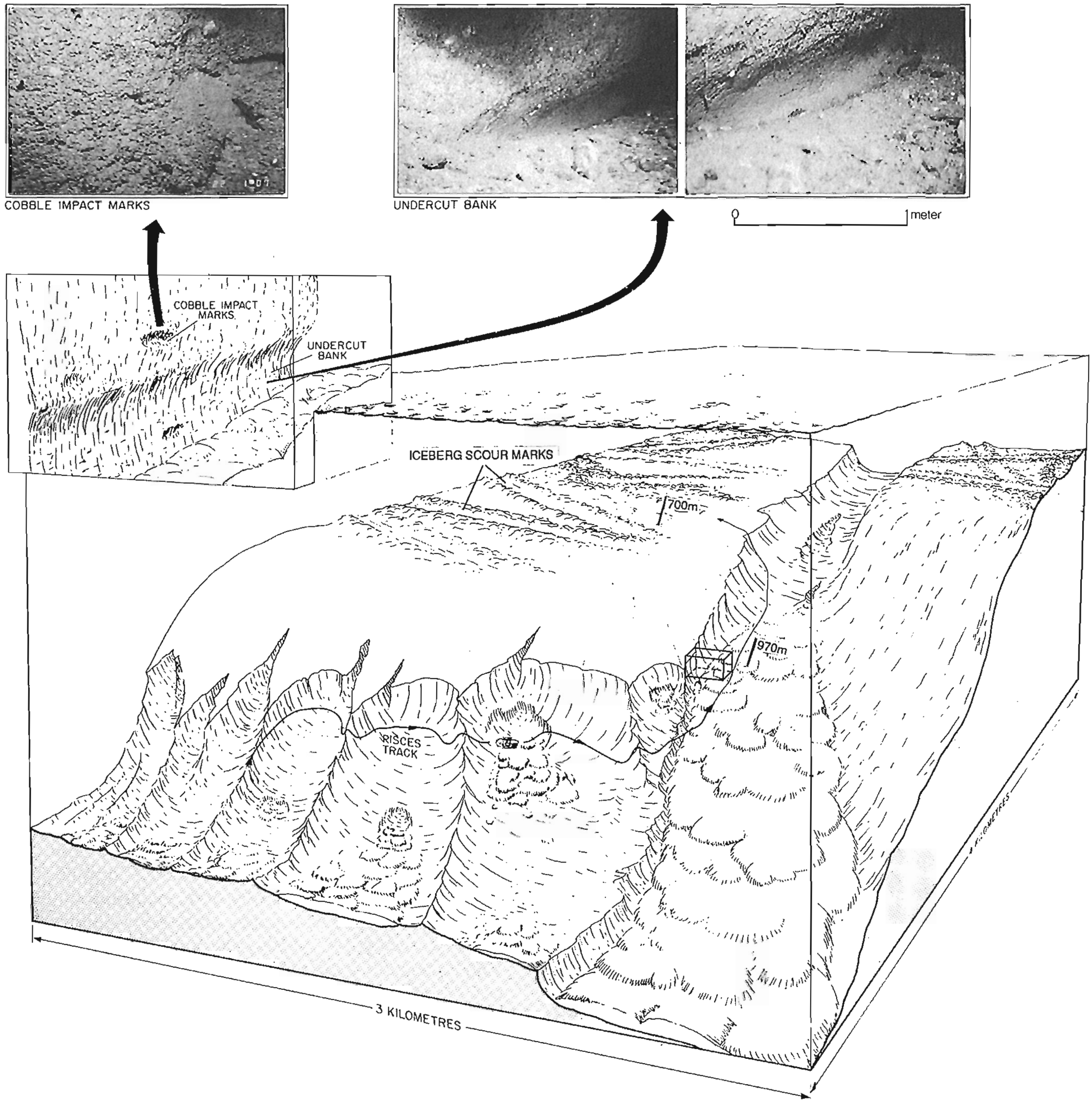


Figure 4.7 Interpretive diagram and bottom photographs of the features observed on the upper continental slope off Makkovik Bank (Dive 1653) (after Josenhans et al., 1987).

in the deep trough and a well stratified silty mud (Unit 4) outcrops in the shallower areas. The seabed is intensely scoured in the shallower areas over Unit 4, but scouring frequency diminishes towards deeper water with only isolated scours observed in the deepest areas.

An intersecting array of scour marks at 175 m water depth in the deepest area of a previously surveyed sidescan mosaic (Gilbert and Barrie, 1985) provided the primary focus of dive 1657. A number of relict, large scour marks were seen but visibility and navigation was too poor to accurately determine which particular feature on the mosaic had been observed.

Dive 1658 was a long traverse from the site of dive 1657 at 173 m depth to the north flank of Karlsefni Trough at 150 m. At the beginning of the dive the seafloor consisted of mud with many ice-rafted cobbles and pebbles. Visibility was poor: considerable suspended material was observed in the water column and as a dusting on all seafloor objects including moving crabs. Sea- state had been calm for two days and settling of fine debris may have resulted from this unusually calm sea. The lack of significant infill within the scour marks and the abundant exposed ice-rafted debris suggests that sedimentation such as observed during the dive must be a rare event restricted to days of absolute calm. As the dive moved into shallower water from the mud of Unit 5a to the silty mud of Unit 4 there was no noticeable change in seabed character. Numerous relict scour ridges 1-2 m high with frequent protruding boulders and pebbles predominate. Biogenic colonization was more varied and abundant than in similar water depths on the southern Labrador Shelf.

From 164 m to the end of the dive at 150 m the number of scours increased and the surface texture became slightly coarser. Overall, however, there was little difference in the appearance of the seabed from the beginning to the end of the dive despite the marked difference in the substrate and morphology seen on both the sidescan mosaic and on Huntec DTS high resolution seismic profiles. The dominant processes controlling the surface veneer were biogenic reworking and removal of fines in the upper 10-15 cm by filter feeders and various bottom dwellers. The local currents were estimated to be about 12 cm/s and thus are strong enough even in the deep part of the basin to remove the fines brought into suspension by the bottom dwellers. The relatively coarse and reworked surface layer found in the upper 15-20 cm of almost all Labrador shelf cores (Josenhans et al., 1986) appears to be produced by this interaction of bottom dwellers and removal of the fine fraction by currents. Ice rafted clasts cover approximately 20-50% of the seafloor, even over the mud (Unit 5a), which was deposited in the last 8000 years (Josenhans, et al., 1986).

"Caroline" scour site on Saglek Bank (dive 1660)

The dive was intended to survey a scour mark in 120 m water depth made by iceberg "Caroline" that had been observed to scour in 1979 and to investigate another much fresher scour mark which had been observed on the 100 khz sidescan data that was collected in 1985 to relocate the "Caroline" scour. The sidescan data showed that this fresh scour mark had crosscut the "Caroline" scour close to its terminal pit and that there was a marked difference in the appearance between scours (Fig. 4.8). On sidescan, the fresh feature had linear groove markings in its trough, parallel to the berms. Raised blocks of material on the berm crest were clearly visible on the sidescan data, appearing as localized acoustic shadows. This clear difference in acoustic character between the two scours suggested that visual identification of the fresh scour would be possible. High resolution seismic profiles indicated that both scours were cut into the glaciomarine Qeovik Silt (Josenhans et al., 1986).

A traverse was followed that first located the "Caroline" berm, and then followed the berm until the fresh scour was located. PISCES then moved across the fresh scour and back onto the "Caroline" berm. This berm was followed until the terminal pit was reached. PISCES then traversed from the terminal pit back to the fresh scour and surveyed that feature to the end of the dive.

The dive began at a depth of 119 m over a pebbly silty seafloor with abundant and diverse biogenic cover. There was less evidence of erosion compared to similar water depths on the southern Labrador Shelf, where a gravel armour is widespread. The "Caroline" berm could be differentiated from surrounding (older) scours in the area by its higher and steeper berms. The berms were approximately 2 m in height, generally steep sided, smooth on the inside of the scour and undulating with subdued sediment mounds on the outside. After following the six-year-old "Caroline" berm for approximately 60 m, the seabed character changed dramatically as the fresh scour was reached, cutting normal to "Caroline" in a north-south direction.

In the "Caroline" scour, there was no evidence for scour infill. Exposed boulders winnowed from the silty clay matrix were observed on the outer berm crests. The seafloor was intensely reworked by the diverse benthos and any sediment blocks on the berm or linear grooves of the type seen in the fresh scour had been reworked or eroded. Push cores in both trough and berm penetrated approximately 20 cm. In contrast the push cores from the fresh scour which cuts the same but unreworked bottom sediment unit penetrated 11 cm on the berm crest and 9 cm in the trough. This difference in push core penetration indicates considerable disaggregation and reworking of the "Caroline" surface veneer. The difference in berm height between fresh and "Caroline" scours was approximately one metre and the subdued relief of the berms as well as the number of exposed, winnowed cobbles on the rims suggest that much of this loss in height in the "Caroline" berms is due to biogenic reworking and erosion.

Fresch scour

The outermost part of the fresh scour berm consisted of reworked sandy silt that had apparently been pushed aside by the leading edge of the iceberg and deposited in a manner similar to material in front of a bulldozer or snow plow. The upper 2 m of the 3-m high berm consisted of large, angular, massive blocks of cohesive silty clay, estimated to be one to three cubic metres in volume, which were resting on the reworked sandy silt of the lower berm. The berm crest consisted of angular sediment blocks on the outer side and a massive, smooth, silty clay surface which extended into the scour trough. The similarity in sediment type, colour and fracture pattern clearly indicated that the sediment blocks seen on the lower part of the outer berm were of the same material as the berm crest and scour trough. This suggests that this sediment is extruded from the scour trough and squeezed out at the berm crest. The presence of sediment blocks still in their original position but up to 2 m away from the berm crest suggests that the material has enough internal strength to support the weight of up to three cubic metres of unsupported sediment over a distance of up to 2 m. On the steep slopes from the berm crest to the scour trough the smooth massive silty clay surface had subdued ridges which extended from the berm top into the scour trough at an angle of approximately 45° to the direction of ice flow. These ridges are interpreted to have formed at the trailing edge of the iceberg by material that was squeezed from below the trailing edge of the berg. The visual observations (Schafer et al., 1986) suggest that a large amount of material is remoulded and transported as a result of the proposed mechanism of scouring in this sediment type. At the base of the

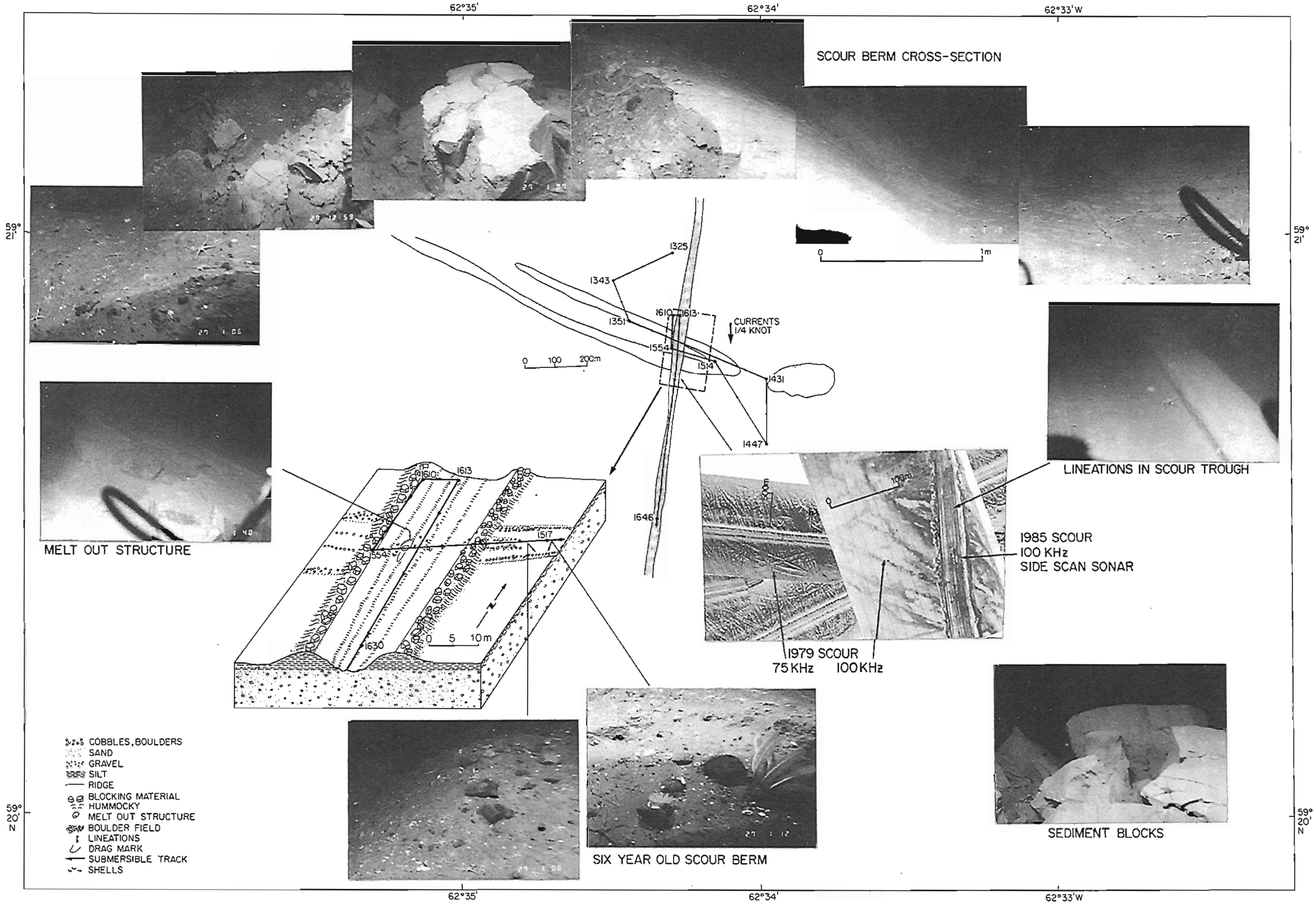


Figure 4.8 Composite diagram and photomosaic of six-year-old scour mark which has been cut by a recently formed scour mark. Note the sidescan data collected in 1979 does not show the feature observed on the 1985 record, indicating that it must have been made after the 1979 data was collected. The amount of erosion in six years is indicated by comparison of the fresh and six-year-old scour berm.

scour berms were numerous fracture joints with gaps up to 5 cm in width dissecting the smooth scour floor. The origin of these fractures is not understood. Ice loading may have produced consolidation of the sediments at the base of the scour (H. Christian, personal communication) and removal of the ice load could lead to elastic rebound (stress relief) to produce the fractures. The trough is dominated by linear structures which are parallel to the berm crests and the direction of ice travel. Smooth, linear, parallel ridges typically 5-10 cm high, 10-15 cm wide and spaced 15-25 cm run parallel to the scour trough. These ridges were followed visually for over 300 m and were seen to change shape slightly or in some cases disappear over a distance of 10-15 m. Many ridges start with a boulder lodged in the seabed and extend in the direction of iceberg movement. The sediment ridge thus infilled the void at the base of the iceberg left when the boulder was dislodged from the ice keel. The relatively short extent of these ridges indicates that ice keels erode and change shape in response to abrasion by the seabed.

Another common feature associated with erosion of the ice keel were dissolution moats in the scour trough. These typically developed around boulders lodged in the seabed. The boulders had conspicuous glacial striae and no biogenic cover and must have originated from the iceberg. Surrounding these boulders were moats or pits extending 20-50 cm from the boulder. The moats are interpreted to have formed as a result of dissolution of ice that had originally surrounded the boulders. Another feature observed within the scour trough were discrete zones of fractured boulders and cobbles all of similar lithologies and devoid of biogenic cover. These zones were observed as patches 20-30 m in area and occurred in areas of the scour trough where the lineations were poorly developed or absent. The rock fragments appeared to have been crushed and some crystalline rock fragments had fresh fracture planes throughout. The origin of this rock fracturing is not understood at this point but stresses developed within the iceberg or glacier are thought to be the most likely mechanisms. The normally consolidated silts of the substrate could not provide enough resistance to result in fracturing of these crystalline rock fragments during the scouring process. These patches of fractured rock debris in the scour trough may have formed from meltout of large sections of sediment-rich and therefore negatively buoyant iceberg ice that broke off the keel of the iceberg during scour formation.

The observations within this fresh scour indicate that erosion and breaking away of the iceberg keel is an important mechanism which accounts for the removal of considerable volumes of ice. Also the frequent number of fresh erratics which must have originated from this iceberg indicate that some bergs have considerable englacial debris, and in some cases there may be enough to make the broken off pieces of the iceberg negatively buoyant.

Sedimentation within the fresh scour was limited to a fine dusting of what appeared to be largely biogenic flocs which were of low density and were easily suspended by the currents generated by the submersible thrusters. The material was dark brown and preferentially deposited in the small grooves between the linear ridges in the scour trough and was so easily put into suspension that even a slight increase in current strength would be enough to remove it from the scour trough. Infilling of the scours within this sedimentary setting thus appears to be slow or absent.

The scour was colonized by only two macrofaunal species: many brittle stars and occasional small communities of sea anemones clustered on boulders within the scour trough. There was no current observed at the beginning of the dive but the current increased to 12 cm/s from the north as the dive progressed. Some variability was noted in current strength and orientation depending on where the PISCES was in relation to the scour features, due to the effect of the local topography on the current. The only evidence for current erosion was seen on the east-facing berms where some of the pebbles and cobbles lodged in the silty clay matrix were beginning to be exposed as a result of winnowing of the fine fraction. This preferential erosion may reflect the orientation of the strongest component of the regional current flow.

NACHVAK FIORD (dive 1659)

This dive in the outer part of Nachvak Fiord was intended to traverse the Tinutyarvik sill in order to determine if it was a bedrock sill or a moraine ridge. The dive began at 197 m in the outer basin of the fiord over a smooth fine muddy seafloor with sparse biogenic cover. Occasional ice rafted boulders were seen but these were much less frequent than those observed in similar water depths on Dive 1658 on the adjacent outer shelf. Visibility was poor and considerably less than on the outer shelf.

The edge of the basin was marked by a steep slope, ten metres high, made up entirely of boulders and cobbles which were densely encrusted with biogenic growth. These were covered by a veneer of buff coloured mud. The dive was terminated after several transects across the boulder ridge. On the basis of texture and relief, it was concluded that Tinutyarvik sill is a bouldery moraine overlying a bedrock ridge.

UPPER CONTINENTAL SLOPE OFF HUDSON STRAIT (dive 1661)

This dive was intended to survey an area previously identified on the SeaMARC I sidescan data as a possible marine proglacial outwash system in water depths greater than 700 m and large (relict) iceberg scour marks in water depths less than 700 m. (Fig. 4.9). The intent was to begin at 1000 m depth and to traverse up slope over the lineated surface to the large relict iceberg scour marks observed at the outer part of Hudson Strait in approximately 700 m. The dive did not reach the iceberg scours due to loss of communication with the surface vessel which forced termination of the dive at 715 m.

A push core was taken at the beginning of the dive at 1004 m and easily obtained full penetration (20 cm) within a massive, almost "soupy", homogenous deposit of pebbles and broken shell debris, supported in a muddy, organic-rich matrix. The PISCES traverse headed upslope, normal to numerous lineated grooves which were variable in size but typically had depths of 20-60 cm and widths of 15-30 cm (Josenhans and Woodworth-Lynas, 1988). These unusual

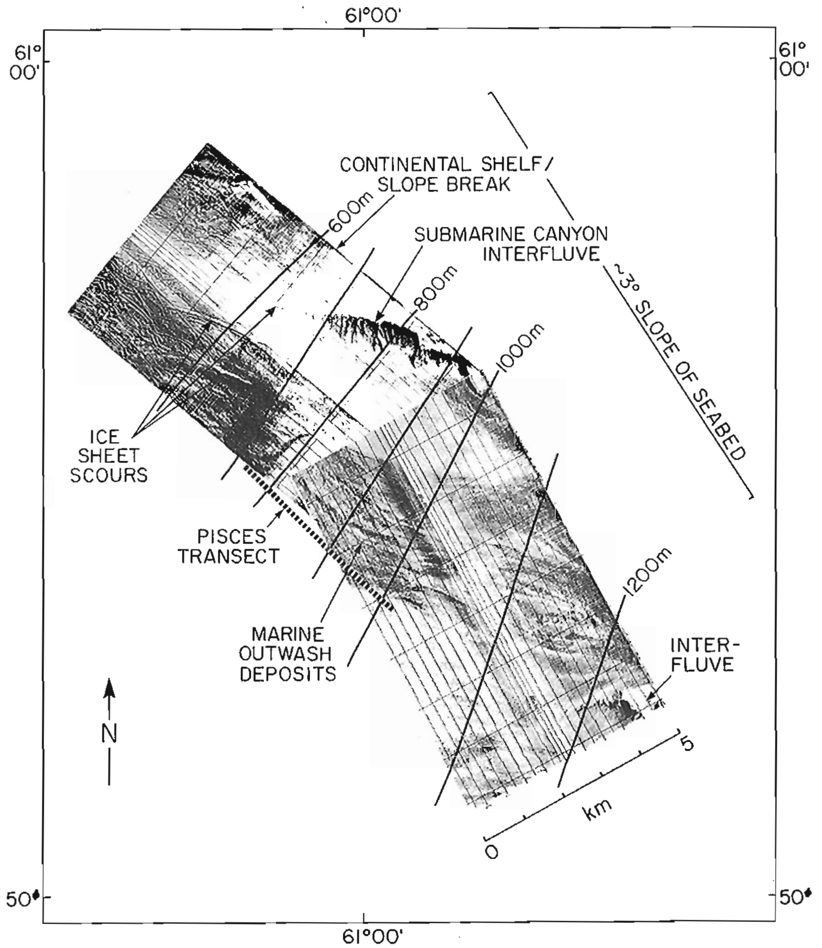


Figure 4.9 SeaMARC I mid-range sidescan record with superimposed bathymetry and submersible track. Note the lower limit of ice sheet scour marks and the downslope trending lineations. These lineations are thought to have formed at a time when an active ice margin in outer Hudson Strait deposited large volumes of proglacial marine outwash deposits at the shelf edge (after Josenhans and Woodworth-Lynas, 1988).

grooves always had small berms of material that appeared to have been ploughed up from within the trough by something contacting the seabed but the combined volume of the berms appeared to be less than that of the groove. Consolidation of the soupy substrate was interpreted to account for the difference in volume. One of the grooves was followed for 200 m and seen to be consistently contour parallel and uniform in shape with groove depth of 40 cm and width of approximately 30 cm. Similar subparallel grooves in various states of preservation dominated the seafloor throughout the extent of the 2-km-long dive transect. Superimposed on these contour parallel grooves were occasional oval-shaped pits which consistently crosscut the grooves at an angle of approximately 30° (Fig. 4.10). These bathtub-sized pits had surrounding berms, which like those of the groove marks did not correspond to the total volume of the depression. No boulders or cobbles were observed in the bottom of the pits although they may have been buried. Near the end of the dive transect some of the grooves and pits were partially infilled by pebble to boulder sized, slightly negatively buoyant yellow sponges which appeared to be rolled into the features after their formation. The sponges did not appear to be associated with the formation of the grooves and pits.

The origin of these depressions is not fully understood but possible mechanisms are presented in Josenhans and Woodworth-Lynas (1988). We suggest negativley bouyant iceberg fragments or manmade rigid objects dragged across the seabed to form the grooves. Whale foraging may explain the origin of the pits.

SOUTHEAST BAFFIN SHELF (dive 1662)

This dive was intended to investigate a possible mud mound off Lady Franklin Island. The dive failed to locate the feature due to poor navigation but did encounter a fresh iceberg scour mark in 232 m. The scour mark had well developed steep sides and linear structures in its trough. The scour was oriented north-south and had a depth from berm crest to scour trough of 5 m. Superimposed on the berms were recently formed bedforms of mobile megaripples, indicative of a very dynamic current regime. The dynamic bottom conditions observed at this site suggest very rapid destruction of scour marks.

SUMMARY AND CONCLUSIONS

The dives have provided important new insights into the processes of iceberg scouring. Most of these processes were illustrated in dive 1660, where two scour marks were surveyed acoustically with sidescan and visually from the PISCES submersible. These scours were cut into the same sediment type and intersected each other at 90°. One of these scour marks "Caroline" had been observed as it formed in 1979, six years before the visual observation took place. The scour which intersects the six year old scour is much fresher in appearance both visually and on the 100 khz sidescan data. Biogenic colonization within the fresh scour is limited to ubiquitous brittle stars and isolated communities of sea anemones clustered on freshly exposed iceberg

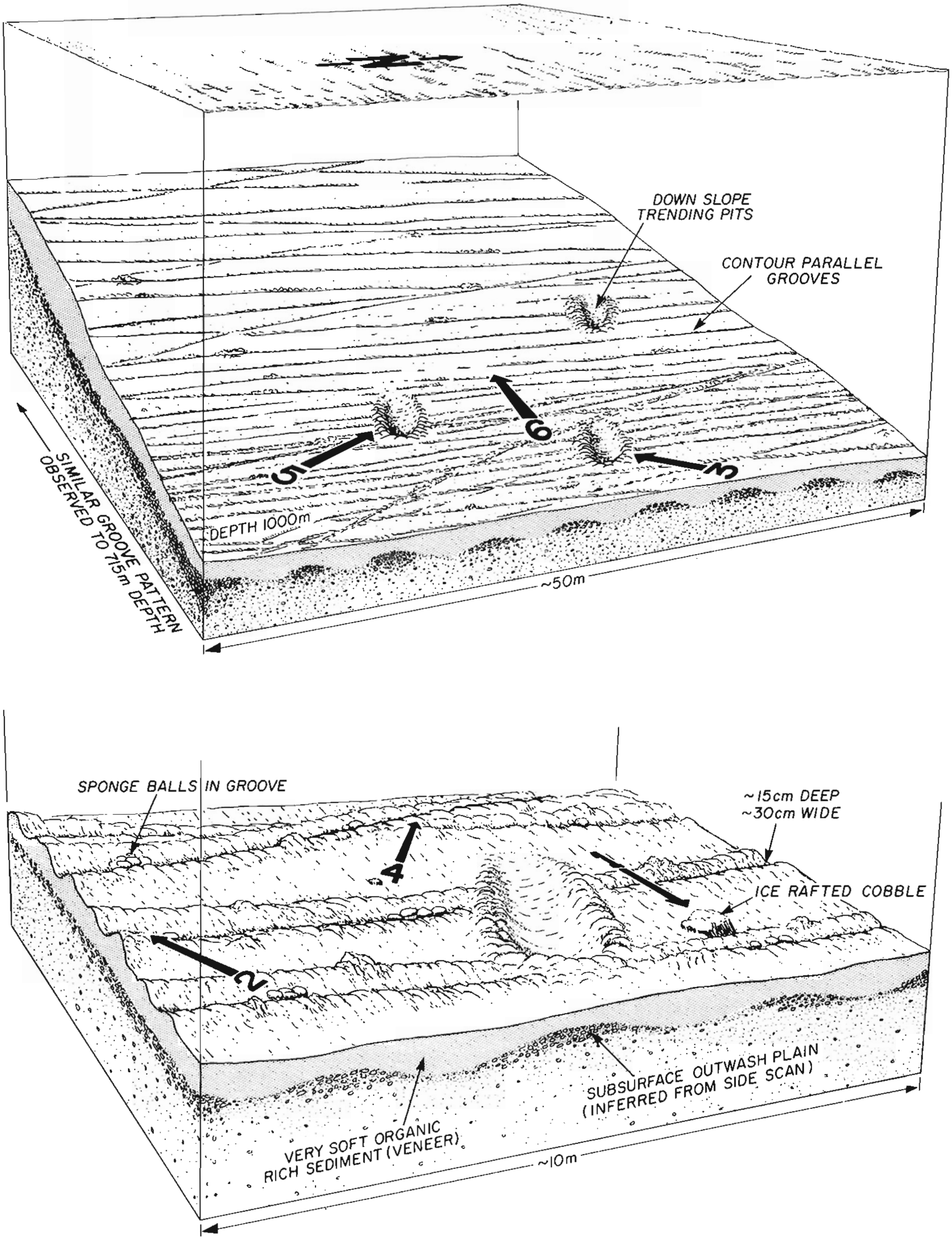


Figure 4.10 Interpretative diagram of contour parallel groves developed on the upper continental slope off Hudson Strait. These grooves are typically 30 cm wide and 15 cm deep. They may be formed by (current driven?) rigid objects dragging across the seafloor (after Josenhans and Woodworth-Lynas, 1988).

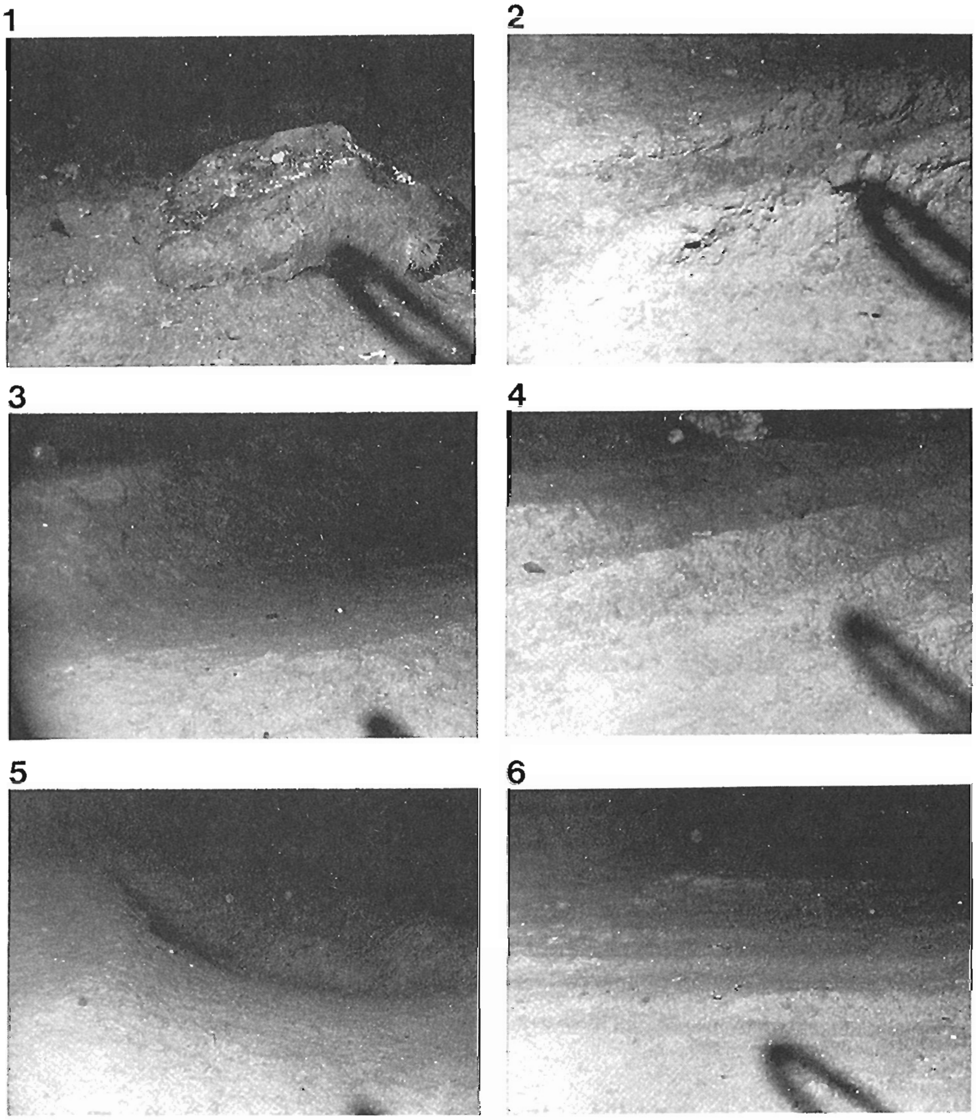


Figure 4.11 Photographs of contour parallel grooves. The numbers correspond to those on Figure 4.10. The arrows indicate the orientation of the photographs.

erratics believed to have been broken out of the berg which carved the scour mark. The six year old scour mark is heavily covered by a wide variety of bottom benthos. The limited biogenic cover on the fresh scours suggests that it is only as old as the age of the oldest sea anemones, interpreted to be less than one year. The fresh scour mark shape has not been significantly modified since its formation and visual observations have helped to interpret some of the detailed mechanisms of scour formation. The outermost part of the scour berms within this sediment type consist of ploughed up surface sediment pushed aside by the leading edge of the berg. The upper two thirds of the outer berm consist of massive remoulded sediment, often in the form of discrete blocks, which have been extruded from below and at the trailing edge of the iceberg keel. Along the inner edge of the berm slopes, which have slope angles up to 60°, are structures indicative of sediment extrusion from the base of the ice keel to the berm crest; 3 m above the scour trough. Considerable sediment remoulding and transport is associated with scouring in this sediment type. Within the scour trough are linear ridges and grooves parallel to the berm crests, which were formed and shaped by the trailing edge of the ice keel. The shape of these ridges and grooves changes considerably over a distance of a few metres indicating abrasion and removal of the ice keel by the seafloor. Fresh uncolonized boulders and cobbles, frequently seen in the scour trough, are thought to have originated from the iceberg which carved the scour mark. These erratics are often partially buried in the scour trough and are almost always surrounded by a moat interpreted as formed by dissolution of ice which had surrounded the erratics. Parts of the scour trough were dominated by zones of fresh rock debris and ice dissolution structures. These are interpreted to have formed as a result of dissolution on the seafloor of large negatively buoyant fragments of ice, rich in englacial debris, breaking off the trailing edge of the iceberg. Erosion of the ice keel and deposition of englacial debris both play an important role in the formation and shape of a scour mark.

Over the entire Labrador Shelf banks, erosion appears to be dominant over deposition. The amount and mechanisms of erosion are indicated by the six year old "Caroline" scour which is thought to have had widths and probably depths similar to those of the crosscutting fresh scour at the time of formation but which is now substantially reduced and altered. Berm height is one metre less than the "fresh" scour and the conspicuous sediment blocks are almost completely removed. The mechanism of scour erosion is interpreted to be the result of two interacting agents, namely biogenic reworking combined with current removal of the fine particles put into suspension by the bottom dwellers and filter feeders. Erosion of the massive cohesive sediment blocks by hydraulics alone would normally require a much stronger current flow acting over a long period of time; disaggregation and suspension by the filter feeders and assorted bottom benthos considerably accelerates the rate of erosion. The 100 khz sidescan data of these scours aided by the visual ground truthing clearly resolves the difference in scour morphology and demonstrates rapid obliteration of a scour mark over a six year period.

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PISCES IV submersible observations in the epicentral region of the 1929 Grand Banks earthquake

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Hughes Clarke, J.E., Mayer, L.A., Piper, D.J.W., and Shor, A.N., PISCES IV submersible observations in the epicentral region of the 1929 Grand Banks earthquake; in Submersible observations off the East Coast of Canada, D.J.W. Piper, editor; Geological Survey of Canada, Paper 88-20, p. 57-69, 1989.

Abstract

The PISCES IV submersible was used to investigate the upper continental slope around 44°N, 56°W, near the epicentre of the 1929 Grand Banks earthquake. Four dives in water depths of 800-2000 m were undertaken to observe specific features identified with the SeaMARC I sidescan system in 1983. Two dives were made in the head of Eastern Valley where pebbly mudstones of probable Pleistocene age were recognized outcropping on the seafloor. Constructional features of cobbles and boulders, derived by exhumation and reworking of the pebbly mudstone, were also observed. These include gravel/sand bedforms (transverse waves) on the valley floor. Slope failure features in semiconsolidated mudstone were recognized on two dives onto the St. Pierre slope. Exposures in these mudstones are rapidly eroded by intense burrowing by benthic organisms.

Resumé

On a employé le submersible PISCES IV pour examiner la partie supérieure du talus continental aux alentours du point de coordonnées 44°N 56°W, près de l'épicentre du séisme survenu en 1929 dans la région des Grands bancs. On a entrepris quatre plongées entre 800 et 2000 mètres de profondeur pour observer des détails spécifiques identifiés en 1983 au moyen du sonar SeaMARC I à balayage latéral. On a effectué deux plongées dans la partie amont de la vallée est, où l'on a identifié des mudstones caillouteuses datant probablement du Pléistocène, et affleurant sur le fond marin. On a aussi observé des accumulations de galets et blocs résultant de l'exhumation et du remaniement des mudstones caillouteuses. Il s'agit en particulier de structures superficielles sablo-gravelleuses (ondes transversales) sur le fond de la vallée. On a déterminé au cours de deux plongées effectuées sur le talus du banc de St-Pierre, des structures d'effondrement des pentes, à l'intérieur de mudstones semi-indurées. Dans ces mudstones, les affleurements sont rapidement érodés par l'intense activité fouisseuse des organismes benthiques.

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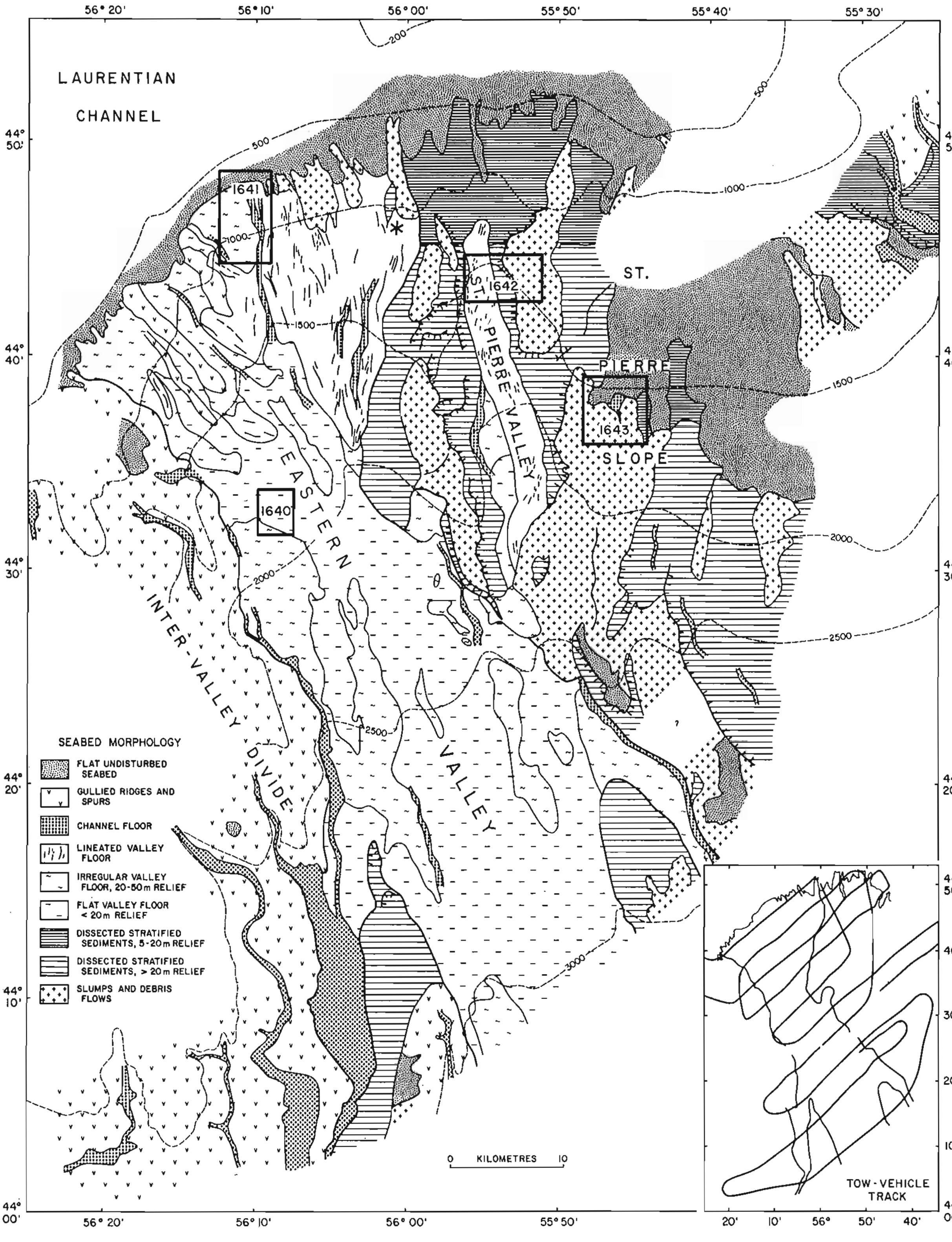

Figure 5.1. Seabed morphology of the area around the 1929 earthquake epicentre (indicated by *) based on SeaMARC I sidescan imagery (from Piper et al., 1985) showing location of Pisces dives.

INTRODUCTION

Scientific background to the area

The epicentre of the 1929 Grand Banks earthquake occurs at 44°42'N, 56°00'W (Dewey and Gordon, 1984). The magnitude 6.8 earthquake is known for an unusual sequence of breaks in underwater communication cables synchronous with and following the event at 2032Z on November 18, 1929 (Doxsee, 1948). Heezen and Ewing (1952) suggested that the sequence of cable breaks resulted from a turbidity current that flowed across the continental rise into the adjacent Sohm Abyssal Plain. Heezen and Drake (1964) suggested that this turbidity current was due to a large scale slump on the upper continental slope. More recent investigations (Masson et al., 1985; Piper et al., 1985) found no evidence for a single major slump. A SeaMARC I survey of a region of 100 by 100 km over the epicentral region (HUDSON cruise 83-017, Fig. 1, Piper et al., 1984; 1985) showed widespread shallow failure on the St. Pierre Slope and at the head of the Eastern Valley of the Laurentian Fan, around the epicentre of the 1929 earthquake (Fig. 5.1). The uppermost continental slope, in less than 600 m water depth, was not affected by slumping. 3.5 kHz seismic reflection profiling and subsequent coring (DAWSON cruise 84-003) also demonstrated widespread stripping of the top 5-10 m of Holocene gas-charged muds on the St. Pierre Slope. In Eastern Valley, headwall scarps on the SeaMARC imagery progress downslope into an area of irregular, discontinuous lineations that appear erosional in origin. Below 2000 m water depth, areas of high intensity of acoustic backscatter with transverse features have been interpreted as gravel waves resulting from the 1929 turbidity current (Piper et al., 1985).

Scientific objectives

On the basis of the SeaMARC I sidescan imagery, eight submersible dive sites were selected to ground truth the imagery and to observe relief below the limit of SeaMARC resolution (pixel size 2.5 m). Diving was limited to four of the eight days available because of fog. Four dives were undertaken, two in the head of Eastern Valley and two on St. Pierre Slope (Fig. 5.1).

The dive objectives in Eastern Valley were to investigate a transition from the headwall scarps, through suspected erosional terrain to a region where the shallowest transverse features (possible gravel waves) developed in the area of high acoustic backscatter occur. Particular attention was to be paid to the identification of features which may have resulted from recent sediment failure or current erosion.

The two dives on the St. Pierre Slope were designed to examine the St. Pierre valley floor and margins and a series of small scarps (appearing like "thumbprints" on SeaMARC sidescan images) that closely resemble rotational slumps on land (LaRochelle et al., 1970; Bentley and Smalley, 1984). An attempt was made to determine the age of these features by examining the extent of bioturbation and the thickness of overlying sediment.

Methods

The program was carried out from the submersible PISCES IV and mother ship M.V. PANDORA II. The operational features of PISCES IV are described by Syvitski et al. (1983). Bottom still photography was by hand-held cameras within the submersible. A continuous video was made by external camera. Navigation of PANDORA II was by Loran-C, corrected by manually logged satellite navigation. Problems were encountered in attempting to identify precise dive locations relative to the 1983 SeaMARC sidescan images. Although the ship's track for the 1983 survey is well known through Loran-C and satellite navigation, the SeaMARC towbody position was not well constrained. In addition, the sidescan mosaics used are only accurate to within 100-200 m, because of problems associated with correction for variations in ships speed and curved track corrections.

PISCES navigation was provided by using surface logged range and bearing from PANDORA II with a Honeywell short baseline acoustic tracking system. Positions were recorded manually every 5-10 minutes. The system performance was poor for dive 1640, but operated satisfactorily thereafter.

Brief descriptions of each dive are presented, based on observations, shipboard reports, and video coverage. Scientists on each dive are identified by their initials.

Acknowledgments

We thank the entire PISCES IV crew for their skillful handling of the submersible and willingness to operate very long, deep-water dives; we also thank the Captain and crew of PANDORA II. Norman Silverberg contributed significantly to observations and ideas reported for Dive 1642. This work was partly supported by the Canada Program of Energy Research and Development and by the Natural Sciences and Engineering Research Council. Manuscript was reviewed by P.R. Hill, G.B. Fader and B. MacLean.

EASTERN VALLEY FLOOR AT 2000 m (DIVE 1640: ANS, JEHC)

This dive consisted of a Z-shaped traverse across the central part of the Eastern Valley floor (Fig. 5.1 and 5.2) between 2000 and 1900 m. The dive was designed to examine an elongate channel developed in a low acoustic reflectivity facies which is parallel to the axis of Eastern Valley and the shallowest occurrence of transverse linear features seen on the sidescan images. These transverse features are better developed down valley, beyond the 2000 m depth limit of PISCES IV, where they appear as asymmetric gravel wave fields.

The major bathymetric feature in the region is an elongate channel or thalweg, striking NW-SE, 30 to 40 m below the main valley floor (Fig. 5.3). The dive began on the thalweg floor at 2006 m and during the first traverse, the submersible climbed out of the thalweg and across two E-W striking low ridges or swells (Fig. 5.4). The second leg of the dive traverse, to the southwest, crossed low amplitude features transverse to the valley, interpreted as gravel

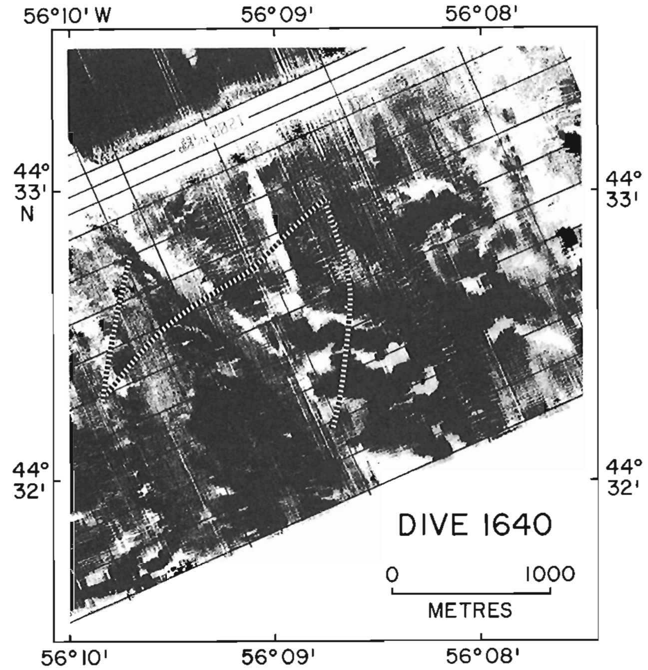

Figure 5.2. SeaMARC I sidescan imagery near dive site 1640 showing approximate position of dive track (dotted line).

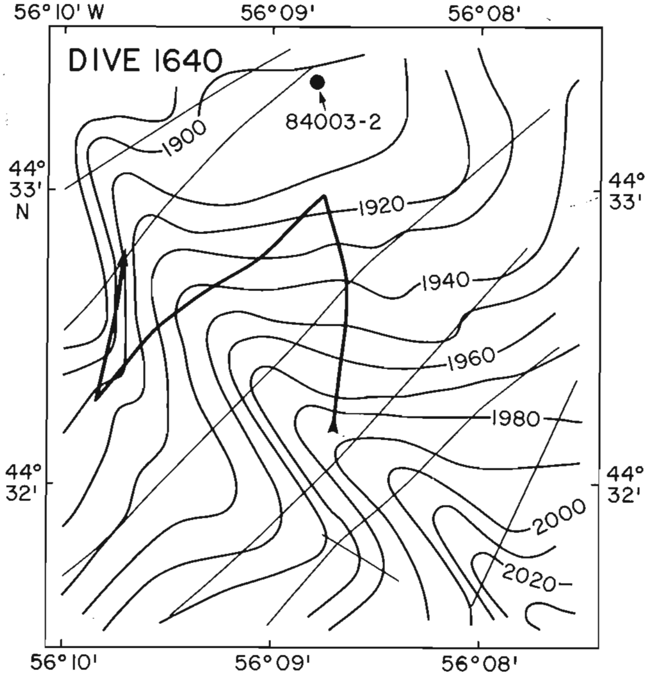

Figure 5.3. Bathymetric map of seafloor in the vicinity of dive 1640 showing dive track (thick continuous line). Bathymetry based on surface sounder profiles (thin continuous lines), using v = 1500 m/s.

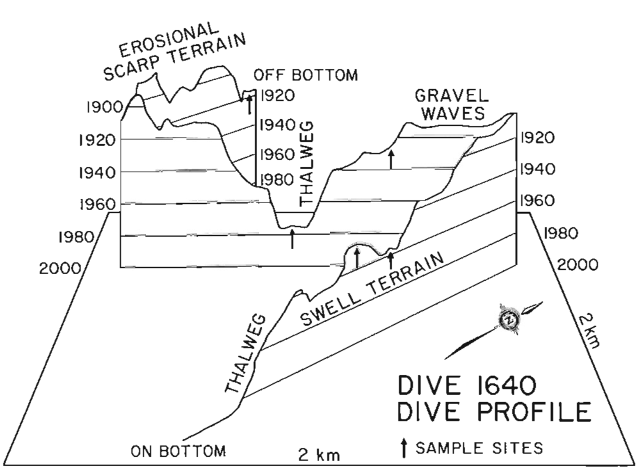

Figure 5.4. Profile of dive 1640 showing geologic terrains (based on submersible pressure depths).

waves, entered the thalweg and then crossed a terrain dominated by scarps and crests of outcropping pebbly mudstone (Fig. 5.4). The third leg, to the northeast, crossed this erosional scarp terrain and re-entered the thalweg. The four geomorphic regions or terrains are described individually below.

Swell terrain

This region corresponds to E-W striking troughs and swells seen on the sidescan immediately to the east of the thalweg. Two swells with an amplitude of 16 m were traversed on the first leg of the dive traverse. Outcrop of pebbly mudstone was seen only in the trough between the two swells and on the south-facing slope at the edge of the gravel wave region to the north. Elsewhere the terrain was characterized by scattered boulders with a thin mud drape. Throughout the region, there were occasional blocks of pebbly mudstone amongst the boulders.

Between the gravel waves and the thalweg on the southwest leg, the submersible crossed the western end of the northern swell. Outcrop of mudstone and pebbly mudstone became more common as the swell was approached. There was a high density of boulders as the swell was crossed, but no outcrop was associated with the 15 m high slope at its eastern edge (Fig. 5.4).

Gravel wave region

This region, situated to the northeast of the swell terrain, consisted of areas of boulders and areas dominated by mud. Wherever the mud was probed, it was underlain by gravel. A series of steep faces were traversed, 2 to 4 m high, striking 030° to 060°, with a spacing of 15 to 20 m. These steep faces sloped at 30° to 40° down valley and were commonly draped by 20 cm of mud. They appeared to be constructional features of clast-supported cobble gravel. The crests of these faces were followed and were seen to bifurcate or die out within 50 m. Between the steep faces, boulders were common on the flatter seafloor (Fig. 5.5) with increasing boulder density towards the base of the faces. These faces

Figure 5.5. Bottom photograph of boulders on seabed in trough in gravel wave field, dive 1640 (1640-P022).

correspond to the gravel waves interpreted from the sidescan images, with boulder lags on the stoss sides of the waves, an increase of boulders in the troughs, and a mud drape over the lee slopes. Other local troughs and depressions in the seafloor may result from scour.

On the southwest leg of the dive transect, low mudstone and pebbly mudstone outcrops were interspersed with these gravel wave constructional features. These outcrops displayed a streamlined morphology which appeared to have been flow moulded. At the base of one crest, a 5-m-long displaced block of red pebbly mudstone was observed. The block had no obvious source and there was no outcrop on the adjacent wave crest.

The presence of flow-moulded outcrop within the gravel wave field implies that the gravel waves and boulders occur in a thin layer overlying an eroded pebbly mudstone. The swell terrain probably is a seabed morphologic expression of outcrops of the underlying pebbly mudstones.

Thalweg channel

The dive began and ended in the thalweg channel, and the channel was crossed a third time in the middle of the dive. Where the dive began, the channel floor was smooth and mud covered, with coarse clastics conspicuously absent. The thalweg channel wall was 30 m high, with an average slope of 20° and consisted of rare exposure of cobbles and boulders in an otherwise mud dominated terrain. East-west striking crests, 3 to 5 m high with the steeper face downslope, were traversed. An isolated, heavily bioturbated mudstone block, apparently sculpted by flow, was seen.

On the southwest traverse in the middle of the dive, the northeast wall of the thalweg was 37 m high, exhibiting no outcrop and had lines of boulders down spurs on the wall. Mudstone blocks were observed at the base of the wall. The crest of the wall was defined by a break in slope and a zone of boulders, which passed upslope into flat muddy seafloor. The thalweg floor was covered with unconsolidated silty clay to the limit of core penetration from the submersible (30 cm), and exhibited low (10-30 cm), axially-aligned mud ridges. The southwest wall was 27 m high and had boulder scree up to the crest, but no outcrops of mudstone were seen.

The dive terminated close to the southwest wall of the thalweg channel, after the submersible had descended 18 m across successive ledges of outcropping pebbly mudstone. Below each ledge, displaced pebbly mudstone blocks occurred. The thalweg channel floor was not reached before the dive was terminated.

Erosional scarp terrain

This region lies southwest of the thalweg, about 70 m above its floor. The seabed consisted of angular crests and scarps, 3 to 5 m high, of outcrop of pebbly mudstone, which lacked any alignment. The presence of large fresh slide blocks below scarps suggested that sediment is continuing to fail. The slide blocks appeared to have been broken up, partly by bioturbation, exhuming large volumes of cobble and boulder sized gravel from within the blocks (Fig. 5.6). The largest boulders observed were 2 m in diameter. Some streamlined, flow-modified outcrop was seen. Most of the relief appears due to failure during the 1929 event and subsequently throughout the last 56 years.

EROSIONAL UPPER PART OF EASTERN VALLEY (DIVE 1641: DJWP, LAM)

This dive was in the upper part of the Eastern Valley of Laurentian Fan (Figs. 5.1, 5.7 and 5.8). It began at a depth of 1268 m on the valley floor and continued for five kilometres up the valley to a depth of about 1000 m. From there, the dive continued upward on one of the ridges that separates the head of the valley into a number of tributaries, terminating at a depth of 647 m where slump scars incise the smooth upper continental slope at the head of the valley (Figs. 5.7 and 5.8). Seven geologically and morphologically distinct zones are distinguished along the dive track (Fig. 5.9).

Figure 5.6. Bottom photograph of pebbly mudstone outcrop from erosional scarp terrain, dive 1640 (1640-P55).

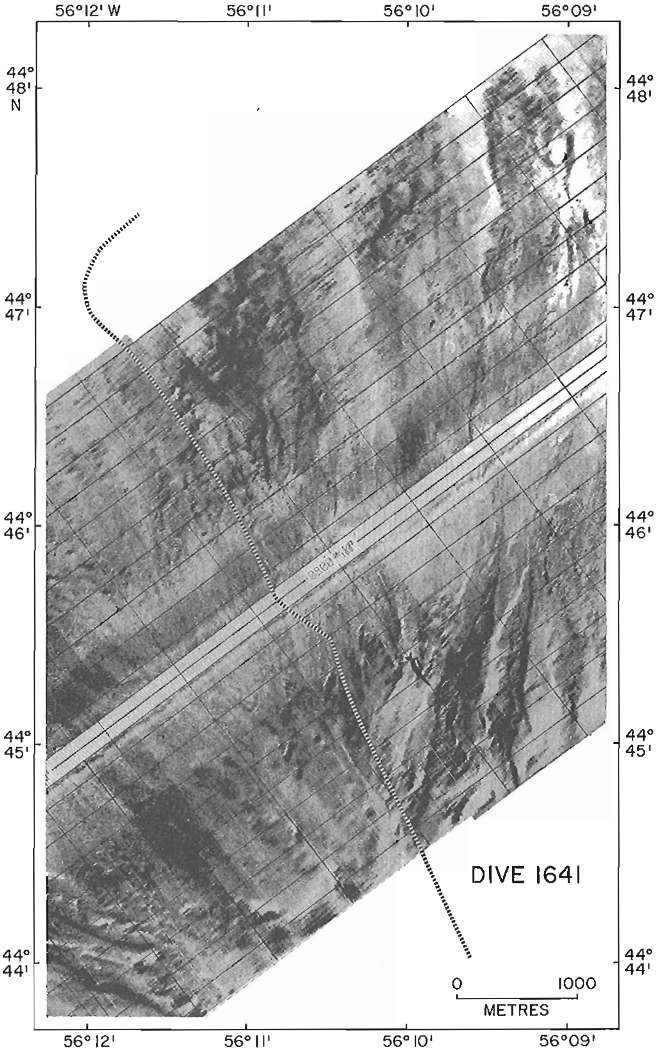

Figure 5.7. SeaMARC I sidescan imagery showing location of dive 1641 (dotted line).

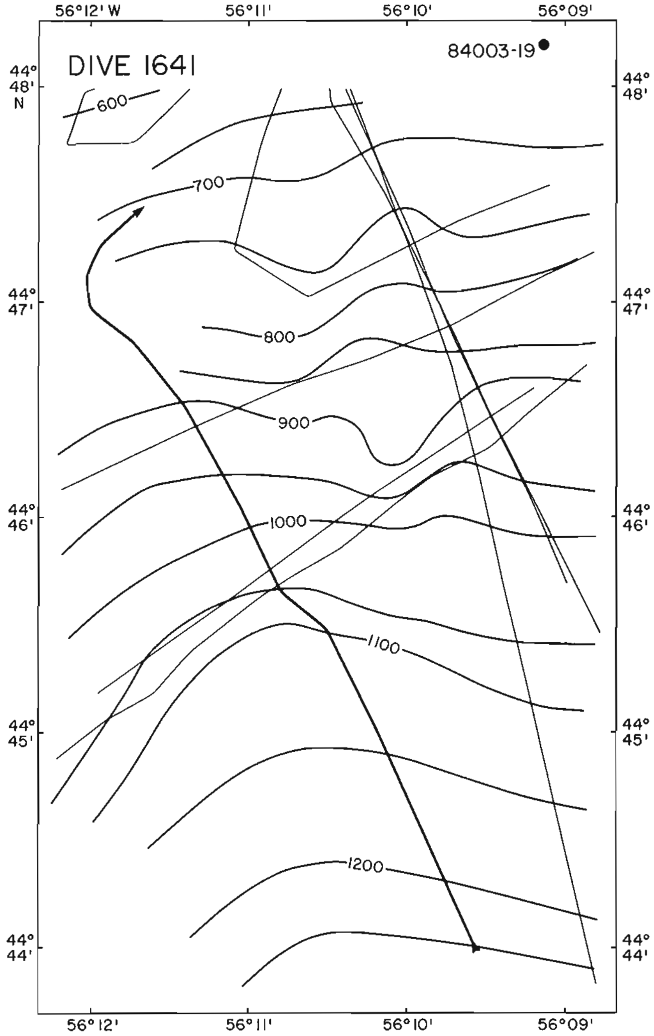

Figure 5.8. Bathymetric map of seafloor in the vicinity of dive 1641 (thick continuous line). Bathymetry based on surface sounder profiles (thin lines) using v = 1500 m/s. Also shows location of piston core 84003-19.

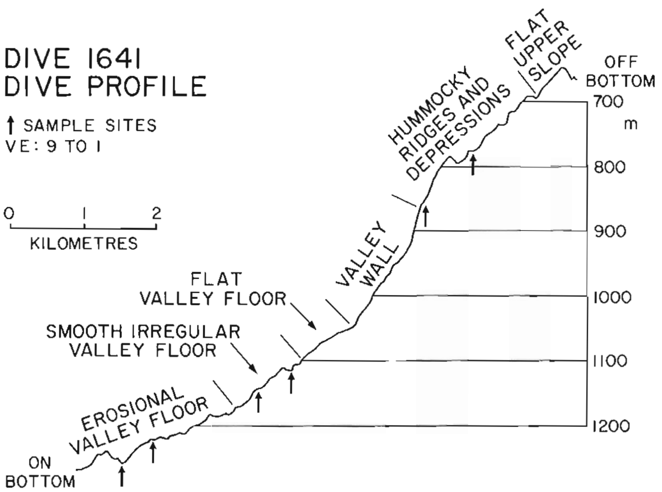

Figure 5.9. Profile of dive 1641 showing geologic terrains (based on submersible pressure depths).

Erosional valley floor

This zone consisted of red mudstones and pebbly mudstones, mantled by soft grey mud. The mudstones outcropped in a series of scarps typically a few metres high and oriented roughly north-south. These scarps alternated with flat terraces apparently defined by bedding and joint planes. Talus slopes and angular blocks of red mudstone occurred at the base of the scarps. Rarely, blocks that were partially detached along joint planes from the subhorizontally bedded outcrops were seen. Some scarps had a scalloped appearance, with chutes. On some flat terraces, there were low elongate depressions (20-30 cm deep) also oriented roughly north-south; these may have formed at the same time as more deeply incised linear chutes.

Outcrops of mudstones were commonest in the deeper part of the erosional valley floor, whereas pebbly mudstones were common in the shallower part. Pebbles, cobbles and boulders were seen embedded in the pebbly mudstone where it outcropped. There was frequently a concentration of these gravel size clasts (resembling winnowed lag) on the flat terraces immediately above the scarps and on low upstanding areas of mudstone. Clasts were also seen on many talus slopes. Elsewhere, small clasts and red mudstone matrix material appeared to have been brought to the surface through the surficial grey mud layer by bioturbation. There appeared to be a correlation between the abundance of surface clasts and the abundance of clasts locally seen in the mudstone, suggesting that the clasts may represent a lag winnowed out of the mudstone (perhaps from partially broken, slumped blocks).

Blocks of mudstones were common below outcrop scarps. They were generally angular, and sometimes appeared like pieces of a jigsaw puzzle, that could be reconstructed. Some showed steeply dipping bedding. They thus appeared to have been derived locally by slumping off the scarps.

At the beginning of the dive, a communications cable was found, which was covered with considerable epifaunal growth (Fig. 5.10a). The cable ran over the edge of several scarps including a 10 m high mudstone scarp, and into areas of large mudstone blocks below the scarps. The cable was bent through an angle of about 50° around blocks up to several metres in size (Fig. 5.10b). The cable was frequently buried in talus and under grey mud. In at least two places it appeared to be buried beneath large blocks of red mudstone (but this observation is not unequivocal). On the basis of these observations, it may have been one of the cables broken in 1929. The Commercial Cable Co. C1 cable was laid closest to the site at which the cable was found.

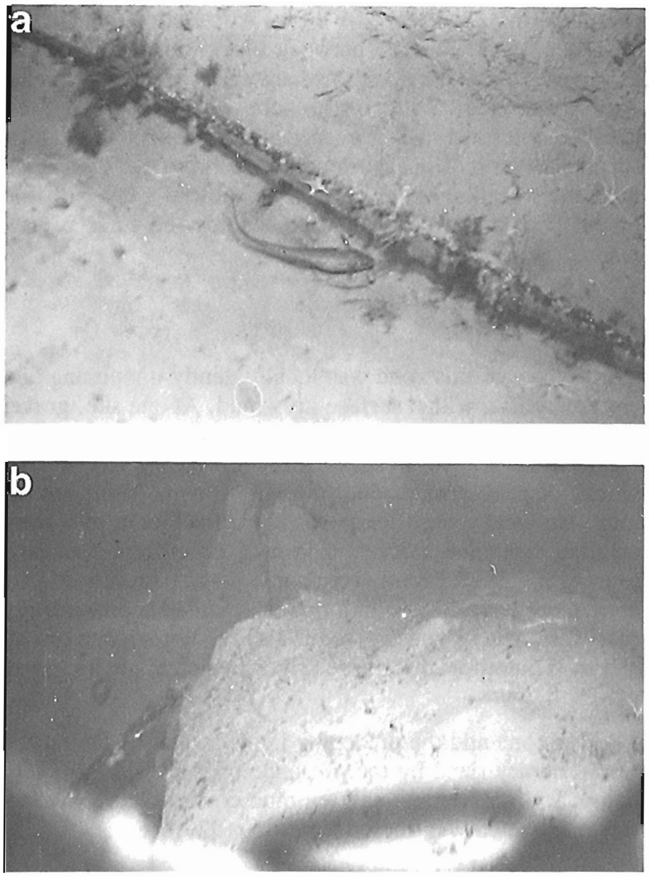

Figure 5.10. Bottom photographs of seabed telecommunication cable on floor of upper Eastern Valley (a: 1641-P04, b: 1641-S09).

The scale of the major scarps and terraces, and the preservation of the cable segment which passes over several scarps, indicate that these larger features may have existed before 1929. The mudstone blocks may have been displaced in 1929. If the surface lag of clasts resulted from in situ winnowing, the concentration of clasts in the pebbly mudstone indicates that only a few metres of mudstone or mudstone blocks would have to be broken up to produce the observed concentrations.

Irregular valley floor

This was an area of irregular topography with occasional low scarps. Red mudstone or pebbly mudstone outcropped only rarely and appeared "weathered" and friable compared with that seen in the scarps to the south. (This friable character may be due to a higher silt content). The significance of the contrast between blocky mudstone on the erosional valley floor and "weathered" mudstone in this zone is not clear. Most of the zone was mantled by grey mud. Cobbles and finer gravel occurred intermittently at the surface, as on erosional valley floor to the south. Two cores from the irregular valley floor both showed a layer of fine gravel with a red sandy matrix beneath the surface grey mud.

Flat valley floor

The surface of this zone was locally gently undulating and elsewhere flat, with a surface grey mud. At one site, gravel was found beneath 1 cm of grey mud. Clasts were seen only locally at the seabed. In one area, there were several isolated blocks of pebbly mudstone, the largest some three metres long. No local source scarp was seen; the blocks may have resulted from ice rafting, slumping or current transport (during the 1929 event) from some distant source. In one area, there were 10-cm-high ridges, oriented approximately east-west, with a spacing of 50-100 m. Sorted fine gravel and mud outcropped on these ridges, which might be gravel waves.

This zone and the preceding irregular valley floor zone were characterized by the presence of gravel immediately below a fairly continuous grey mud cover. They may thus represent a thalweg facies from the 1929 event.

Valley wall

The steep valley wall between 1010 m and 863 m consisted of a series of irregular ridges. Red mudstone and pebbly mudstone outcropped in scarps 1 to 5 m high. These scarps were much more irregular than on the erosional valley floor, and lacked terraces. Much of the slope was covered with grey mud. Cobbles and gravel patches occurred locally.

Hummocky ridge and depression terrain

A distinctive seabed morphology, correlated with ridge and gully terrain in SeaMARC sidescan images, occurred between 863 m and 657 m. The scale of features observed from PISCES was much smaller than the ridges and gullies in the SeaMARC sidescan images. This terrain consisted of a very hummocky pattern of ridges and depressions with a resemblance to badland topography seen on land. However, not all of the depressions were continuous, and some, up to 1 m deep, were closed. Many of the ridges were rounded in profile, whereas others exhibited pinnacle-like crests composed of grey and red mudstone. These were very intensely bioturbated on their flanks, particularly by large sub-horizontal burrows. Chutes of sediment at the angle of repose were visible. Pebble lags were seen along gully axes and appeared to represent concentration of pebbles exhumed through bioturbation of the gully walls (Fig. 5.11). Mass wasting through bioturbation offers an explanation for the irregular surface morphology. However, prior slope dissection to form the ridge and gully system was necessary.

Figure 5.11. Bottom photograph of gravel lag below outcrop of gravelly mudstone on Eastern Valley wall (1641-S51).

Flat upper slope

This zone was monotonously flat and smooth, with a highly bioturbated grey mud surface. It is correlated with the smooth upper slope seen on SeaMARC sidescan images.

Upper slope recessional slumps

Recessional slumps were seen on either side of the flat upper slope, cutting into it to form a series of steep, scalloped scarps and terraces. The scarps were many metres high and exposed grey-green sediment. Large blocks appeared to have fallen off the scarps, and remnant ridges with pinnacles occurred.

ST. PIERRE VALLEY WALL (DIVE 1642: ANS, NS)

This dive began on the floor of St. Pierre valley at 1620 m (Fig. 5.1) and traversed to the east across the floor to the valley wall, climbed 370 m up the wall, and crossed into wrinkled to smooth mud terrain at 1170 m (Figs. 5.12, 5.13 and 5.14). Three main geomorphic regions have been distinguished on the basis of SeaMARC sidescan images and the dive observations.

St. Pierre Valley floor

The floor appeared largely erosional, with linear mud ridges oriented down valley, spaced at 5 to 7 m and with an amplitude of 40 to 150 cm. The bottom was stiff mud, as indicated by the dropweight and arm probing. Small flakes of semi-lithified clay aggregates occurred scattered on the surface. The ridges were sometimes developed as a series of benches as the valley axis was approached, implying outcropping bedding planes. Rare, widely scattered boulders were present, although none appeared to be part of outcrop. These ridges and benches are believed to correspond to the axially oriented sidescan features imaged on the valley floor by SeaMARC.

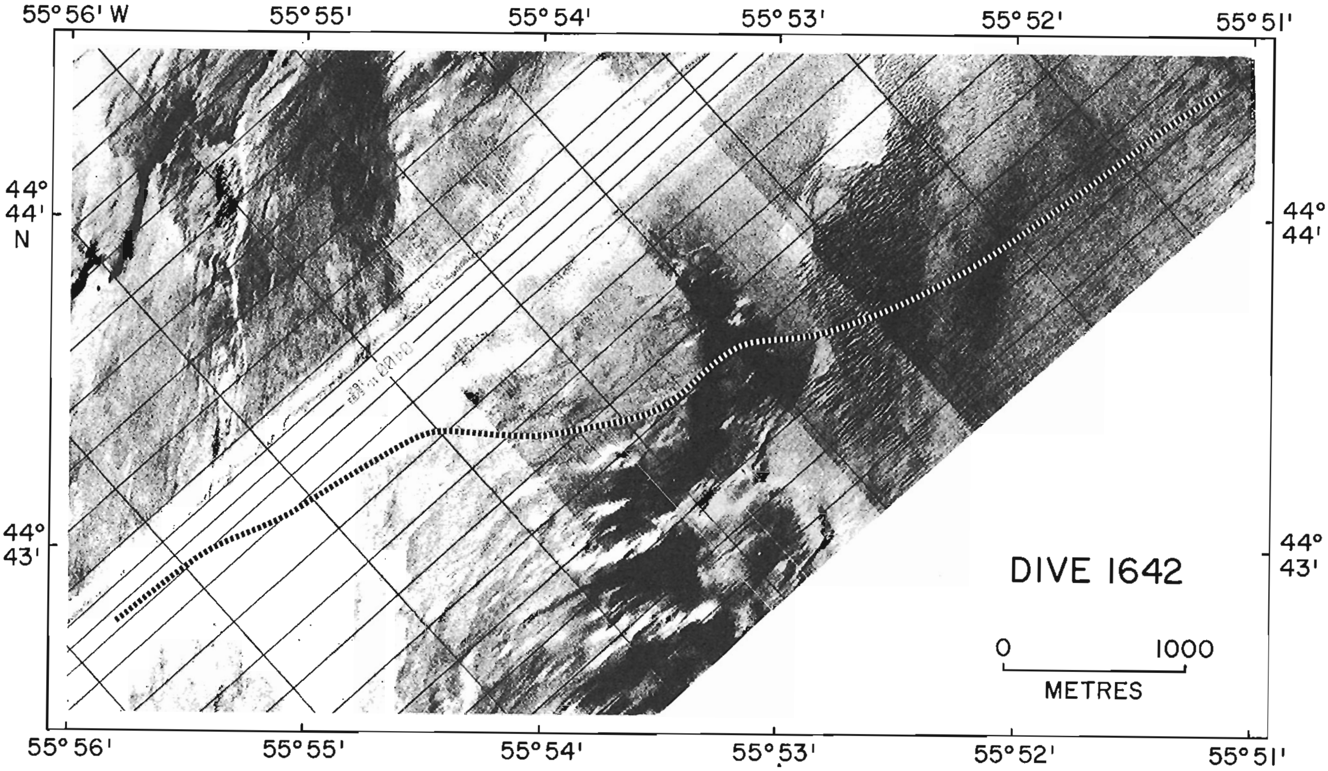

Figure 5.12. SeaMARC I sidescan imagery showing location of dive 1642 (dotted line).

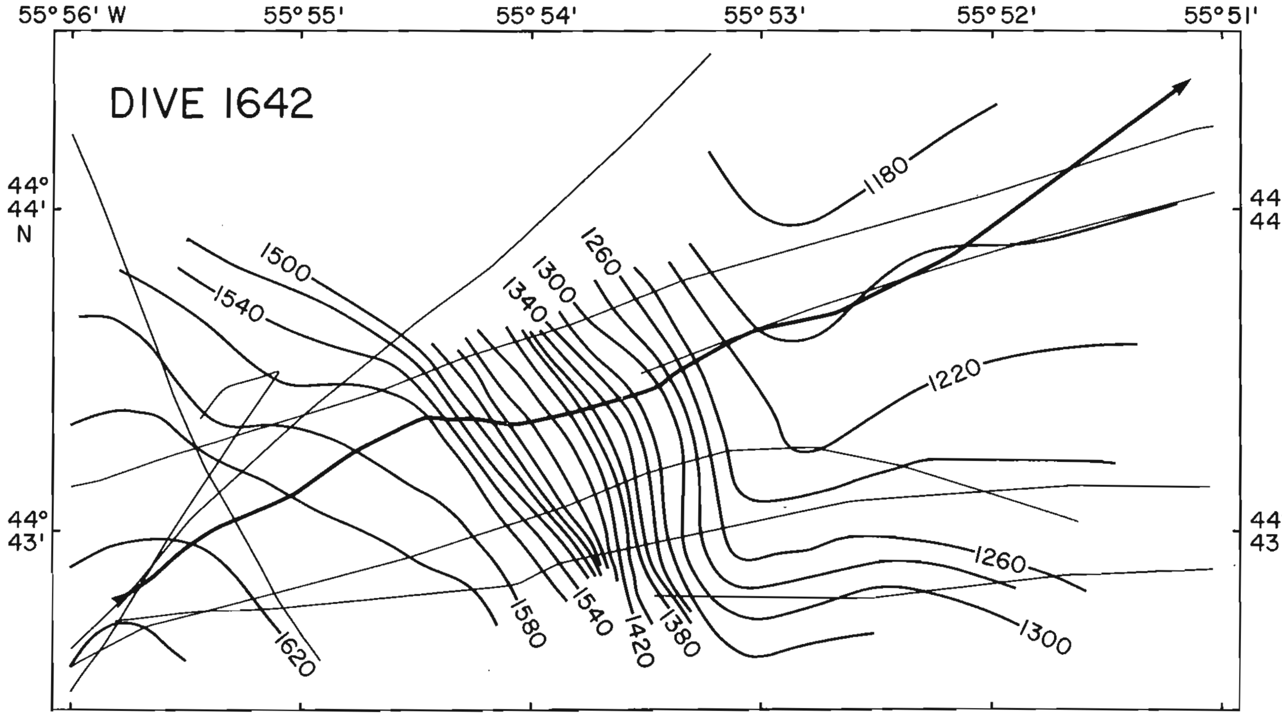

Figure 5.13. Bathymetric map of seafloor in the vicinity of dive 1642 (thick line). Bathymetry based on surface sounder profiles (thin lines) using v = 1500 m/s.

Valley wall

As the eastern wall was approached, isolated mudstone blocks occurred. The gradient of the wall averaged 30° and was steeper and dissected into gullies and spurs where there was extensive outcrop. Outcrops included well bedded red mudstone and occasional semilithified mudstone with a few pebbles and cobbles were also seen in the outcrop. Displaced blocks were seen with sharp unbioturbated faces, some with a brownish stain. Angular scarps from which blocks presumably had been detached were observed.

Wrinkled terrain

Over the top of the valley wall, elongate asymmetrical ridges were again common, with the steeper faces to the south. The orientation of these ridges was variable, with strikes from 060° to 140°. The ridges merged and diverged across the terrain. The submersible sonar indicated that the region was one of poorly aligned ridges and mounds spaced approximately 3 m apart. These ridges correspond to the finely wrinkled terrain on SeaMARC sidescan images. No cobbles or boulders were seen and outcrop was rare. A possible gas escape structure was seen.

ROTATIONAL SLUMPS ON ST. PIERRE SLOPE (DIVE 1643: DJWP, JHC)

This dive crossed the ridges which resemble thumbprints on SeaMARC I sidescan images (Fig. 5.15) east of St. Pierre Valley, in about 1600 m of water depth (Fig. 5.1). A gully leading down from an amphitheatre-shaped scarp was

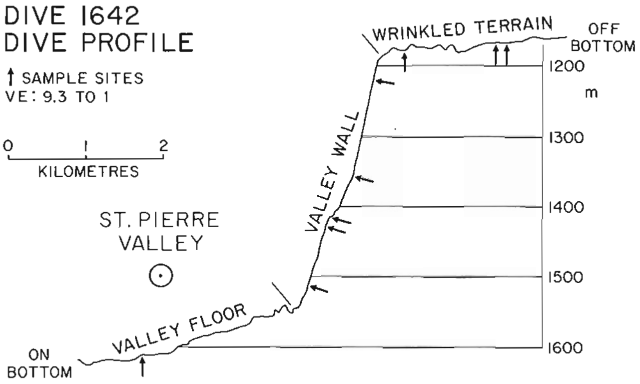

Figure 5.14. Profile of dive 1642 showing geologic terrains (based on submersible pressure depths).

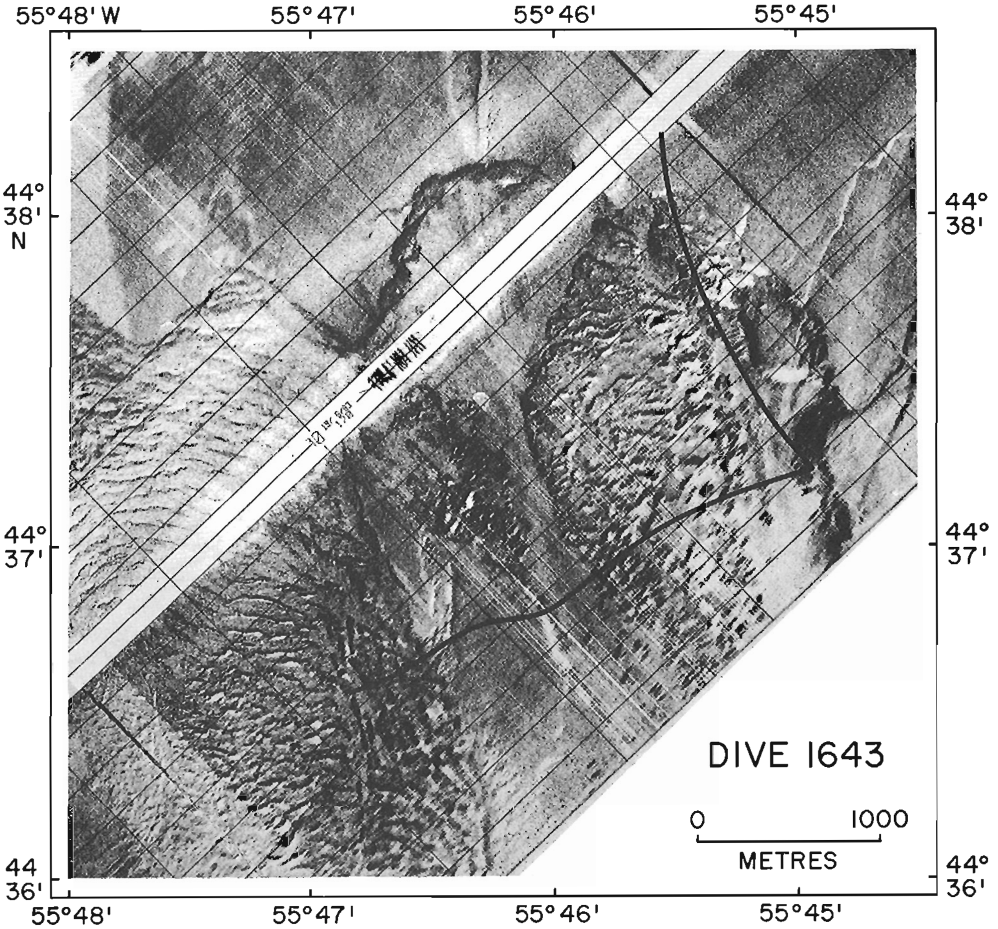

Figure 5.15. SeaMARC I sidescan imagery near dive site 1643 showing approximate position of dive track (dotted line) across "thumbprint" slumped area.

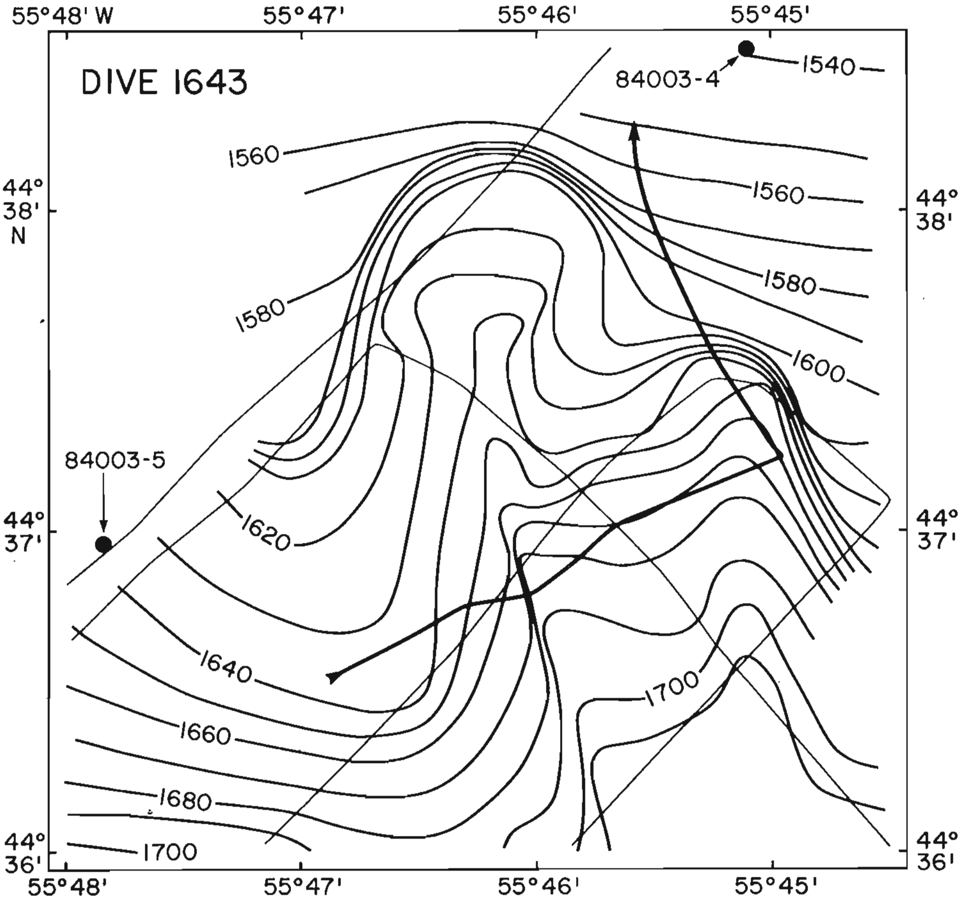

Figure 5.16. Bathymetric map of seafloor in the vicinity of dive 1643 (thick line). Bathymetry based on surface sounder profiles (thin lines) using v = 1500 m/s. Also shows location of piston cores 84003-4 and -5.

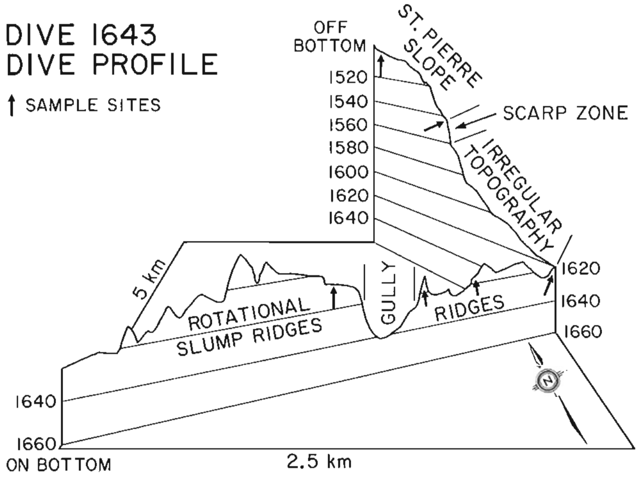

Figure 5.17. Profile of dive 1643 showing geologic terrains (based on submersible pressure depths).

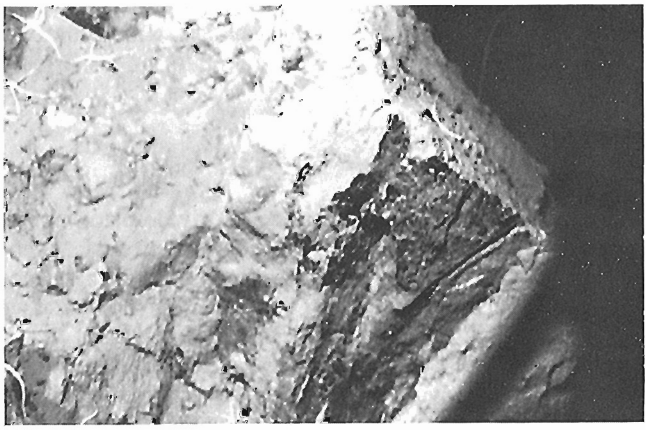

Figure 5.18. Outcrop of mudstone on crest of rotational slump ridge on St. Pierre Slope, dive 1643 (1643-S13).

crossed (Fig. 5.16). The dive then traversed upslope across irregular terrain onto the smooth St. Pierre Slope at about 1490 m water depth.

Six geomorphic regions are distinguished on the basis of the sidescan images and dive logs (Fig. 5.17).

Rotational slump ridges

Seven discrete ridges were crossed. The ridges had an amplitude of 5 to 15 m, were spaced 200 m apart, and consisted of fresh outcrops of red and green mudstone, with some bedding inclined at up to 60°. Fresh failure surfaces were observed, with displaced angular mudstone blocks and yellow staining on exposed faces (Fig. 5.18), suggesting that the outcrops are eroding today. Between the ridges were low regions of irregular relief of 50 to 100 cm amplitude, of intensely bioturbated, randomly oriented mud blocks. A series of blocks were seen that demonstrated the transition from fresh failure, through progressive degrees of biodegradation to intensely bioturbated mud mounds. Similar ridges continued to the east of the gully, but became more subdued and died out before the northern leg of the dive.

Smooth region

A low relief zone of seafloor was crossed between the area of rotational slump ridges and the gully. This corresponds to the north-south oriented featureless region west of the gully on the sidescan images (Fig. 5.15). There was no outcrop and the only relief features were smooth, 20-cm-high mounds.

Gully

The floor of the gully was reached below a 20-m drop over a series of steep cliffs which did not show any outcrop. The floor of the gully was smooth and muddy, with a conspicuously low faunal density. Low relief lineations oriented NNW-SSE were recognized.

Irregular topography

A transition from slump ridges to poorly defined irregular topography occurred east of the gully. The irregular topography was similar to the slump ridge terrain in that it consisted of alternating regions of ridges (though with little outcrop) and low areas, but relief was more subdued. The ridges were more rounded and the regions of subdued bottom more extensive. The irregular topography continued up slope to 1560 m where the gradient steepened.

Scarp zone

From 1560 to 1540 m fresh outcrop was again observed. This was the steepest section of the dive, and corresponds to the upper limit of a distinctive topography interpreted on the sidescan images as due to creep. A series of steep faces were traversed, one of which demonstrated outcropping red mudstone with bedding dipping at 60° to the northwest. This zone is interpreted as the headwall scarp of the rotational slump zone.

St. Pierre Slope

The lower part of St. Pierre Slope, just above the scarp zone, has irregular rounded hummocky topography with a relief of up to 2 m. Possible similar irregularity was seen on dive 1642 just above the steep eastern wall of St. Pierre Valley. Upslope, the roughness decreased, and the bottom above 1500 m was flat. The origin of the hummocky bottom is unclear.

DISCUSSION AND CONCLUSIONS

The outcrops and talus slopes observed on all the dives indicate that the region has experienced recent extensive mass wasting. On steep valley walls and headwall scarps, the fresh outcrops suggest that occasional mass wasting is continuing. This is in contrast to the heavily bioturbated rotational slump observed in dive 1643, which was inferred to have formed during the 1929 event. The PISCES observations did not provide clear evidence for the amount of failure in Eastern Valley. The cable that was found on Dive 1641 indicated that the major scarps and terraces of the erosional valley floor were probably present before 1929, and that mass wasting was restricted to the failure of large blocks from these scarps. The erosional scarp terrain on Dive 1640 gave the appearance of much more extensive failure.

The PISCES observations provide supporting evidence that the "thumbprint" terrain on St. Pierre Slope represents rotational slumps, probably dating from the 1929 earthquake. The relief in this area, however, was unexpectedly muted; deposition of sediment either during the 1929 event, or subsequently as a result of bioturbation, has infilled the depressions and rounded most of the ridges. Thus useful seabed observations were restricted to the rare outcrops. To the northwest, the smaller scale "wrinkles" were observed to consist of low ridges, but useful clues as to their origin were not seen.

Outcrops on the St. Pierre Valley and St. Pierre Slope consisted almost entirely of mudstone; coarse clasts were rare either in outcrop or as an erosional or mass wasting lag. In contrast, there were extensive outcrops of Pleistocene pebbly mudstone in Eastern Valley to water depths of at least 2000 m. These may reflect a major supply of glacial detritus through the Laurentian Channel; it is not known whether they are mass flow deposits, ice rafted facies, or (on the uppermost slope) true tills. They correspond to a seismic facies of incoherent reflections beneath the uppermost part of Eastern Valley described by Meagher (1984). The pebbly mudstones, with clasts up to boulder size, provide a source for the widespread coarse clasts recognized in Eastern Valley (Hughes Clarke, 1987).

The observations on the suspected gravel waves were inconclusive. They appear to overlie irregular topography eroded into Pleistocene pebbly mudstones. They were constructed of apparently locally-derived clasts, reworked into asymmetric dune-like features. The main gravel-wave fields of Eastern Valley were beyond the depth range of PISCES IV.

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Submersible observations of surficial sediments and seafloor morphology on the inner Scotian Shelf

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Abstract

The research submersible PISCES-IV was used to make direct observations of surficial materials and seafloor morphology along a 3-km track on the inner Scotian Shelf off Cole Harbour, Nova Scotia, in water depths of 20-33 m. The dive provided ground-truth data to complement interpretations derived from sidescan sonar and shallow seismic records, grab samples, vibracores, and limited photographic coverage obtained using surface vessels. Another objective was to sample material forming large, symmetrical, gravel ripples and to make direct measurements of bedform dimensions.

Gravel ripples with wavelengths up to 2.8 m, formed in sand-pebble mixtures with modal sizes up to 45 mm or larger, appear to be scaled to the orbital diameter of the near-bottom motion under competent winter storm waves with mean recurrence frequencies of more than 40 hours per year. The ripples form narrow, quasi-parallel, isobath-normal ribbons, which may be analogous to shallow, rippled, scour depressions reported from other inner-shelf locations. Much of the adjacent seafloor is covered by an apparently stable gravel armour, with encrusting algal growth on all but the finest gravel. The surficial gravel in the study area is believed to be primarily relict beach gravel dispersed after abandonment on the shoreface to form a thin veneer over large areas of the inner shelf.

An outcrop of finely-stratified sandy mud occurs at a present water depth of 29 m. This outcrop material is tentatively correlated with a subsurface acoustic unit that appears to be truncated at the seafloor. This unit has been interpreted as a back-barrier estuarine and tidal channel deposit. Other features observed include an extensive area of sand with small-scale, wave-formed ripples and, particularly in shallower water (20-25 m depth), cobble-boulder lags with large populations of seaweed, dominated by Agarum cribrosum.

Résumé

On a employé le submersible expérimental PISCES IV pour réaliser des observations directes des matériaux de surface et de la morphologie du fond marin suivant une voie de 3 km, dans la portion intérieure de la plate-forme continentale Scotian au large de Cole Harbour en Nouvelle-Écosse, entre 20 et 33 m de profondeur. La plongée a fourni des mesures sur site témoin qui complètent les interprétations dérivées de l'étude des enregistrements sismiques à faible profondeur et des relevés effectués avec le sonar à balayage latéral, de l'examen d'échantillons macroscopiques ramenés du fond et de carottes recueillies avec une foreuse vibrante, et de l'étude de la couverture photographique limitée déjà obtenue avec des navires de surface. On a aussi cherché à échantillonner les matériaux formant de grandes rides symétriques composées de gravier, et à mesurer directement les dimensions des structures superficielles du fond.

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Il est apparu que les dimensions des rides de gravier, de longueur d'onde atteignant un maximum 2,8 m, apparues dans les mélanges de sable et galets de dimensions modales atteignant 45 mm ou plus, étaient proportionnelles au diamètre orbital du mouvement engendré près du fond par les vagues compétentes de tempêtes d'hiver qui sont caractérisées par un taux de récurrence supérieur à 40 heures par an. Les rides forment des rubans étroits presque parallèles, normaux aux courbes isobathes, qui sont peut-être analogues aux dépressions peu profondes sillonnées de rides, produites par affouillement, signalées dans d'autres régions de l'intérieur de la plate-forme continentale. Le fond marin adjacent est en grande partie recouvert d'une cuirasse de graviers apparemment stable dans laquelle tous les graviers exceptés les plus fins sont recouverts d'algues encroûtantes. On pense que dans la région étudiée, les graviers superficiels sont essentiellement des graviers littoraux résiduels qui ont été dispersés après leur abandon sur l'avant-côte, et ont ensuite formé un mince placage sur de grandes étendues de l'intérieure de la plate-forme continentale.

*Il existe actuellement, à 29 m de profondeur, un affleurement de boues sableuses finement stratifiées. On a provisoirement corrélé cet affleurement à une unité acoustique de subsurface qui paraît tronquée au niveau du fond marin. On a interprété cette unité comme constituant un dépôt marginal d'estuaire et de chenal de marée. Parmi les autres détails observés, citons une vaste étendue de sable portant de petites rides formées par les vagues, et en particulier en eau moins profonde (entre 20 et 25 m de profondeur), des pavages de galets et blocs accompagnés par un grand nombre de plantes marines dominées par l'*Agarum cribrosum.

INTRODUCTION

This report summarizes the results of a short submersible traverse on the inner Scotian Shelf off Cole Harbour (Fig. 6.1) in mid-May 1985. This traverse (PISCES-IV dive 1604) was planned to ground-truth interpretations of seabed characteristics derived from sidescan sonar, shallow seismic reflection, and limited photographic and sample data obtained on earlier surface cruises in the area (Boyd, 1984; Hall, 1985). Another major objective was to observe and sample gravel bedforms identified on the sidescan records (Hall, 1985; Lapierre and Boyd, 1985). While these were known to be important bottom-roughness features and indicators of localized gravel mobility, they were poorly understood and could not be evaluated adequately without information on bedform dimensions and grain-size that was difficult to obtain from the surface. The PISCES-IV dive provided the basis for a detailed study of these bedforms by Forbes and Boyd (1987). Some results of that paper are included here, together with additional observations. Vibracore and shallow seismic data obtained more recently in the study area (Forbes, et al., 1988) provide additional insight into the factors affecting seafloor features observed from the submersible, and we therefore make reference to appropriate parts of this material also.

The major focus of this paper is on the detailed observations of seabed features that a submersible such as PISCES-IV makes possible. The submersible enables trained scientific observers who would not otherwise have access to the seafloor to make direct observations rather than depend on second-hand information from divers. A submersible also provides the means to cover a large area in a short time, with simultaneous video coverage and conversation between observers. This provides a view of the seafloor distinct from but complementary to that provided by other tools such as SCUBA, towed vehicles, or sidescan sonar. Remotely-operated vehicles may provide nearly-equivalent results in some cases (Judge and Forbes, 1987). Further details on the submersible operations that form the basis of this report can be found in a cruise report by Forbes and Boyd (1985).

Methods and equipment

The PISCES-IV submersible was launched from MV PANDORA-II. The location of the submersible with respect to the surface ship was determined at 4- to 15-minute intervals using a Honeywell-904 sonar range and direction system. At the same time, the position of PANDORA-II was obtained using a combination of radar, Loran-C, and a single Miniranger range. Radar- and Miniranger-corrected Loran-C positions yielded a track that matched earlier sidescan sonar data collected in the area (Fig. 6.2).

Observations during the dive were recorded on voice tape and in a written log. Two hand-held 35-mm cameras were used, one with a 50-mm lens and an exterior flash, the other with a 28- to 90-mm zoom lens and available light (natural and exterior flood). In most cases, better results were obtained with available light. Excellent records were obtained with the exterior video camera. Adequate measurements of seabed features were obtained by comparison with known dimensions of the extended manipulator arm and clam-shell grab.

Grab samples were collected using the arm and grab in materials ranging from fine sand to coarse gravel, with minimal loss of fine material. The coarser gravel fractions could not be sampled and for this reason the cobble and boulder material seen at some points in the gravel ripple troughs is not represented in our samples. Furthermore, the sample size of roughly 5 to 10 kg was minimal for material of coarse pebble to fine cobble size ($20 < D < 100$ mm) and inadequate for sediment containing larger clasts (Church, et al., 1985). We conclude from the sample sizes and size frequency distributions that sediment in gravel ripple crests was adequately characterized by our samples, but that cobble-size material ($D > 64$ mm) in the ripple troughs was not appropriately sampled.

Study area

The inner Scotian Shelf is an area of irregular bathymetry and complex surficial sediment cover, characteristics that

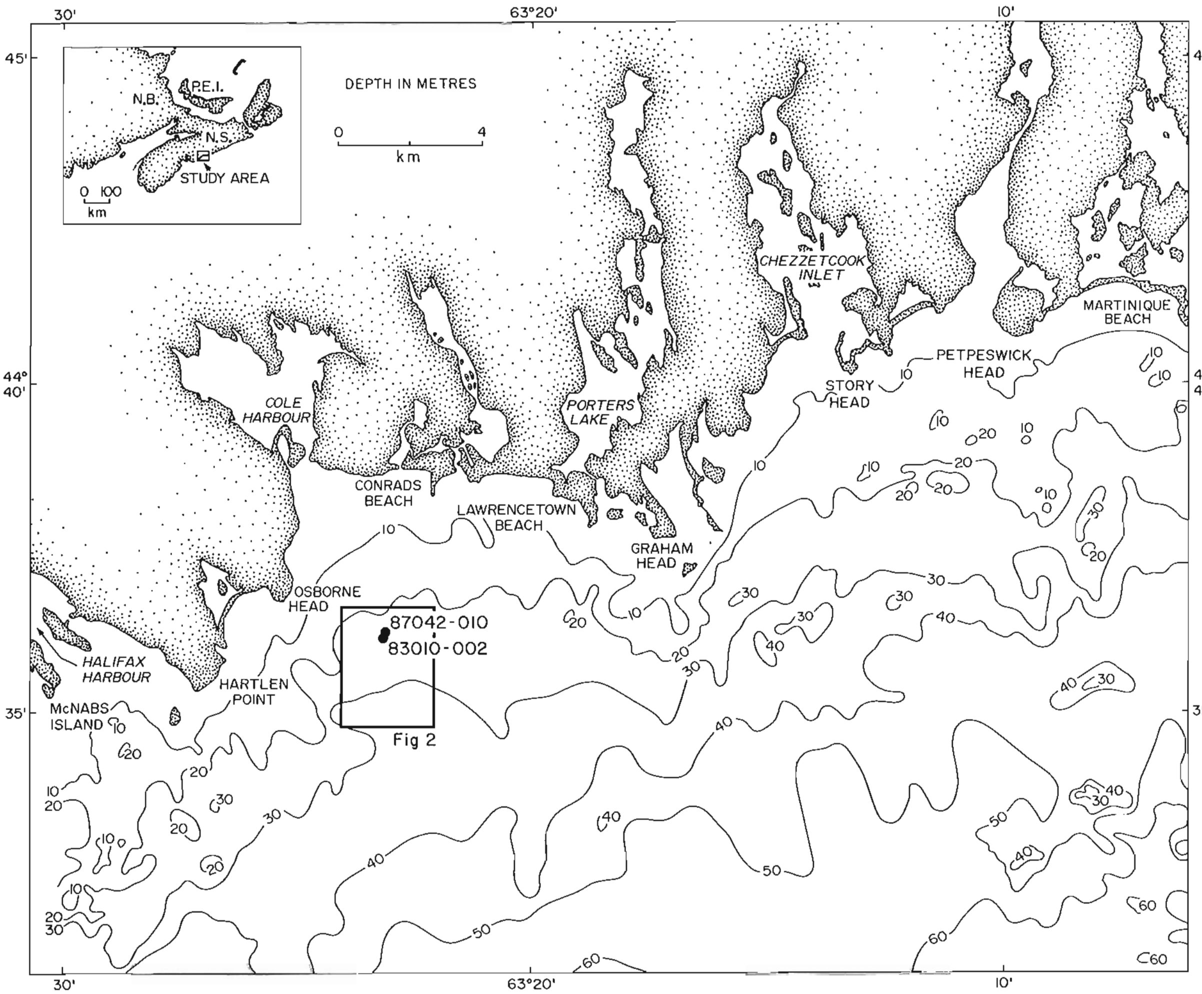

Figure 6.1. Part of the inner Scotian Shelf east of Halifax, Nova Scotia, showing study area and core locations. Box represents location of Figure 6.2.

reflect its recent history of Late Quaternary glaciation and postglacial marine transgression (King, 1970; King and Fader, 1986; Piper, et al., 1986; Boyd, et al., 1987; Scott, et al., 1987; Boyd, et al., 1988b). These processes have acted on a pre-existing erosion surface cut into resistant rocks of the Cambro-Ordovician Meguma Group (King, 1972; Schenk, et al. 1980). The sedimentary record of glaciation in the study area is contained in a succession of tills observed in coastal exposures (Stea and Fowler, 1979a, b) and in shallow seismic records offshore (Hall, 1985). Two general features of major importance in the study area are (1) the extensive Eastern Shore drumlin field (Stea and Fowler, 1979b) and (2) the numerous shallow valleys trending normal to the coast and extending offshore several kilometres (as seabed or sub-seabed features) to depths of about 60 m (Boyd, et al., 1988b). These valleys form protected depressions in which glacial and proglacial deposits have been preserved and in which estuarine sediments have accumulated during the Holocene transgression (Hall, 1985; Honig, 1987; Boyd et al., 1987). The drumlin field, which formerly extended some distance offshore, has provided the major source of sediment to the coast through erosion of drumlin headlands, which control the evolution of coastal features (Boyd et al., 1987; Carter, et al., 1987) and subsequently (after transgression) form topographic highs capped by cobble-boulder lag deposits on the inner shelf. The large proportion of gravel in surficial sediments of the inner Scotian Shelf is attributable to their provenance from glacial deposits incorporating resistant bedrock lithologies.

The small area off Cole Harbour investigated using PISCES-IV contains many features typical of the area. The dive track lies along the axis of a shallow depression underlain by a buried valley (Fig. 6.2), the seaward extension of Cole Harbour. The valley is flanked by topographic highs with a veneer of coarse lag material, predominantly cobbles and boulders. Shallow seismic records obtained in this area (Fig. 6.3) show acoustic basement (Meguma Group slates of the Halifax Formation) overlain by a lower incoherent acoustic unit (acoustic facies B) believed to be glacial till equivalent to one of the tills exposed in nearby coastal cliffs onshore. This material is in turn overlain by a lower acoustically stratified unit (acoustic facies C) within a valley cut into facies B. This lower valley fill is up to 20 m thick, with weak and irregular stratification in part conformable with

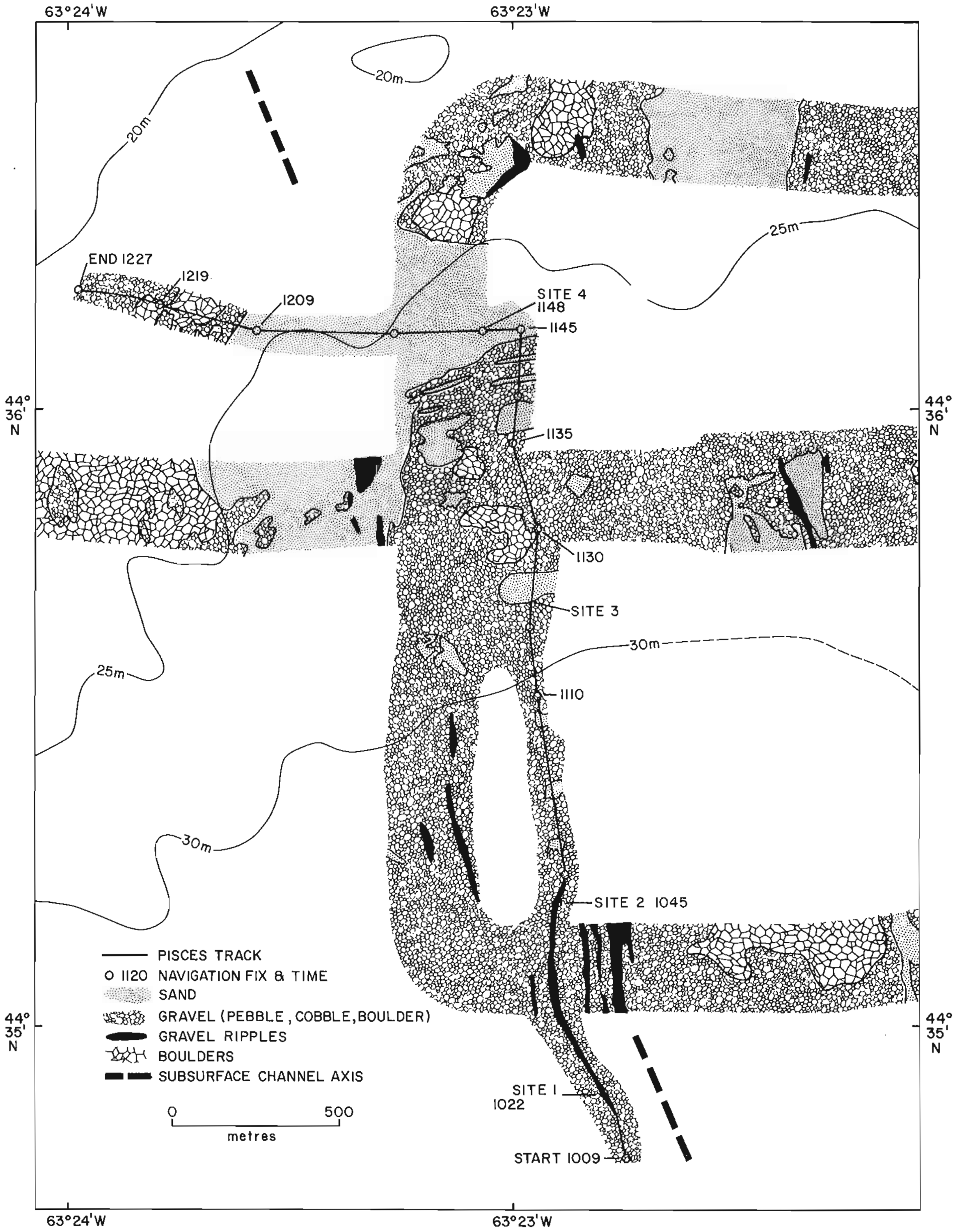

Figure 6.2. Detailed map of study area (Fig. 6.1) showing bottom types (based on sidescan sonar and submersible observations) and track of PISCES-IV dive 1604.

the lower boundary. This unit has been interpreted as a glaciofluvial deposit formed in either a subglacial or a near-ice-contact setting. The upper boundary of this lower acoustic unit is defined by a prominent reflector 3-9 m below the seabed, believed to be the Holocene transgressive contact, overlain by a complex acoustically stratified unit (acoustic facies D). The lower part of facies D shows an onlap structure within channel incisions into the lower stratified valley fill, but a weakly conformable character outside these channels. This unit is interpreted as a Holocene back-barrier estuarine deposit equivalent to the estuarine muds accumulating at present in the Cole Harbour estuary,

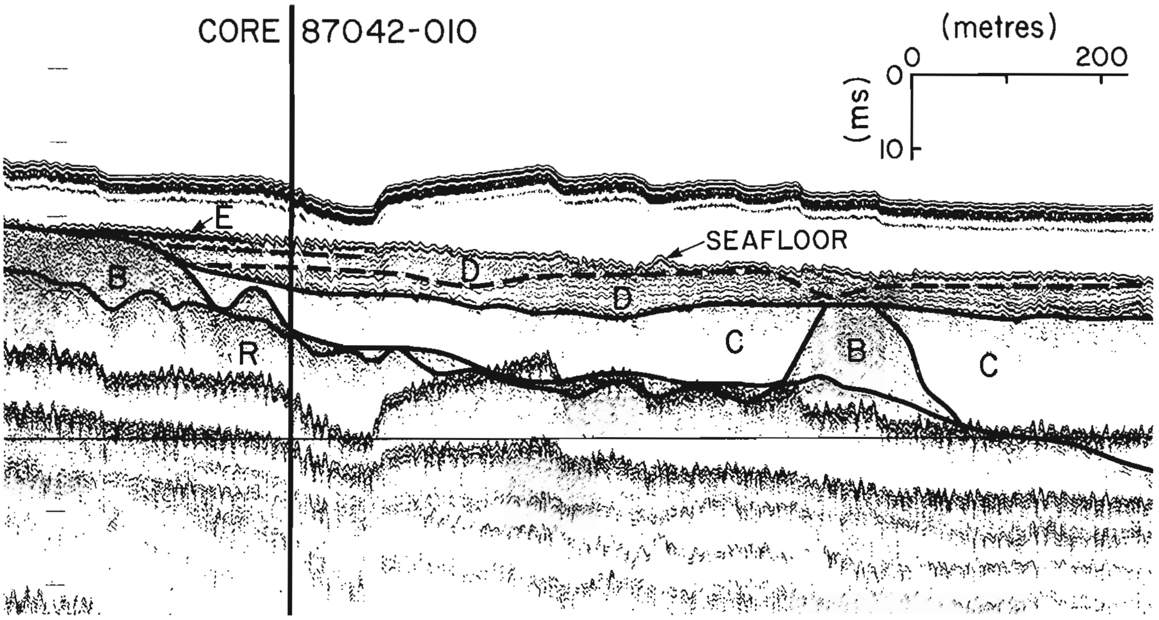

Figure 6.3. Part of deep-tow sparker shallow seismic record obtained in the study area during CSS DAWSON cruise 87042, with interpretation (see text for explanation of acoustic facies notation).

although a non-marine lacustrine or fluvial depositional environment is possible for at least part of the section. The upper part consists of high-angle structures indicating cut and fill in laterally-migrating channels considered most likely to be of tidal origin. This unit and the underlying part of acoustic facies D appear to be truncated and potentially exposed at the seafloor in a few locations. A thin discontinuous veneer less than 1 m thick (acoustic facies E) can be seen in places at the top of the seismic section. This is interpreted as sand and gravel formerly incorporated into beach and barrier deposits, and dispersed after transgression to form the nearly ubiquitous surficial sand and gravel veneer observed in the area of the dive track described below.

A 4.6-m vibracore (87042-010) was obtained in 28 m water depth offshore from Cole Harbour (Fig. 6.1). This core contained 0.2 m of pebbly sand, interpreted as a transgressive marine unit, overlying 3.5 m of massive dark-grey silty clay with organic lenses, shells including bivalves and gastropods both whole and fragmented, and small shale clasts. This middle unit, interpreted as estuarine mud, was in turn underlain by 1 m or more of red-brown pebbly clay, intepreted as a glacial diamict. Another short core (83010-002) from 26 m depth in the same vicinity (Fig. 6.1) contained 0.1 m of medium sand, considered to be the modern marine unit. This was underlain by 0.2 m of muddy sand, in turn underlain by 0.1 m of sand and gravel, and at least 0.5 m of sandy mud and muddy sand with shell fragments and balls of organic material (Hall, 1985). Organic muddy sand approximately 0.5 m down-core gave a radiocarbon age of 7425 ± 255 years B.P. (GX-10027).

Acknowledgments

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OBSERVATIONS FROM PISCES IV

Dive 1604 was 2 hours and 27 minutes in duration, beginning at 1003 ADT (1303 UT) on 15 May 1985 (time references in the following text are included to facilitate identification of positions in Fig. 6.2). The bottom was first encountered at 1009 ADT in 32.5 m water depth, where visibility was estimated to be approximately 15 m, with abundant comb jellies (ctenophores) and other organisms in the water column. The seabed at this location (Fig. 6.2) had the appearance of a flat gravel pavement (Fig. 6.4a). Some sand was visible in the interstices of the pebble-cobble seabed deposit. The latter was interpreted as a thin surficial armour, analogous to so-called armour layers found on fluvial bar surfaces (Bray and Church, 1980). Exposed faces of cobble and coarse pebble clasts were covered with

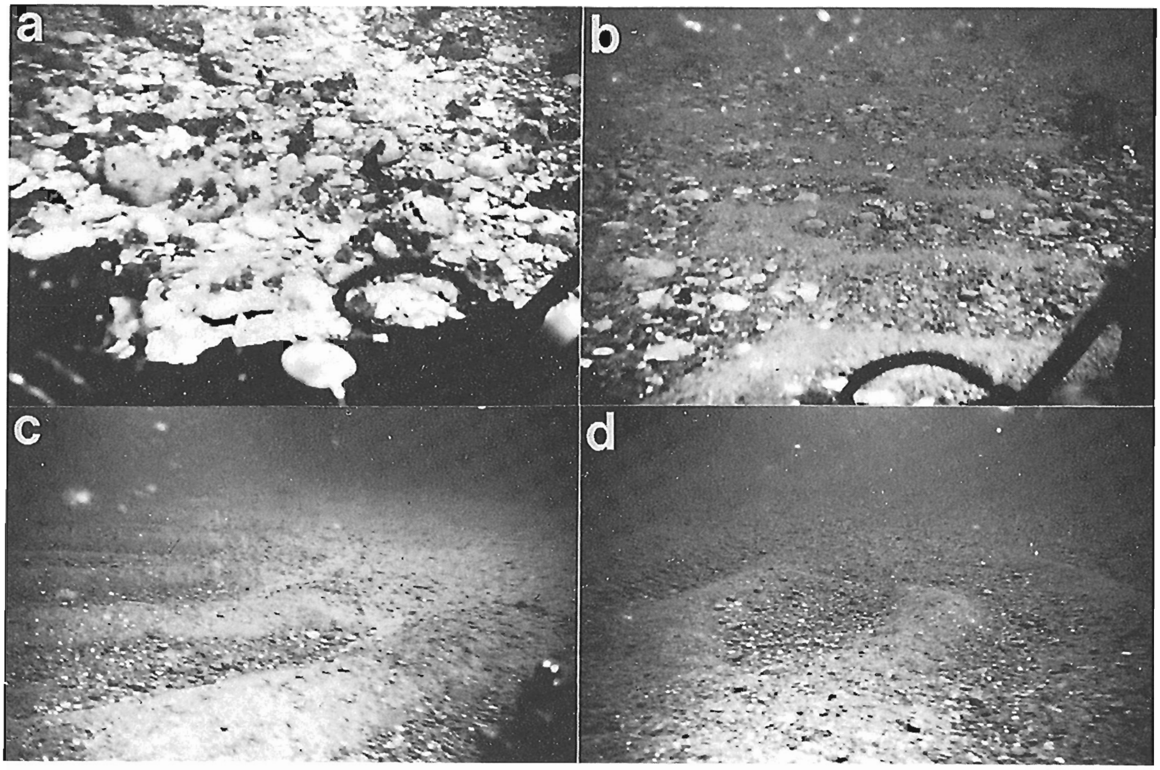

Figure 6.4.

(a) Gravel lag surface near start of dive, with encrusting growth on all but the finest clasts, and sparse population of small macroalgae.
(b) Starved coarse sand and granule ripples resting on gravel surface.
(c) Edge of gravel ripple ribbon. Note concordant level of ripple crests and adjacent surface, and depression of troughs.
(d) Strike view of gravel ripples showing profile and edge of ribbon.

encrusting growth (probably *Lithothamnion* sp.), but the finer pebbles were clean, implying recent mobility. Occasional solitary sand and granule ripples were encountered resting on the gravel armour layer (Fig. 6.4b). The seafloor in this area had an extremely sparse macroalgal population, primarily scattered small specimens of *Agarum cribrosum*.

The dive track crossed onto gravel ripples at 1017 ADT (Fig. 6.2) and continued along the axis of a long narrow patch or ribbon of ripples for the following 750 m. On the basis of sidescan sonar data (Fig. 6.5), this ribbon was recognized as one of a number of quasi-parallel ribbons aligned roughly normal to the isobaths. The ripple crests were approximately normal to the axes of the ribbons. The width of the ribbon observed from PISCES-IV ranged up to 25 m, with a modal value of 5-10 m. Ripple wavelength ranged from 1.7 to 2.8 m. The edges of the ripple patch showed an abrupt transition to the adjacent flat gravel lag surface (Fig. 6.4c, d). The ripple crests were at or slightly above the level of the adjacent unrippled surface, whereas the ripple troughs were depressed approximately 0.20-0.25 m (Fig. 6.4c).

Detailed observations of the gravel ripples were carried out at two sampling sites, one near each end of the ribbon (Fig. 6.2). The outer station (site 1) was in 32.0 m water depth. The ripple crest material at this site (Fig. 6.6a) had a sample median size of about 6 mm and a major mode of about 7 mm, with a number of secondary modes, including 1.6 % coarser than 45 mm. In contrast, the sample taken from the ripple trough had a median size of about 15 mm and contained more than 20 % coarser than 45 mm. A boulder was observed in the ripple trough near the sample site. Ripple crest length (the width of the ribbon) was no greater than 3 m. The ripple cross-sectional profile was roughly trochoidal, with wide troughs and narrow sharp crests. The ripple wavelength was 2.8 m and the ripple height 0.23 m.

Between sites 1 and 2, the ripples displayed a gradual change in morphology, with an increase in crest width and frequency of bifurcations (Fig. 6.6b, c). Boulders up to 1 m were observed at various places in the ripple troughs. At 1042 ADT, shortly before reaching site 2, a boulder mound (Fig. 6.6d) was observed on the west side of the ripple patch, extending to site 2. The gravel ripples were seen to extend into the adjacent boulder field and over some of the boulders.

Site 2 was in 30.5 m water depth (Fig. 6.2). As at sample site 1, the material in the troughs was much coarser than that in the crests, although the sample of crest material collected here had more than 7 % larger than 45 mm. The sample median size for the crest material was about 14 mm and the major mode about 17 mm. The sample taken from the ripple

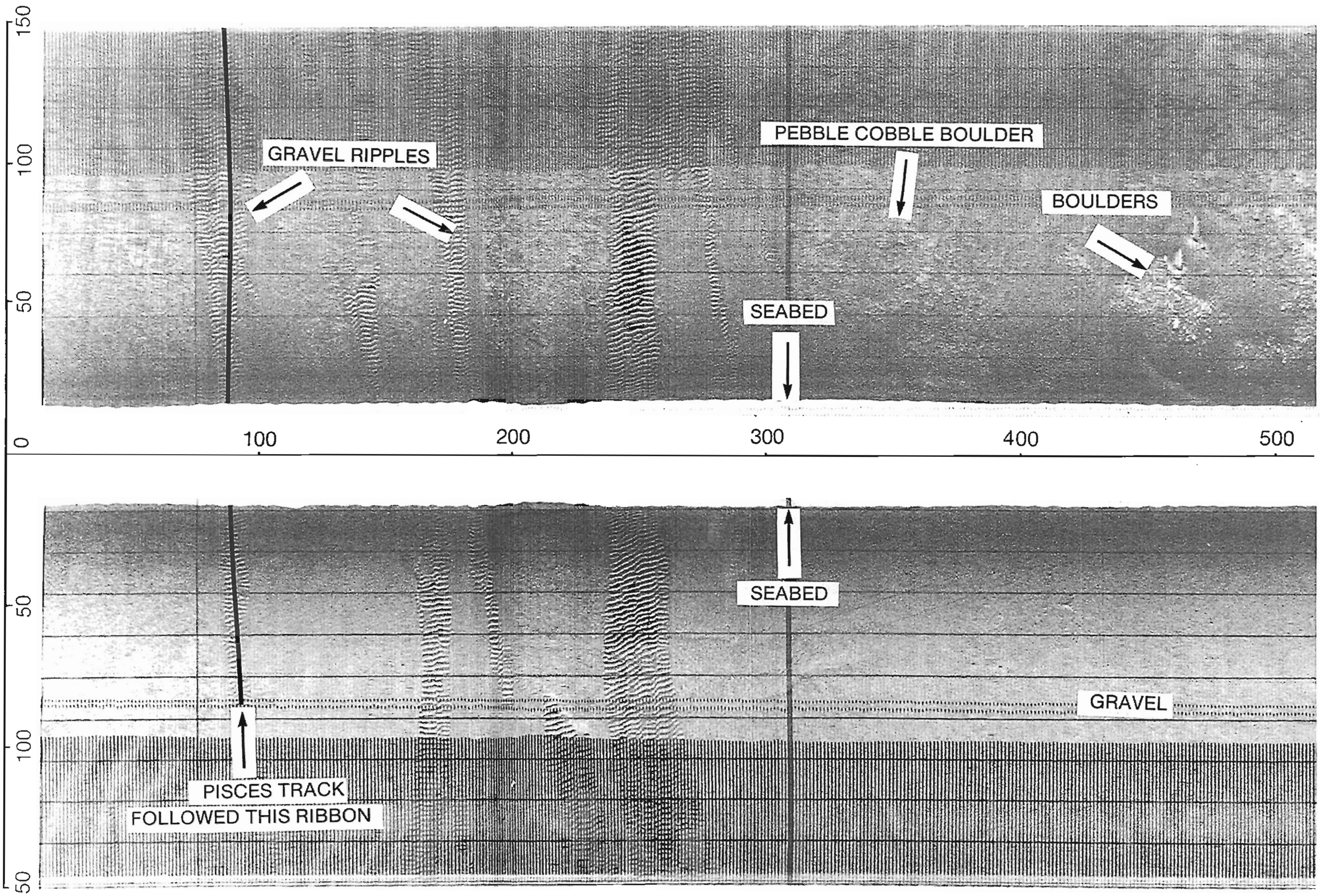

Figure 6.5. Sidescan sonar record obtained during CSS DAWSON cruise 84033, showing quasi-parallel ribbons of gravel ripples and PISCES-IV dive track along axis of ribbon (after Forbes and Boyd, 1987).

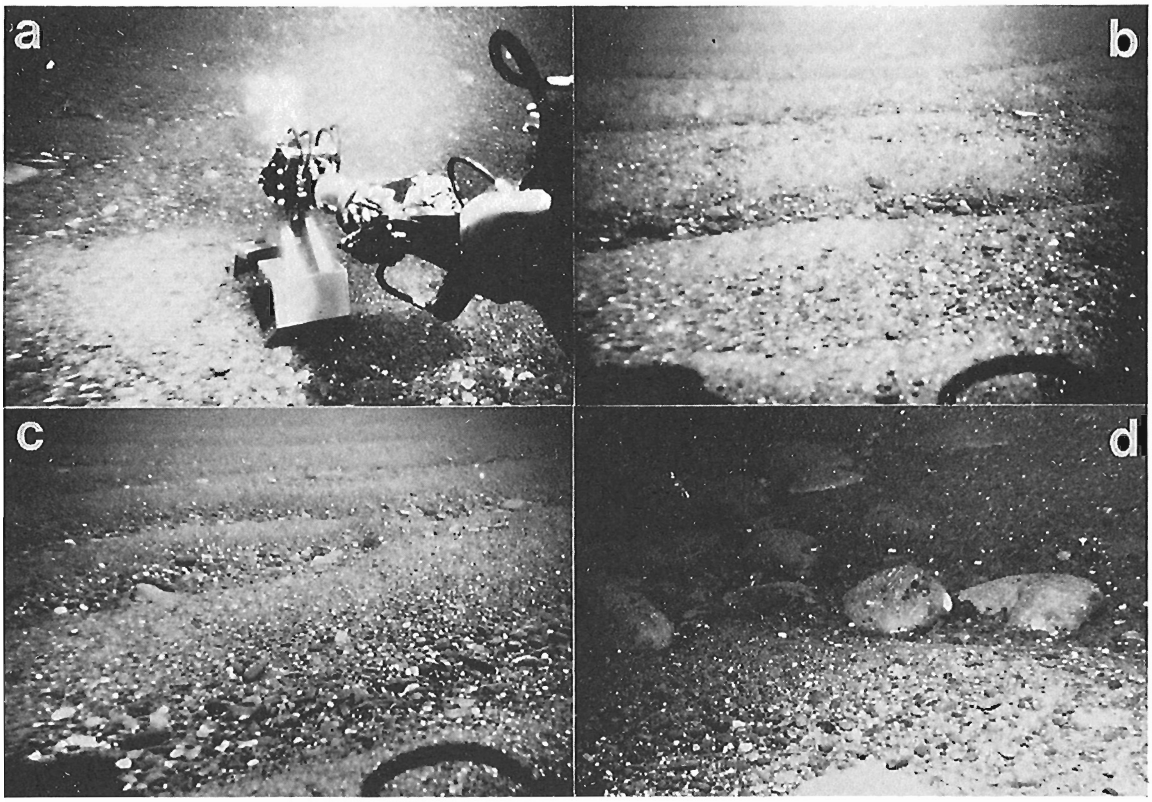

Figure 6.6.

(a) PISCES-IV arm and grab sampling ripple crest gravel at site 1.

(b) Gravel ripples near site 2, showing shallow dish-shaped depression in ripple crest in foreground.

(c) Gravel ripples near site 2, showing bifurcation and exposure of coarse cobble-boulder material in ripple troughs.

(d) Gravel ripples and boulder mound near site 2.

trough had a median size of 28 mm and more than 28% coarser than 45 mm. At the time of sampling, this was described in the dive log as 50- to 200-mm material, although the sample analysis showed nothing larger than 91 mm. The ripple morphology at site 2 was quite different, with narrow troughs and wide, often-bifurcated, plateau-like crests (Fig. 6.6b, c). The crests were approximately 1.0 to 1.5 m wide, representing about three-quarters of the ripple wavelength, which averaged about 2.0 m at this site. Ripple height was about 0.25 m, not significantly different from that at site 1. Here too the ripples were symmetrical, but shallow, dish-like, crest depressions were noted in some places where the crest width was broader. In some cases it was difficult to differentiate between bifurcations and shallow elliptical depressions in the crest.

The dive continued north from site 2 onto a pebble-cobble lag surface similar to that at the beginning of the dive. There was some sand and shell hash between the gravel clasts. Local concentrations of sand formed occasional solitary ripples or small ripple patches, up to five wavelengths, overlying the gravel surface. The latter supported some patchy seaweed growth (predominantly *Agarum cribrosum*) and a few yellow sponges (Demospongiae). Stalked tunicates (*Boltemia ovifera*) occurred here and elsewhere along the dive track on stable gravel surfaces. At about 1107 ADT, the submersible crossed a small cobble-boulder patch with a low lumpy relief, followed by an area of flat pebble-cobble gravel on which there were starved ripples of coarse sand with wavelengths greater than 1 m. At 1111 ADT, a gravel ripple patch was observed on the port side, but the dive track continued over an unrippled, sparsely-vegetated, pebble-cobble surface with occasional patches of finer sediment or areas with more seaweed growth.

At 1123 ADT (Fig. 6.2, site 3), we encountered an outcrop of anomalous, somewhat resistant, laminated sediment projecting through a discontinuous cover of rippled sand and an adjacent overlying gravel veneer in 29-m water depth. The outcrop had an irregular relief of about 0.3-0.5 m, with near-horizontal lamination visible in some vertical faces (Fig. 6.7a). No sample was taken from the outcrop. Irregular scour depressions in the outcrop surface (Fig. 6.7b) contained cobbles similar to material on the surrounding gravel seabed, as well as cobble-size fragments believed to be composed of the underlying outcrop material.

As the dive continued into shallower water, some reduction in visibility was noted. At 1128 ADT, while traversing an area of fine gravel with some sand and seaweed cover, we observed a ridge of gravel up to 1 m high extending parallel to the submersible course. Occasional large encrusted

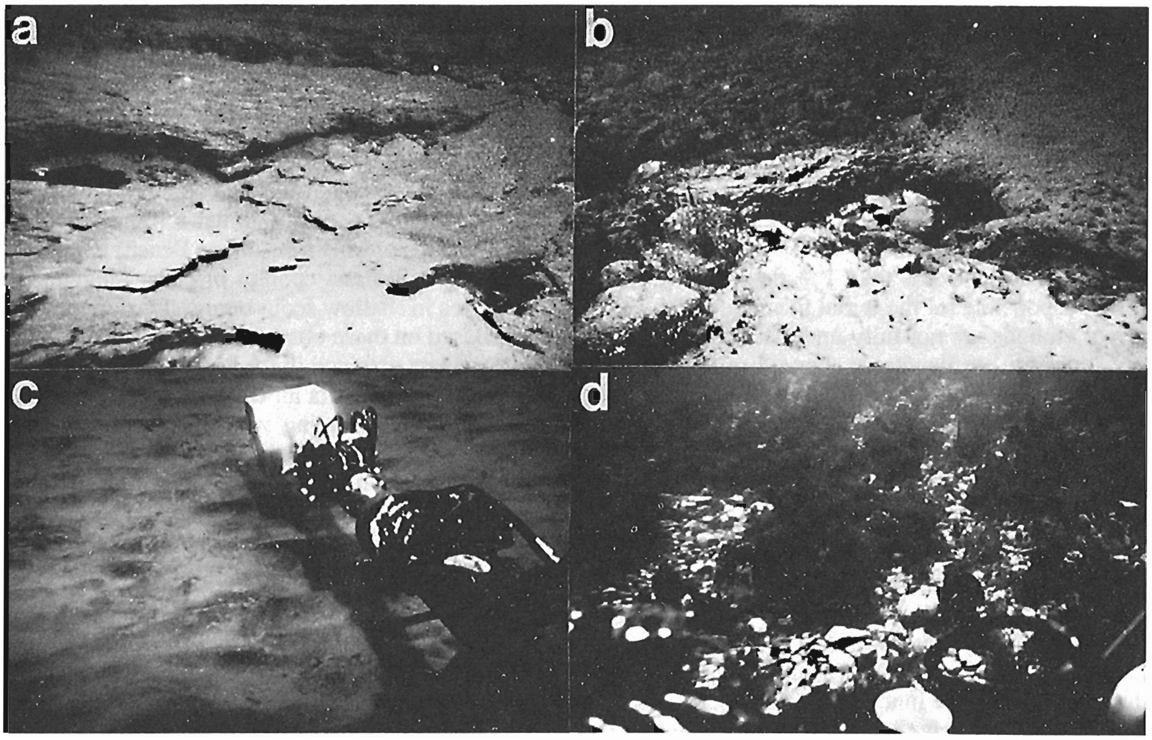

Figure 6.7.

(a) Outcrop of sandy mud at site 3, showing near-horizontal stratification and differential erosion.
(b) Outcrop of sandy mud at site 3, showing overlying gravel unit, pothole-like erosion, and accumulation of cobbles (both from surficial gravel unit and from outcrop material) in scour depression.
(c) Manipulator arm and grab extended over partially-degraded sand ripples near site 4.
(d) Heavy macroalgal growth on cobble-boulder surface in approximately 23 m water depth near end of dive. Mixed *Agarum-Laminaria* community. Note the contrast in vegetation cover between this site and the region shown in Figure 6.4a.

boulders and small patches of fine pebble gravel with no seaweed occurred in an otherwise monotonous region of stable, vegetated, pebble-cobble gravel. Here again *Agarum cribrosum* was by far the dominant species.

At 1136 ADT, we moved into an area of interspersed gravel and rippled sand patches. Bands of sand up to 10 m wide extended across the dive track. These appeared to represent the irregular margin of an extensive area of sand encountered at about 1144 ADT, shortly before changing course toward the west (Fig. 6.2). The ripples encountered following this change of course (Fig. 6.7c) were partially degraded, with somewhat mounded and irregular crests, common terminations and occasional bifurcations (type 3 and 4 ripples of Boyd, et al., 1988a). The crest alignment was 270 degrees. Despite a thin brown algal slime and some evidence of bioturbation, including trails of sand-dollars (*Echinarachnia parma*), the ripple crests remained well-defined. The ripple wavelength was about 0.1 m. Pebble-cobble gravel supporting seaweed growth was exposed in rare shallow depressions within the sand, indicating that the latter is a very thin unit in the area of site 4 (Fig. 6.2). As we moved up from 25-m water depth to about 22 m, the ripples became less degraded, showing well-defined linear crests roughly 2 to 3 m long, with limited bifurcation.

The dive track crossed back onto gravel at 1212 ADT (Fig. 6.2). For the most part, the seafloor consisted of pebble-cobble gravel with seaweed cover, some boulders, and small amounts of sand, fine gravel, and shell hash between the larger clasts. Occasional patches of small gravel ripples were noted adjacent to the dive track. One such patch in 20 m of water had ripples with an estimated wavelength of 0.6-0.7 m developed in granule to fine-pebble gravel (estimated grain-size about 1 to 4 mm).

At 1215 ADT, in a water depth of 23 m, the visibility was reduced to 5 m or less. Numerous boulders up to 1 m in diameter and a marked increase in the vegetative cover (including *Agarum cribrosum* and *Laminaria* spp.) were distinctive features of the gravel seafloor in this area. Similar conditions prevailed until shortly before the end of the dive track, where the sediment was somewhat finer and algal growth only patchy. The dive terminated with PISCES-IV on the surface at 1230 ADT (1530 UT), having traversed about 3 km of varied inner-shelf terrain.

DISCUSSION

The linear ripple patches or ribbons in the study area may represent shallow scour depressions analogous to rippled depressions described from the West African and Californian shelves by, respectively, Newton, et al. (1973) and Cacchione, et al. (1984). It is not clear what determines the extent of scour in the ripple patches on the inner Scotian Shelf, but observations of cobble- and boulder-size material at some places in the ripple troughs suggest that the process may be limited in part by exposure of material too large to be moved. The volume of sediment removed from a ripple patch to form the depressed troughs may bear some relationship to the proportions of sand or finer material in the pre-existing seafloor sediment, the sand being susceptible to removal in suspension. Samples taken from the ripple crests included 7-14 % sand and less than 1 % mud. In addition, the processes responsible for the initial formation of the ripple patches or ribbons are not fully understood, although a number of possible explanations have been proposed (Forbes and Boyd, 1987).

Gravel in the ripple crests was found to be very loosely packed and this 'overloose' condition together with the steep ripple side slopes can be shown theoretically to reduce the threshold shear stress for gravel entrainment by 50 % or more (see, for example, Smith and Wiberg, 1986). The analysis presented by Forbes and Boyd (1987) suggested that the coarse 17- to 45-mm modes forming the ripple crests may be mobile on average for more than 40 hours per year. More recent diver observations of gravel ripples in equivalent depths elsewhere on the inner shelf (Judge, et al. 1987; Judge and Forbes, 1987) have indicated that the ripples are activated frequently during moderate winter storms, in general supporting the conclusions of our earlier study.

The origin of the shallow depressions found in the ripple crests at site 2 is not fully understood. It may be that these represent incipient bifurcations. The ripple morphology at this site, where the crests were much wider than the troughs, may represent a situation of partial but curtailed adjustment of ripple morphology to changing flow conditions. Non-equilibrium bedform morphology may occur in gravels more commonly than in sand because of the higher threshold shear stresses of the coarser material.

Stable gravel and cobble-boulder surfaces in the study area are interpreted to represent, respectively, dispersed barrier gravel and drumlin-lag deposits. They provide important habitats for benthic macroalgae. These plants tend to show a patchy distribution that often appears unrelated to varying substrate conditions. The distribution of seaweed species observed during the dive was essentially consistent with that reported by Edelstein, et al. (1969) from surveys off Lawrencetown Beach, a short distance east of the study area (Fig. 6.1).

The outcrop deposit at site 3 (Fig. 6.2) was initially interpreted, on the basis of colour, stratification, and limited resistance to erosion, to be a partially indurated sand. Brittle fracture morphology of thin units on the margin of the exposure appeared to support this interpretation. These observations suggested a deposit analogous to cemented Holocene beach sands observed above present sea level at a few sites in eastern Canada (Shaw and Forbes, 1988; R.B. Taylor, pers. comm., 1988), although no such occurrence has been found elsewhere along the Eastern Shore or in vibracores from the inner Scotian Shelf. However, this material is similar to a cohesive mud (interpreted as estuarine sediment of Holocene age) exposed in localized depressions on the inner shelf some 25 km to the east, off Martinique Beach (Judge et al., 1987; Judge and Forbes, 1987). The PISCES-IV video record shows what appear to be burrow structures in parts of the outcropping material. In addition, some parts of the outcrop show a sculptured erosional morphology reminiscent of (but much less well developed than) that observed off Martinique Beach. There is evidence for some vertical lithostratigraphic variability in one wall exposure. In addition, rounded cobble fragments of material derived from the deposit (similar to mud cobbles observed in the depressions off Martinique Beach) appear to be present with pebbles and cobbles of other Meguma and exotic lithologies in shallow scour depressions on the outcrop surface. Based on these observations together with the seismic and core data obtained in the vicinity (Fig. 6.3), we believe the outcrop represents an exposure of acoustic facies D at a break in the overlying veneer of former barrier gravel. The latter forms the surrounding surface and the source of the gravel found in scour depressions on the outcrop. These facies D sediments are believed to represent mud, sandy mud, or muddy sand deposited in an estuarine or tidal-inlet environment at an earlier Holocene sea level 25-30 m below present. Variations in outcrop morphology may reflect variability of sand content.

The foregoing discussion highlights the complementary nature of the submersible observations and shallow seismic data. Although the dive was planned primarily to ground-truth sidescan sonar data, it has also aided our interpretation of the seismic stratigraphy. The PISCES-IV observations revealed the extensive distribution of thin surficial gravel and sand, seen only locally on the seismic records (Fig. 6.3) as acoustic facies E. The observed outcrop supported interpretation of underlying facies D deposits, which appear in the seismic records to be truncated in places at the seafloor.

CONCLUSIONS

1. A manned submersible such as PISCES-IV provides an outstanding tool for seafloor studies, even in shallow-water areas accessible by other means.
2. Dive 1604, although only about 2.5 hours in duration, provided successful ground-truthing of surficial units defined previously only on the basis of sidescan sonar data and also valuable support for stratigraphic interpretations developed from shallow seismic profiling.
3. Outcrop of material correlated with subsurface acoustic facies in the seismic records was of a scale unlikely to be detected using sidescan sonar. This feature represented an exposure of a predominantly subsurface acoustic facies, providing an important window on the acoustic stratigraphy. It has been interpreted as a relict estuarine or tidal inlet deposit and is thought to correlate with estuarine sediments sampled in two cores collected nearby.
4. Observations and sampling of large-scale gravel ripples provided data necessary to evaluate the stability of these bedforms under prevailing wave conditions in the area. Gravel ripples occurred in elongated shallow depressions normal to isobaths, were up to 2.8 m in wavelength, formed in material predominantly of fine- to coarse-pebble size, and were found to be active under moderate winter storm conditions.

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