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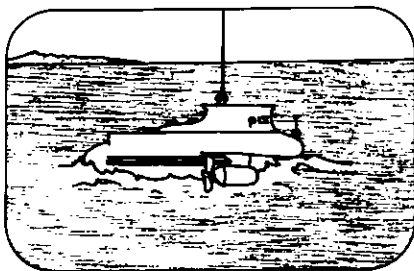
Seabed Investigations of the Canadian East Coast and Arctic using *Pisces IV*

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Introduction

Ever since the first submersible (*FNRS II*) made its initial test dive in 1948, submersible design and development has been carried out in most major industrialized countries. Although good science evolved from the submersible dives in the 1960s and early 1970s, scientists were essentially still evaluating this new technology (Keller, 1977). Our aim is to provide the reader with information on the Canadian submersible *Pisces IV* and its effectiveness in reaching a wide range of scientific objectives during a program carried out in the Eastern Canadian offshore in 1981. In conjunction with a survey schedule involving shipboard water and sediment sampling and geophysical profiling, the staff of the Atlantic Geoscience Centre (Geological Survey of Canada) and associates from abroad participated in 35 dives on five separate cruises; each to a different geographic region and for distinctive program objectives (Fig. 1). In general, our work involved an investigation of geologic problems and phenomena identified by previous surface ship surveys through use of site specific submersible sampling and photography. For instance, among the questions being posed were, how representative are surficial grab samples taken from a ship? What seabed morphology is responsible for a given acoustic response on sidescan sonar?

Specifically, we address a cross-section of objectives that highlight the effectiveness of a submersible. These include the investigation or characterization of:

1. megaflutes (large scale erosional features) in Placentia Bay, Newfoundland
2. the local distribution and character of suspended particulate matter in deep estuary (Laurentian Trough)
3. macrobenthic activity as related to sediment (substrate) stability and mobility (Grand Banks, Scotian Slope, St. Lawrence Estuary)
4. iceberg scour processes over different seabed substrates in terms of furrow formation and preservation (Labrador, Baffin and Grand Banks Shelves)
5. slump features and sediment dynamics on the upper continental slope (Scotian slope)
6. submarine hydrocarbon seepage (Scott Trough, Baffin Shelf)

The Submersible *Pisces IV*

In 1972, the Canadian Department of the Environment purchased its first research submersible, *Pisces IV*. In brief, *Pisces IV* can be described as a small, electrically-powered submarine (6.1 m length, 3.0 m beam, 3.6 m height; Fig. 2) that can operate to a depth of 2,000 m with a cruising speed of 1.5 km hr^{-1}. It weighs approximately 11 tonnes with a payload capacity of nearly 1 tonne. Dive duration varies between 2 and 12 hours and the vessel has the capability for about two dives per day, subject to daylight, weather and battery power constraints. The submersible's peripheral hardware includes two hydraulically-operated manipulators: one with a large claw and four degrees of freedom,
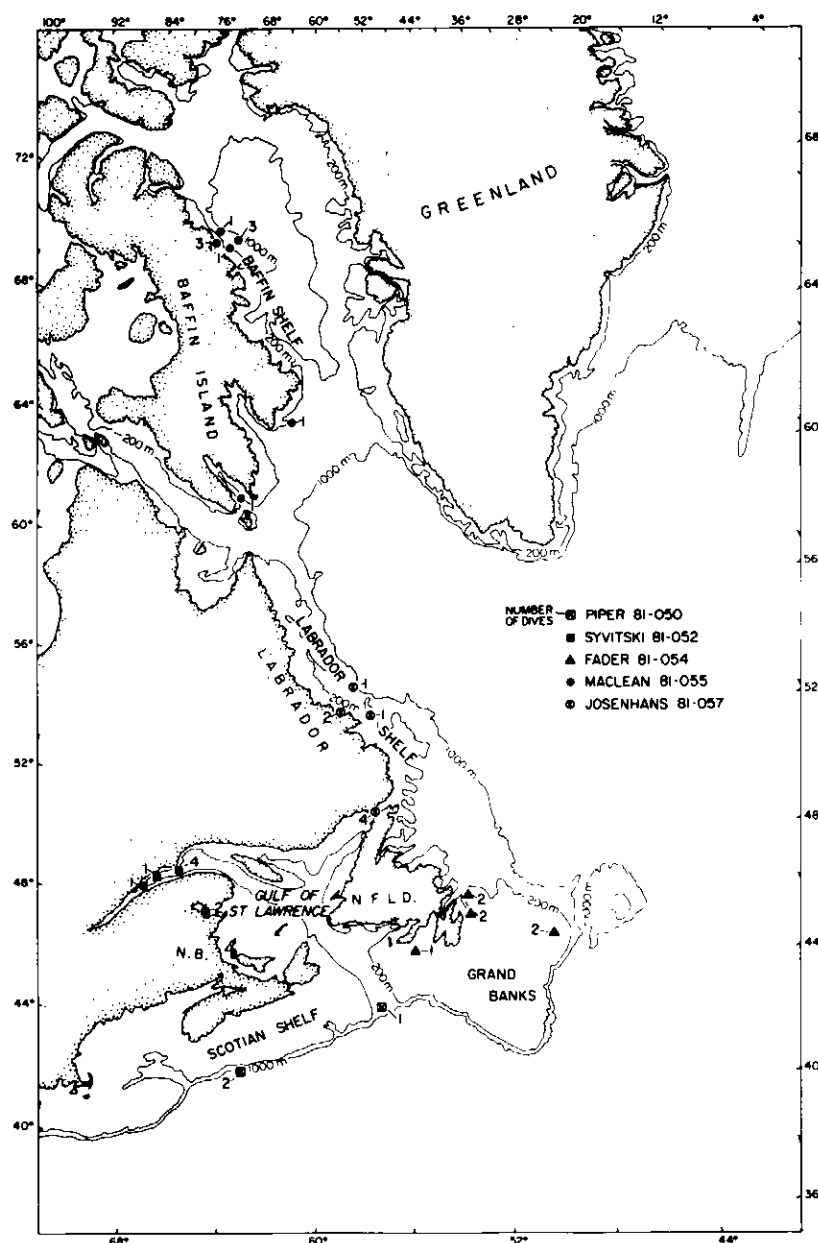

Figure 1 *Submersible dive locations in 1981 with number of dives and chief scientist responsible.*

another with a small claw and 6 degrees of freedom (lift capacity of 70 kg). The submersible can be fitted with a variety of sample holding devices.

Pisces IV carries one pilot and two observers, and with recorders for hull-mounted scientific gadgetry, the 1.5 m diameter personnel sphere is crowded. Each of the three divers (including scientists) has access to a 15 cm diameter viewing port (Fig. 2). Observations are voice recorded and photographed using 35 or 70 mm stills, colour video or 16 mm movie film. Samples are collected with a manipulator arm and stored in pre-labelled containers in a collection basket fitted to the frame of the vessel. Water can be taken into the passenger compartment for either immediate or subsequent analysis, through a valve fitted in the hull. Hull-mounted instrumentation varies depending on the purpose of the dive, and can include STD (salinity and temperature probes), current and/or attenuance metres, and profiling equipment. Scientific personnel are usually too occupied to reflect on any discomfort due to the crowded and enclosed working conditions (Fig. 2).

Pisces IV normally is housed and launched from a tug-towed barge (in sheltered areas) or from its mother ship *MV Pandora II* (Fig. 2). Either method has five limiting factors that, if exceeded, can lead to aborting a dive. These are that 1) sea state must be below 2 m wave height; 2) wind level should be less than 25 knots (12 m.s^{-1}); 3) the submersible's position must be continuously known; 4) visibility must be greater than 2 km; and 5) water currents must be <1.5 m.s^{-1} and not too turbulent. These factors severely limited the number of successful dives, by 50%, in our North
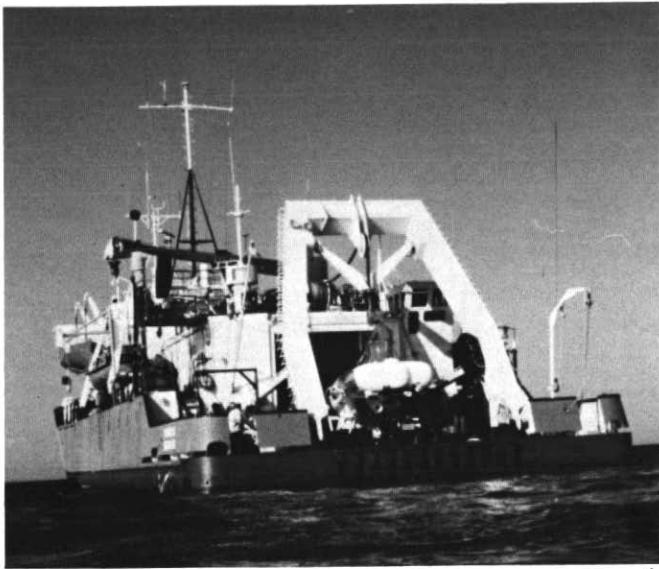
A.

C.
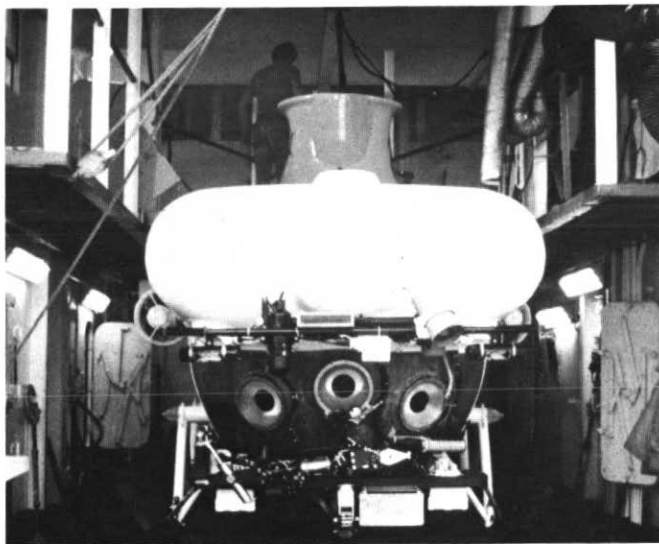
B.

D.

Figure 2 *A) MV Pandora II with Pisces IV on aft A-frame. B) Frontview of submersible; note observation windows and manipulators. C) Locator pinger on top and electrical thruster on side of submersible. D) Cramped living quarters for one pilot and two observers.*

Atlantic cruises. Since 1972, *Pisces IV* has averaged over 100 dives per year, second only to Woods Hole's *Alvin* in terms of total number of dives.

1981 East Coast Offshore Investigations

Megaflutes. Large Scale erosional features or "megaflutes" on the eastern flank of Placentia Bay were first identified, in 1978, on sidescan sonograms and Huntec Deep Tow seismic reflection profiles. They occur in a 4 km wide and 60 km long zone in muddy sediments, with individual mega-flutes extending to over 300 m in length (Fader and King, in prep.). They are be-lieved to be morphologically similar to flute marks which are triangular depressions a few centimetres in length. Flute marks are known to develop on mud surfaces by the action of highly turbulent currents due to seabed irregularities (Allen, 1981). One east-west submersible transect made in the Bay between 160 m to 200 m depth crossed the megaflute field. Unusual cave-like features were discovered cut into the side slopes of the megaflutes (Fig. 3). These ranged in width up to 1 m, 0.5 m high and were 1 m deep. Each megaflute had a number of caves lining its parimeter. One theory suggests that their origin is contemporaneous with that of the parent megaflute, i.e., nodal points at the separa-tion of turbulent flow. The caves are pres-ently occupied by fish and other burrowing organisms: fecal debris and other ejecta surround the openings (Fig. 3). Evidence for present day active erosion of these bedforms was not seen on this dive, sug-gesting that their formation may be linked

to irregularly spaced oceanographic events (e.g., storm surges).

Suspended Particulate Matter (SPM)

Conventional sampling of SPM normally includes the filtering of a known volume of seawater onto a preweighed filter. The water may be collected using rosette-trig-gered water bottles or by using an *in situ* pump. The quantity and nature of filtrate residue provides the basis for our present understanding of particule dynamics: sedi-ment transport, deposition and subsequent erosion. Other state-of-the-art techniques, such as monochromatic light attenuance and high frequency acoustic profiling of the SPM concentration distribution, improve our data base, yet they also ultimately re-quire "ground truth" from *in situ* observa-tions. *In situ* observations can contribute to our understanding of sediment dynamics. For example, two different environments may have the same particle concentration yet have very different suspended particle types (each with different settling charac-teristics).

The character of SPM was observed during 6 dives in the Lower St. Lawrence Estuary. Details of methods and results can be found elsewhere (Syvitski *et al.*, 1982). The first unexpected observation was the presence of large numbers of housings of *Oikopleura*, and Appendicularia tunicate, in the Surface Layer water (0 to 50 m). These housings or globular flocs (2 to 4 cm in diameter) act as sponges as they settle, picking up a fine coating of mineral and biogenic floccules.

The water column also contained marine

snow (large organic-rich agglomerates), 0.5 to 1 cm in diameter, that were evenly distributed through much of the Interme-diate Layer (50 to 250 m; see Fig. 4). The water was clear between the globular flocs and marine snow; SPM was orga-nized in what appeared as a uniform lattice structure.

The upper part of the Intermediate Layer (50 to 175 m) contains a fine water struc-ture characterized by "step-ladder-like" STD profiles, i.e., 2 to 3 m water layers with steep pycnoclines overlying thicker (10 m) mixed water layers. These steep pyc-noclines (and thermoclines) were marked visually by a zone of thermal distortion, possibly due to internal shear. The shear produced a noteable change in the SPM character in which larger particles of marine snow were reduced in size producing an

Figure 3 *Cave-like depression on side wall of megaflute (Placentia Bay, Newfoundland); note fecal debris and other ejecta. Width of photo represents 3 metres.*
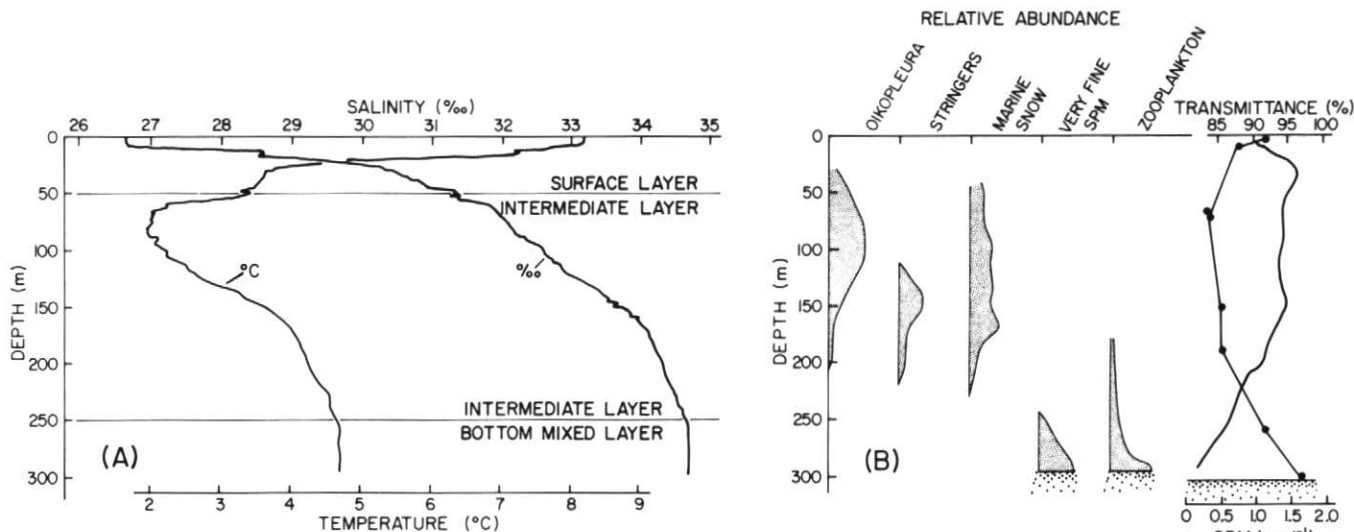

Figure 4 *A) Typical STD (salinity temperature depth) profile of the Lower St. Lawrence Estuary with the three water layers. B) Summary of seston observations as given on Dive 81-052-11.*

increase in the proportion of fine flocculant material (Fig. 5).

The lower part of the Intermediate Layer (175 to 250 m) was devoid of fine structure and contained long chains of marine snow joined together by an extremely delicate filament (Fig. 5). Some were bifurcated on the bottom, all were vertically oriented as a consequence of being weighted more on one end by a higher concentration of floccules. The filaments, 2 to 8 cm long, are thought to be composed primarily of bacteria (Syvitski et al., 1982). They reached maximum abundance between 120 m and 200 m. Below that depth stringer size decreased, indicating an increase in the intensity of turbulent shearing, until they became absent in the Bottom Mixed Layer (Fig. 4). Before the stringers completely disappeared there was a marked zone of poorly sorted SPM (in terms of size) above the Bottom Mixed Layer, with the number of finer particles increasing as the marine snow, globular flocs and stringers broke up. The SPM appeared very fine grained and milky (hazy) in the Bottom Mixed Layer (Fig. 4).

Sediment Stability and Mobility as Related to Macrobenthos Activity

The erosion of sediment is generally thought of as a physical process, i.e., grain size versus current-generated shear stress. Empirical flume experiments support this hypothesis. Yet through the processes of bioturbation and bioerosion, benthic fauna can substantially alter the physical properties of their substrate (Hecker, 1982). One effect of macrobenthos activity relates to the bottom roughness and subsequent calculations on bottom drag. The likelihood of bed erosion increases with increases in the bed drag coefficient (Tunnicliffe and Syvitski, 1982). Once colonized, a flat muddy bottom may develop microrelief,
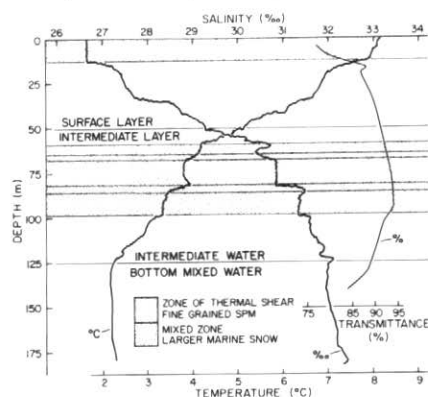
Figure 5 *"Fine-structure" in the Intermediate Layer. Indicated are some mixed zones with large marine snow, and thermal shear zones containing only fine-grained SPM (suspended particulate matter). The attenuance metre (i.e., measurement of light intensity) mounted on the hull of the submersible did not pick up these observable changes.*

both from the animals and their by-products (mounds, pits, fecal debris). Dives on the Scotian slope revealed intense bioturbation on the muddy mid-slope, producing a hummocky bottom with pits and mounds (microrelief up to 20 cm). In the Laurentian Trough, the fauna compete with their by-products for importance as roughness elements (Fig. 6). For instance, the Bathyal Trough Zone (>300 m depth) is highly bioturbated, mostly from the activity of bottom dwelling fish, yet has little sediment microrelief (1 to 3 cm). In that zone, roughness elements are mostly from sessile epifauna (anemones and seapens protruding 15 to 30 cm above the sea floor). Upslope on the trough side walls, the Infaunal Zone (≈200 m depth) has rough-

ness elements that reflect the protrusion of infaunal polychaete worm tubes (up to 15 cm), and a sediment microrelief of 4 to 8 cm from mud volcanoes, burrow openings and fecal coils (for details see Syvitski et al., 1982).

In contrast to the aforementioned environments, some burrowers can completely eliminate roughenss elements. In parts of the Hibernia area of the Northeast Grand Banks, sand lance fish actively swim and burrow through large sand patches. This flattens out small scale bedforms (ripples) and again highlights the major role that the benthic community plays in disturbing the seafloor (Fig. 6). Other less dramatic but equally effective benthos that reduce sediment roughness elements are the
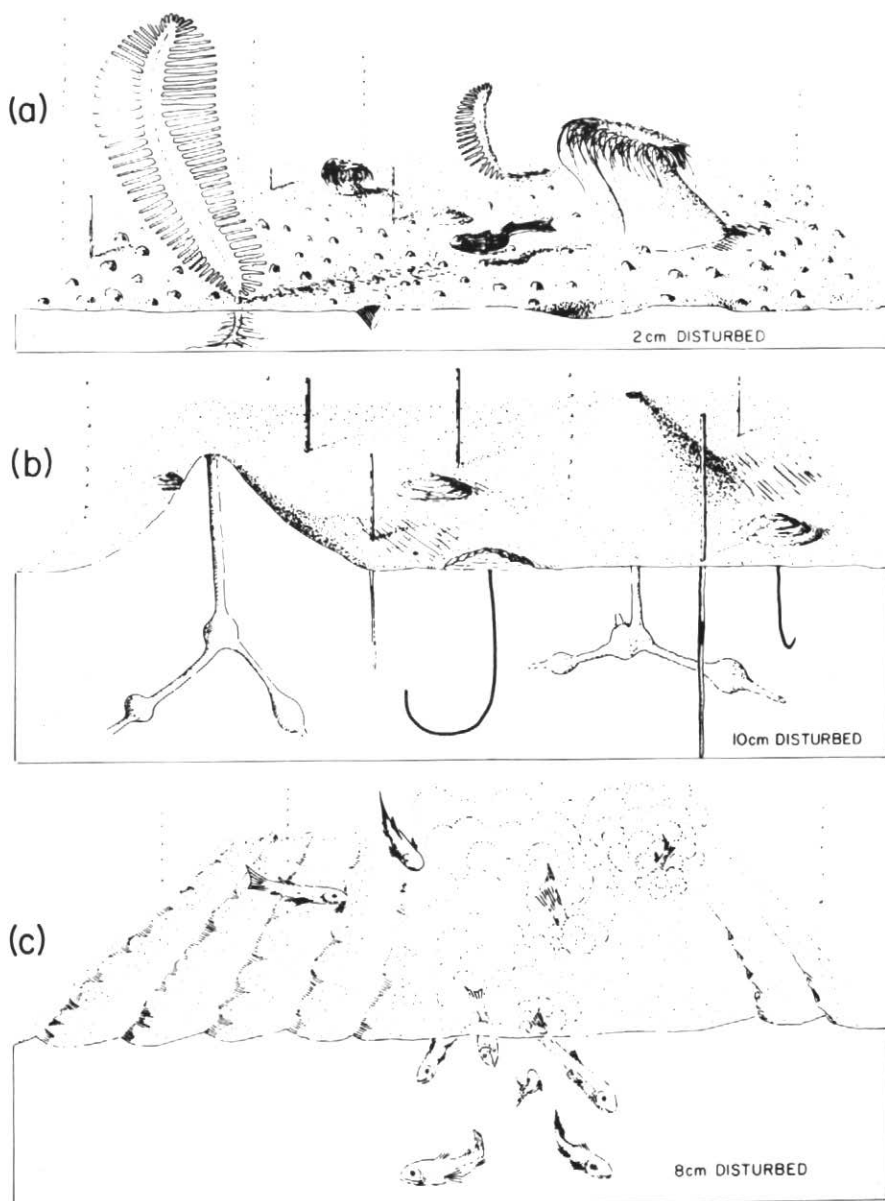
Figure 6 *Artist's conception of biologically induced/reduced roughness elements on the seabed (note depth of disturbance for scale). A) Sessile epifauna of the Bathyal Trough Zone— Laurentian Trough. B) Infaunal Zone activity— Laurentian Trough. C) Bedform roughness elimination due to fish burrowers—Hibernia, Grand Banks.*

mobile echinoderms (sand dollars, brittle stars, starfish), crabs, flat fish (sole, rays) and eel fish (snake blenneys, eel pouts); all are operative in the St. Lawrence Estuary (e.g., Schafer, 1967).

The process of bioturbation can re-expose subsurface sediment and, conversely, work recent material downward. On the Scotian slope, late-Pleistocene reddish coloured mud was brought to the surface, while on the Laurentian Trough floor burrow ejecta introduced anoxic grey mud onto the oxidized surficial sediments (Fig. 7). The Hibernia area is partly covered by a gravel lag. On this lag we observed randomly distributed sand mounds (less than 10 cm in diameter). Here, then, the burrowing activity has brought sand into an environment where it may be easily eroded and redeposited during winter storm conditions. The gravel lag therefore only partly armours the subsurface sediment from erosion, i.e., the surface lag remains stationary in an environment undergoing net erosion (Fig. 7). In contrast, troughs of iceberg scour marks (furrows) on the Northwest Grand Banks contain boulders that have been worked downward through the till matrix by burrowers depositing the matrix sediment above and adjacent to the boulders (Fig. 7).

The activity of benthos also is important in causing resuspension: directly by stirring or egesting turbid water upward, or indirectly by increasing the sediment water content and decreasing or increasing particle binding, thus affecting the bed shear stress needed to erode. Direct methods also act as a sediment sorting process by allowing the fines to be transported by an ambient current (Fig. 7) which is otherwise too weak to erode the bottom sediment (e.g., the Laurentian Trough situation). Although previous work has placed emphasis on the turbid aqueous egestion mechanisms of both passive and active filter feeders, the overwhelming process we observed was through the interaction of mobile macrobenthos with the sediment.

Iceberg Scour Marks
The Arctic and Eastern shelves of Canada are in many places traversed by icebergs. Bergs which impact upon the seafloor create furrows (scour marks) with paralleling berms (rims, levees, lateral embankments) of displaced sediment (Fig. 8) and pits. When grounded, bergs can overturn and deposit mounds of boulders. During travel southward, icebergs melt and release englacial material referred to as icerafted debris (Fig. 9). In past research, the furrow marks of iceberg scour activity were mostly studied via sidescan sonograms (Fig. 8). Models developed to predict past and present levels of scouring (King, 1976;

Lewis, 1980; Fader and King, 1981) resulted in the discovery of the variability of furrow morphology within various geographic localities. Dives were made with *Pisces* to investigate three type localities (the Baffin Shelf, the Labrador Shelf and the Grand Banks) in order to study the variations seen in sonograms.
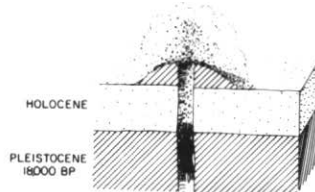
In an area north of Scott Trough, on the Baffin Shelf, the *Pisces* traversed a 1.85 km section of an intensely iceberg-scoured seabed (Fig. 8). Furrows up to 30 m wide and 6 m deep (from top of berm to bottom of scour) were developed on a relatively level seafloor (140 m depth) and covered mainly with fine sediment. Margins of the furrows were sharply defined (Fig. 10a) with inward curving side slopes mostly up to 30° but occasionally up to 60°. Little change was apparent in the type of sediment forming the immediate seafloor within or outside the furrows, except for gravel exposures on the berms. In contrast, scour marks in 280 to 290 m of water off Cumberland Sound, SE Baffin Shelf, were much more subdued features. Scour depths varied between 0.5 to 2 m and cut into hard sedimentary material that was presumably the limiting factor controlling the shallow character of the scours. Again, cobbles and small boulders covered by epilithic organisms were exposed along the flanking berms. Furrow variability in the two areas is, then, controlled primarily by sediment type.
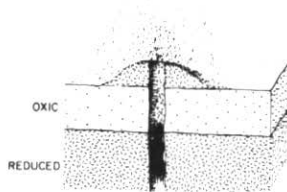
Two distinctly different types of iceberg

scour marks were identified on the Labrador Shelf dives (Josenhans and Barrie, 1982). The first type, interpreted as fresh furrows, had levees up to 2 m high with slopes of 6 to 20° rising above the surrounding seabed (Fig. 11). These berms were composed of cobbles and boulders that protruded slightly from a matrix of silty sand. The trough floor was blanketed with fine, well-sorted sand intermixed with shell debris. The 30 m trough width appears to channelize local currents that winnow the sediments. A random scattering of boulders observed inside and outside the furrows are thought to have been ice-rafted. Most contained a dense covering of epilithic organisms, although some boulders with clean surfaces might have been recently ice-rafted. The second type of furrow on the Labrador Shelf is considered to represent old and degraded scour marks. These forms lack a fine matrix within their ridges and are of low relief (Fig. 12). Over a period of time, seabed currents have winnowed all of the finer material from the berms. Isolated mounds (15 × 15 m) of large cobbles and boulders also were observed throughout the dives. These boulder mounds are thought to result from the melting of grounded bergs with concommitant deposition of englacial material (Fig. 9).

In the Hibernia area, NE Grand Banks, observations from *Pisces* revealed one iceberg furrow of 10 m width and a 0.5 m high rim developed on sand and gravel
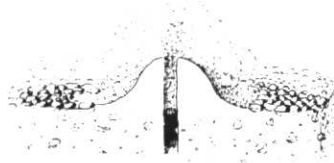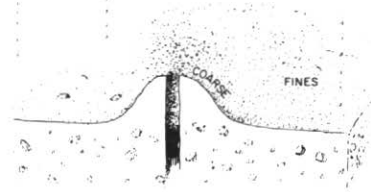
(a) AGE INVERSION (SCOTIAN SLOPE)

(d) RESUSPENSION AND SORTING

(b) REDOX REVERSAL (LAURENTIAN TROUGH)

(e) BOULDERS BEING WORKED DOWNWARD (GRAND BANKS)

(c) EROSION OF SUBSURFACE MATERIAL (GRAND BANKS)

Figure 7 *Effects of bioturbation on sediment turnover.*

sediment. The trough floor consisted of small sand waves normal to the furrow trend. The furrow terminated in a large semicircular pit, 15 m in diameter and 3 m in depth, containing a large 2 m angular boulder which appeared to have been partially pushed into the termination wall of the pit. Several small 1 m mounds of unsorted till-like debris were found in the pit. Apparently, the associated iceberg rolled over and deposited the material after the formation of the pit.

On the NE Newfoundland Shelf, iceberg furrows that developed on glacial till had rims armoured with boulders with rims as high as 5 m (Fig. 10c). The slopes of the inner sides of the troughs were much steeper, up to 35°, and some of the boulders appear to have rolled down the inner slope. The trough floors were very flat and composed of well sorted angular cobbles (Fig. 10d). In this area ice rafting does not appear to play a major role in the deposition of sediment subsequent to fur-
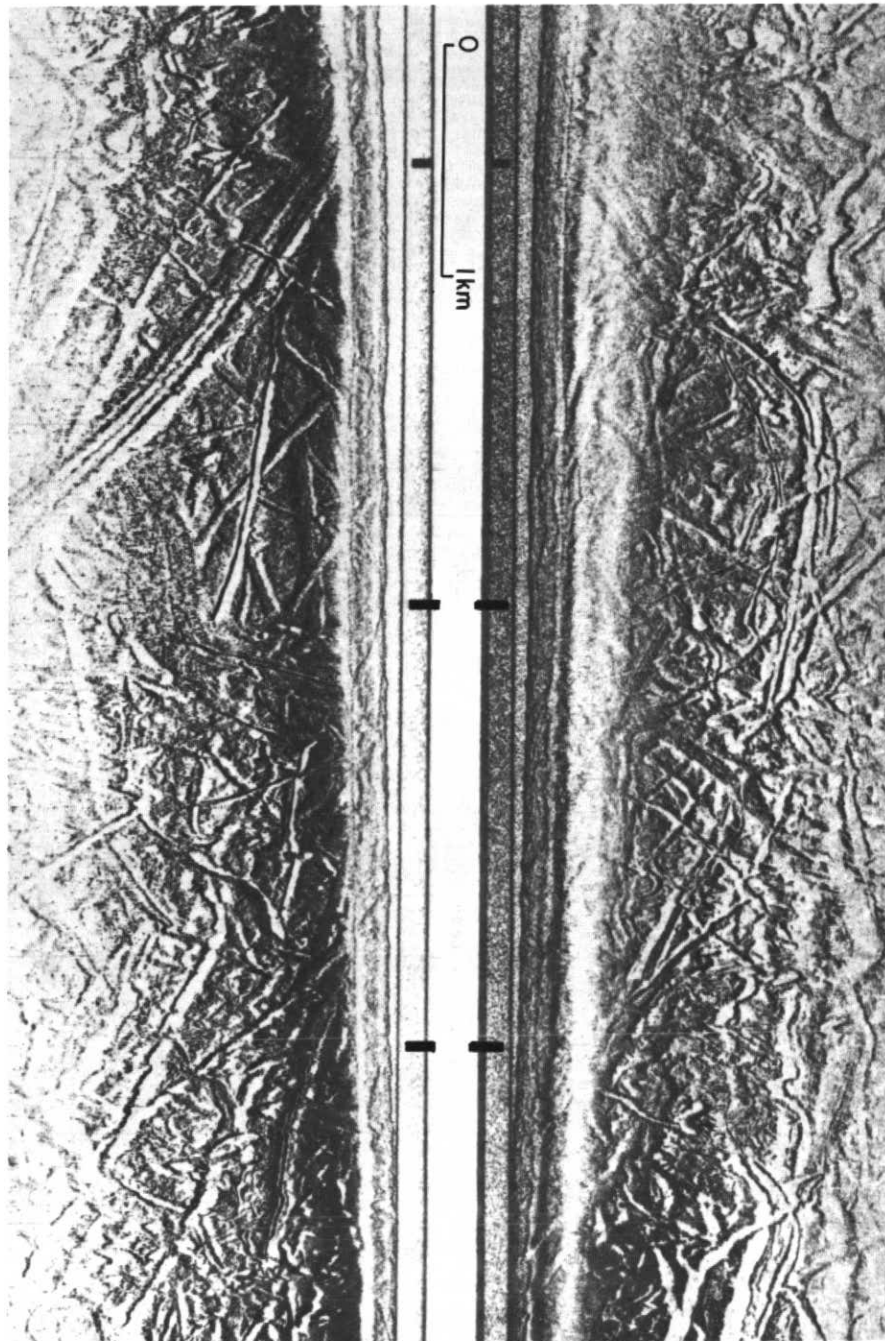

Figure 9 *Artist's conception of a grounded iceberg that is melting and causing a local boulder dump.*

row formation, since randomly-distributed cobbles and boulders in the troughs of furrows were not common. These direct observations of iceberg scour marks have provided new insight beyond the resolution of sidescan sonar. The high degree of variability in furrow character appears to be determined primarily by sediment properties (Lewis et al., 1982).

Upper Continental Slope
Two dives were made on the Scotian Slope, in water depths of 300 to 700 m (Hill et al., in press). The seabed had a rough irregular profile on a horizontal scale of tens to hundreds of metres, largely undetectable from surface ship observations. This relationship is in agreement with the previous geophysical interpretation of this area, which notes the occurrence of late Pleistocene slump blocks covered with a thin veneer of Holocene mud (Hill, in press). Relict late Pleistocene boulders were seen in places. In water depths of less than 500 m, the surface sediments are sandy. Evidence of current scour around boulders (Fig. 13a) and the development of gravel lenses (Fig. 13b) were found to water depths of 450 m, confirming that the modern current regime either actively moves coarse sediment in substantial water depths or that it winnows away the finer sediment. Boulder ridges on the outermost continental shelf are probably of glacial origin. The shelf edge appears to be an area of net sediment removal, with the development of lag gravels.

Figure 8 *Sidescan sonar record showing intensely iceberg scoured seabed on the northeastern Baffin Island Shelf between Scott* Inlet and Buchan Gulf. The seabed was traversed with Pisces IV along track between black bars.
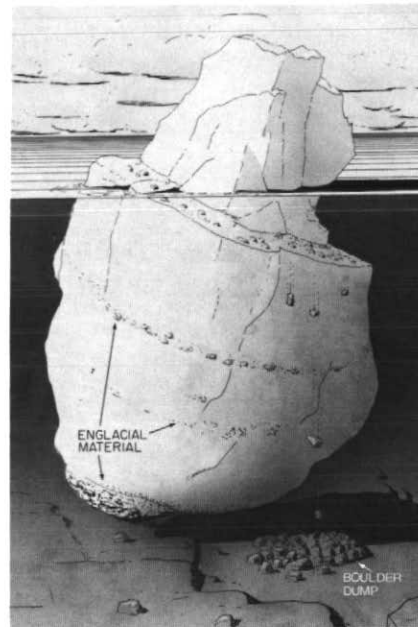
Submarine Oil Seepage

A submarine oil seep that occurs offshore from Scott Inlet was investigated from *Pandora/Pisces*. The seep is evidenced by slicks and by an eruption of oil droplets and gas bubbles at the sea surface (Levy and MacLean, 1981). Three dives, totalling 14 hours, transected the seafloor beneath the slick. Several anomalous circular to elongated patches in the seafloor sediments (a few cm to several metres in diameter) were characterized by a whitish growth or coating of the surface sediment particles (possibly Sulfur-reducing bacteria). These are believed to mark areas where seepage occurs, probably on an intermittent basis (MacLean, 1982). Localities where these phenomena were observed fall on a trend that parallels the

underlying bedrock structure. Seepage appears to occur either along the contact between Precambrian rocks that form a high beneath the outer southern wall of Scott Trough and flanking pre-Tertiary strata, or by migration up-dip in the flanking strata (Maclean and Falconer, 1979; MacLean et al., 1981; Fig. 14).

Summary and Future Implications

Research submersibles constitute an important and effective tool to enable marine geologists to obtain first-hand visual, photographic, sample or other data on significant geological features or phenomena that cannot be studied using remote techniques. Submersibles also provide the ability to selectively sample or conduct measurements on the basis of these visual

observations. To some extent, such data can also be obtained by bottom drift camera packages (i.e., UMEL Stereo Camera) and unmanned, tethered submersibles. Both have lower risk and cost factors in addition to an increased weather/sea day/night operational window, compared to manned submersibles. However, *in situ* "eye" information has proven invaluable in developing strategies for selective sampling. In this regard, the *Pisces IV* has proven extremely useful.

The *Pandora/Pisces* system is not without flaws, or without the need of further development. The present lack of a proper navigation/location system for the submersible makes detailed site selection surveys impossible and also limits the theoretical depth capability, for reasons of
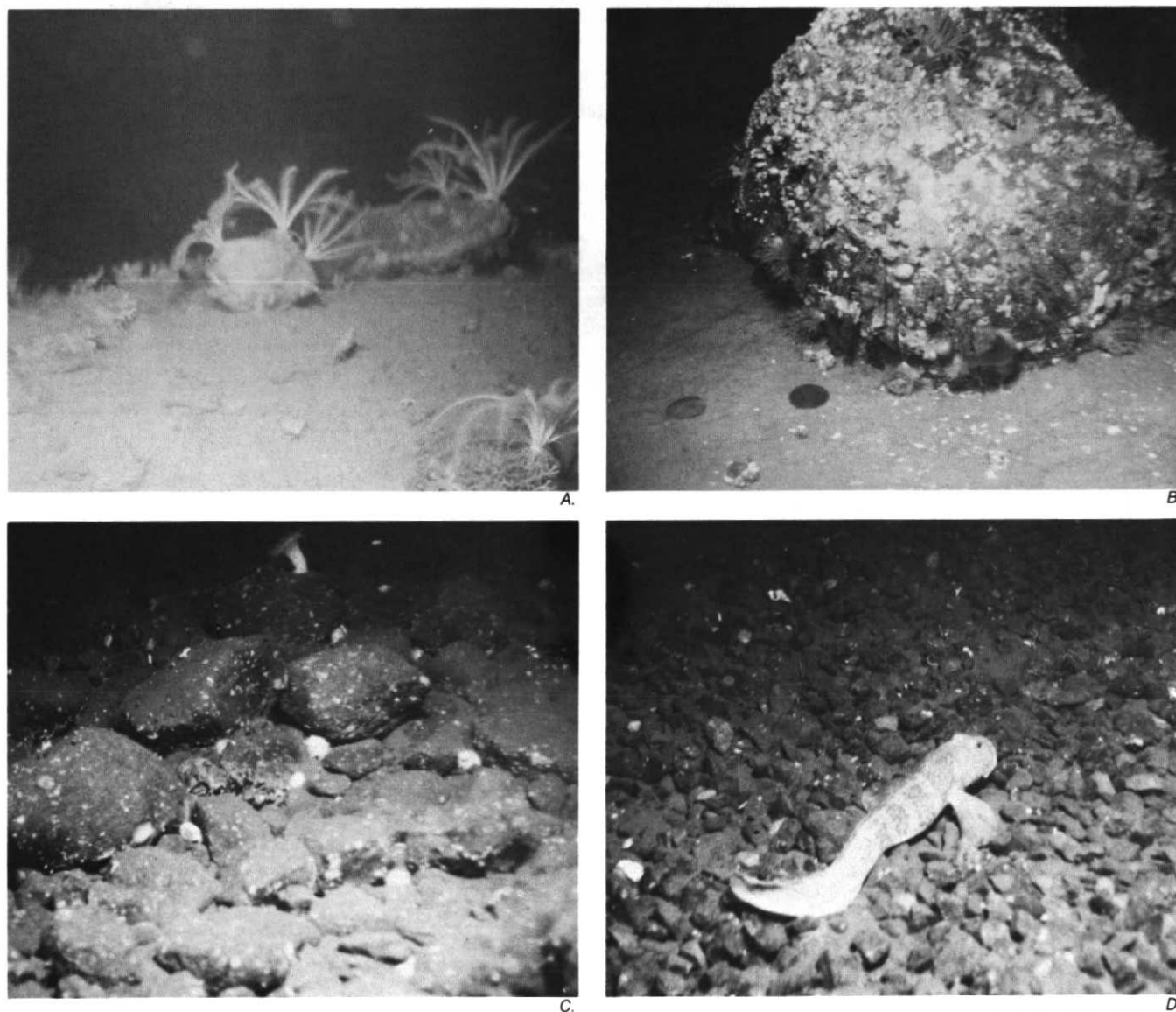

Figure 10 A) Photograph taken at the edge of an iceberg scour in the area indicated in Figure 8 showing the abrupt truncation of the seafloor and gravel fragments along the flanking embankment. B) One m diameter boulder, covered in epilithics, lying on a flat seabed of well sorted sand and scattered shell debris (Hibernia, Nfld.). C) Iceberg furrow ridge, 4 m in height, surface covered entirely with boulders (NW Grand Bank, Nfld.). D) Trough of a 20 m wide iceberg furrow consisting of well sorted angular cobbles (NW Grand Bank, Nfld.).

safety. Instrumentation and sampling capabilities, especially for bedrock sampling, require further development.

This paper highlights a cross-section of geologic observations which have contributed new information to previous surface ship surveys. They include: 1) cave-like depressions that were found indenting the walls of megaflutes; 2) aspects of the dynamics of suspended particulate matter (SPM) stressing the role of "fine-structure" of water masses and SPM character; 3) observations on the widely varied role that macrobenthos plays in changing the purely physical response of sediment to the local bottom current regime; 4) variations of iceberg scour morphology as a function of seabed texture and other factors, and of the relative age of scours; 5) the character of seabed morphology on the upper continental slope and related indications of the contemporaneous mobility of coarse surficial sediment and 6) the occurrence of white coatings as indicators for aqueous seepage of oil.

Future projects now in the planning stage include the acquisition of ground truth to define acoustic type areas, investigation of seabed stability as a function of benthos, currents and slope, real time observation of ice scour dynamics, bedrock mapping and structural delineation, studies of Arctic pingos, mud lumps and mud volcanoes, investigation of shelf edge slump scars, evaluation of submarine oil or gas vents and pockmarks, assessment of thermokarst collapse features, specific geotechnical investigations of soil properties, animal-sediment interaction studies, time dependent/depth of sediment disturbance experiments, relative sealevel studies, investigation of ice grounding process on sediment transport, measurement of the transport direction of bedforms and, finally, further detailed experiments on *in situ* SPM dynamics. Details of these proposed future projects are available from the senior author.
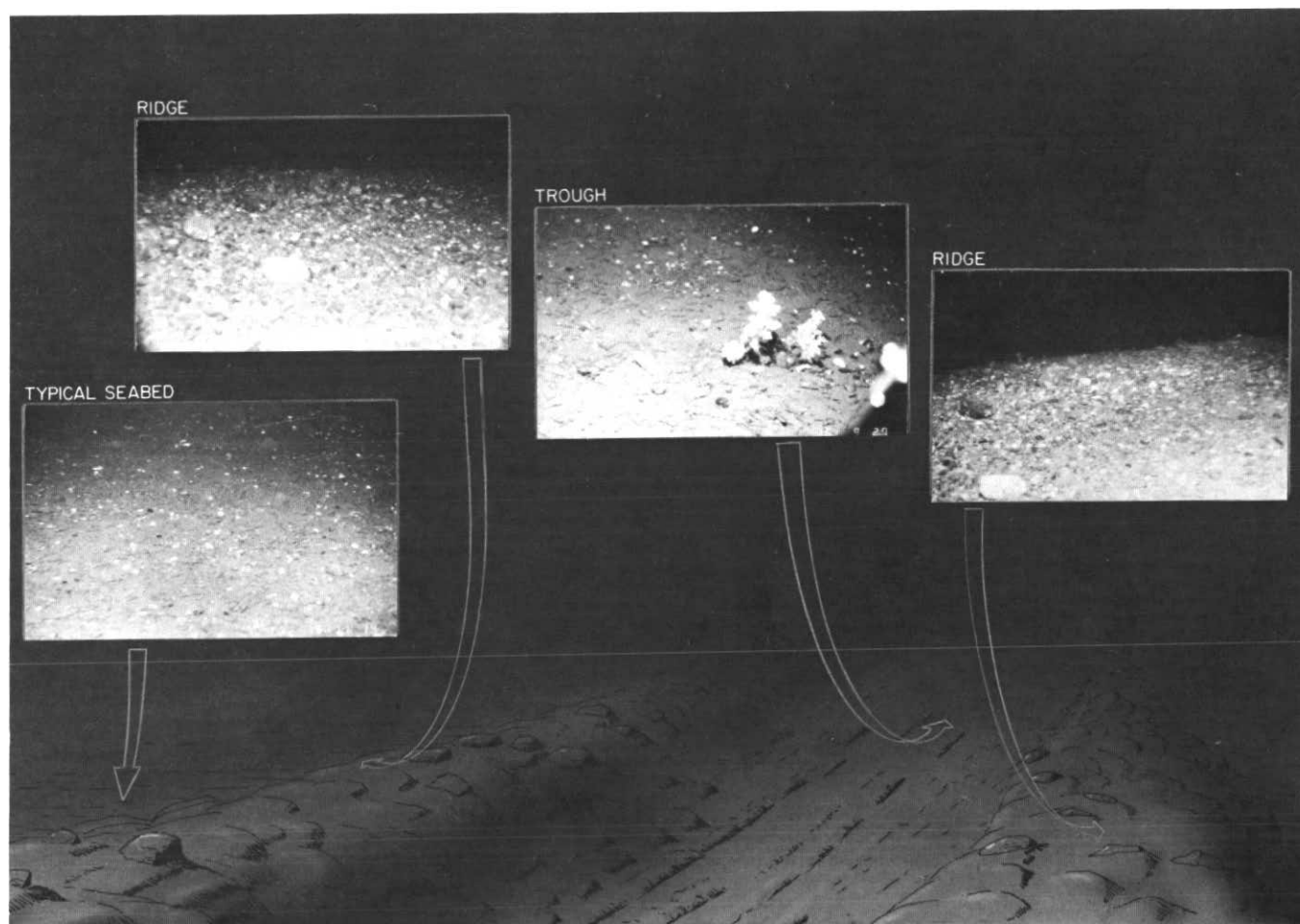
Figure 11 *Fresh iceberg scour on the Labrador Seabed.*
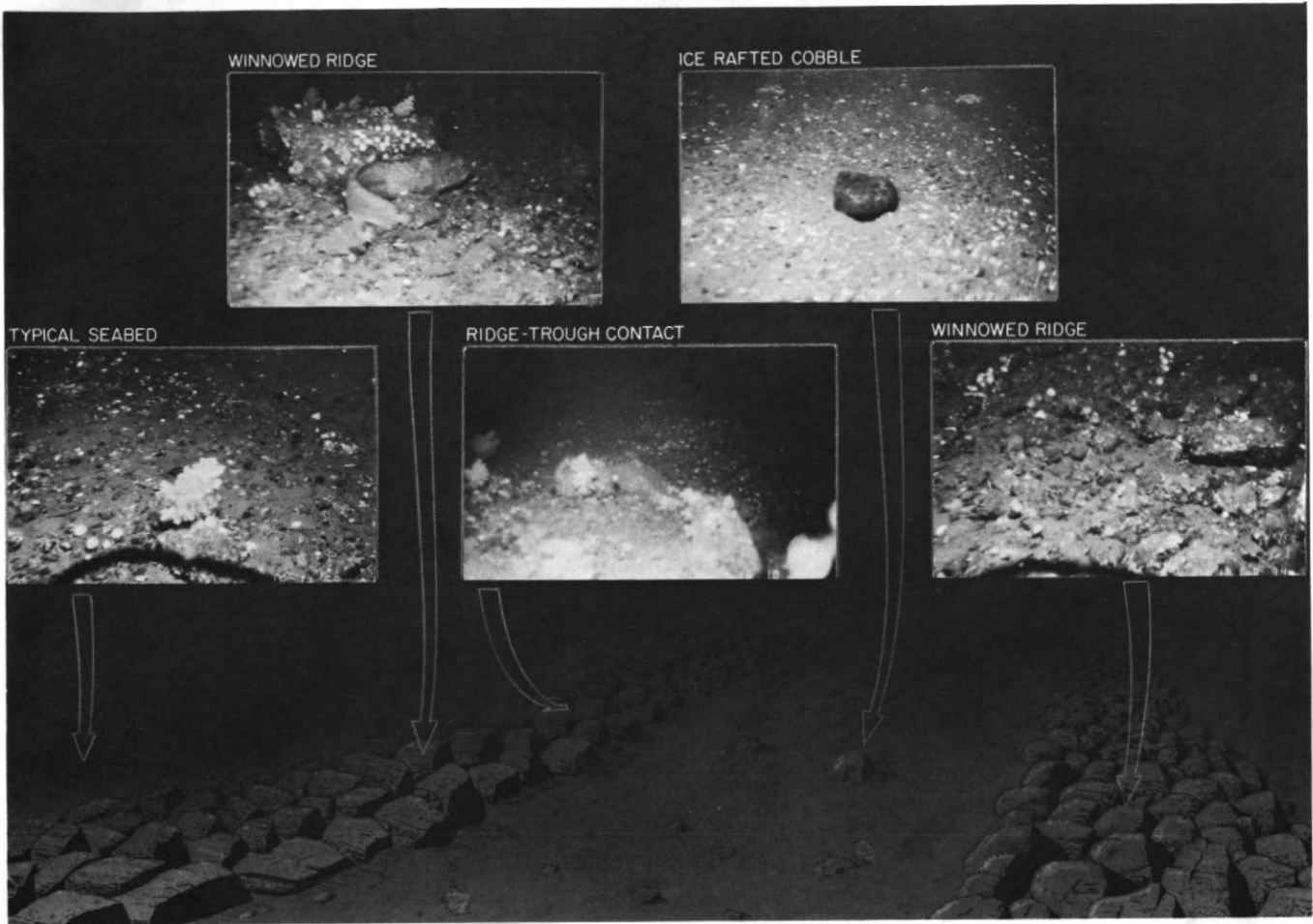
Figure 12 *Old degraded iceberg scour on the Labrador Seabed.*

Figure 14 *Cross-section through Scott Inlet oil seep area.*

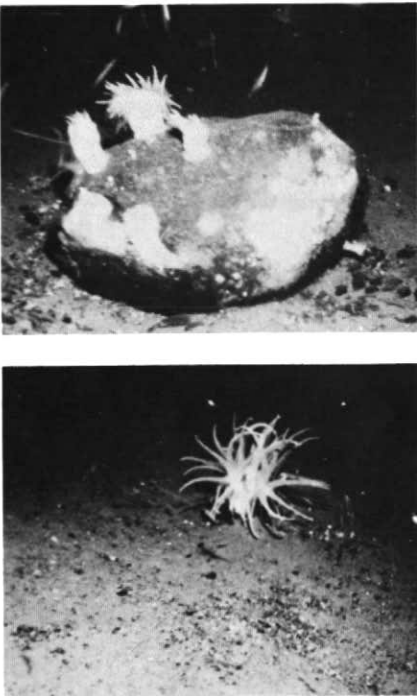**Figure 13** *A) Boulder sitting in current scour pit, 410 m depth, Scotian slope. B) Gravel lens on upper part of the Scotian Slope.*
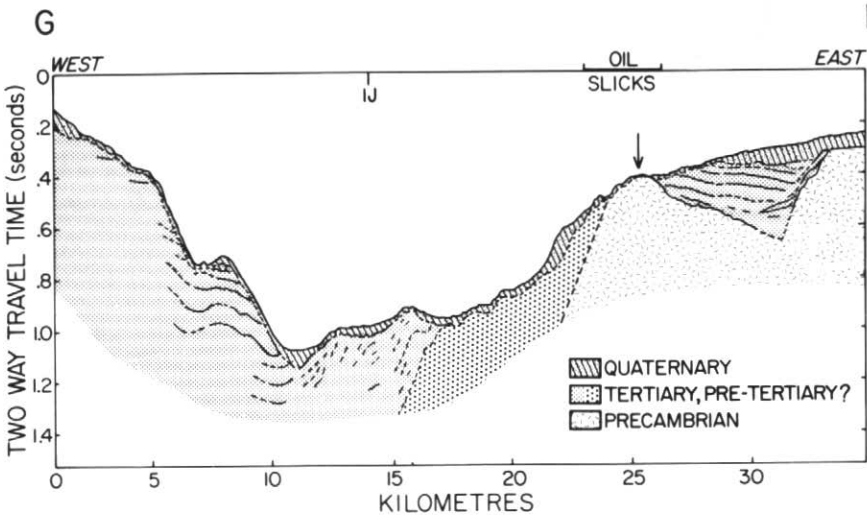
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