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Aller au sommaire du numéro

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Résumé de l'article

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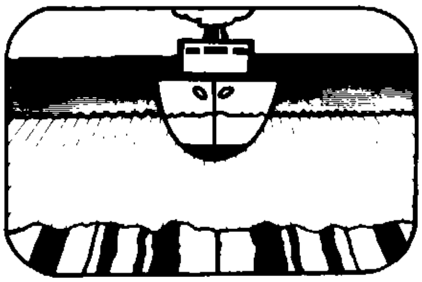

Application of High-quality Bathymetry to Geological Interpretation on the Scotian Shelf

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ABSTRACT

Techniques are now available to prepare bathymetric maps of the sea floor with detail similar to that of topographic maps on land. Gridded data sets can be displayed as shadowgrams to enhance particular morphologic features. Glacial geomorphological features on the continental shelf off eastern Canada can be interpreted in a manner analogous to glacial features on land. The last major data set acquired by the *CSS BAFFIN* from the eastern Scotian Shelf shows a complex topography interpreted as a series of glacial tunnel valleys, which indicate several episodes of sub-glacial meltwater flow and erosion.

INTRODUCTION

The topography of the sea floor is one of the most readily determinable features of the oceans, providing important geological information (Keen, 1968, Ch. 3). Our ability to measure and display bathymetry has improved enormously in the past 30 years. We are on the threshold of a significant leap in technology of ocean-bottom surveys and subsequent increase in our knowledge, so it is timely to describe the achievements to the present. We review the evolution of the art and techniques of mapping the topography of the sea floor and illustrate some of the scientific consequences and practical applications of the study of sea-floor bathymetry.

In response to the needs of offshore hydrocarbon exploration and engineering development, *CSS BAFFIN*, and its accompanying launches carried out a number of bathymetric surveys on the Scotian Shelf in the past decade. [*CSS BAFFIN*, a 4986 tonne displacement scientific and hydrographic survey vessel, was mothballed in April 1991 after 35 years of service.] The result of these surveys is a unique digital data file. It represents a convergent culmination of three technologies: i) positioning of ships at sea (navigation); ii) determination of the depth of the sea (bathymetry); and iii) handling of large data sets (computer data processing the manipulation).

DEVELOPMENT OF METHODS OF DETERMINING BATHYMETRY

Since time immemorial, man has sailed the oceans in search of food, to open new trade routes, to exercise a military advantage, or to find adventure. In following these pursuits, the early mariners quickly recognized the importance of the knowledge of sea depths. It was not until the 17th century, however, that the science of marine geology and the practice of hydrographic surveying were born. The latter achieved its modern standard of accuracy and precision under Captain Cook, whose great accomplishment of charting the waters offshore Newfoundland (1763-66) has stood the test of time and has served as a basis for charts which continued in use until a few years ago.

Until the advent of modern echo sounding equipment, all the soundings were acquired with a measured length of weighted rope dropped to the sea floor. The method is independent of the properties of seawater and, although slow, works well on continental shelves in depths up to a few hundred metres. In deeper water, a strong rope is required to support its own weight and therefore successful soundings in the deepest parts of the ocean could not be accomplished until the mid-19th century. Such knowledge had little application until the laying of the first underwater telegraph cables in the 1860s. These measurements were difficult to perform, and required several hours and specialized ships and equipment. Even as late as 1910, there were fewer than 10,000 spot soundings from all the deep ocean areas (Murray and Hjort, 1912).

An alternative technique of determining the depth is to measure the time required for the passage of a weighted object to the bottom of the sea and the return to surface of a released float. A lack of knowledge of the sinking (and rising) velocities and poor time-control precluded successful implementation of such techniques until the physical objects were replaced by sound waves, which can travel easily through the seawater column and which are echoed back from the sea floor. The idea of using audible waves was first suggested in 1838 (Wilkes, 1848), but the techniques for generating sound pulses and accurately timing their echoes were not available until the end of World War I. Efforts to detect submarines and improve the ranging of coastal batteries during that war expanded the knowledge of underwater sound propagation, leading to the first practical echo sounder in 1924. The method has been greatly improved by precise electronic timing and hard copy recording on chart paper, but it suffers from two fundamental limitations. First, in order to obtain the depth of the sea, the precise travel time of the sound pulse must be multiplied by the velocity of sound in seawater. This velocity depends on the density of seawater, which in turn depends on salinity, temperature and pressure. These depend on "ocean climate", vary in time and space, and require independent measurement. Second, if the sea-floor surface is rough with substantial local relief, then the spreading acoustic pulse may average over a range of depths, and the exact point beneath the ship from which the echo was received may be unknown.

A modern conventional echosounder transmits a sound pulse that is reflected from the sea floor. The returning pulse (echo) is detected by the sound receiver mounted on the hull of the ship. The sound frequency must be chosen carefully. It must be sufficiently low so that the sound is not attenuated in the water column, but sufficiently high that small sea-floor irregularities are resolved. Frequencies used range from as high as 200 kHz in shallow water to 10 Khz for a full-ocean depth sounder. Lower frequencies (such as in the widely used 3.5 kHz sounder) are used to obtain reflections from sub-bottom sediment layers.

Conventional sounders emit a broad cone of sound to the seabed (typically about 20 degrees), so that in deep water there is poor spatial resolution and in rough topography only the shallowest depths are clearly imaged. This is of little concern to hydrographers whose mandate is safe navigation, where shallowest depths need to be identified. The large area illuminated by the sound cone in deep water limits the application of the conventional echosounder in geological studies where the true shape of the seabed is of importance. Furthermore, the conventional echosounder acquires data only along the ship's track, requiring interpolation of contours between the adjacent tracks.

To overcome the limitations of conventional echosounders, narrow beam transducers were developed using focussing techniques similar to those used in the design of antennas in radio astronomy. These echosounders give a more accurate picture of the seabed profile directly beneath the ship, but information about the lateral extent of topography is lost. To increase the spatial coverage, special multibeam sounders were developed to image a strip of sea floor (sometimes called "swath mapping")(Burke and Hally, 1990). By adjusting the track spacing so that the strips overlap, a complete coverage of the sea floor is possible. Another approach is to use autonomous vessels remotely controlled from a mother ship to steam along parallel tracks. A Canadian development of this type of instrument, called "Dolphin", was first tried from *CSS BAFFIN* (Kerr and Dinn, 1985).

At least in principle, 100% sound imaging of the sea floor is now within reach. The full depiction of sea-floor morphology with the resolution comparable to the best satellite photography is now a possibility, with additional detail available from sidescan sonar imagery (Belderson *et al.*, 1972).

DEVELOPMENT OF NAVIGATION

To utilize bathymetric information fully, we must be able to plot it accurately on a map. Thus, progress in marine geology and the acquisition of bathymetric data have been linked with the progress in the "haven-finding art" of navigation.

Of primary importance to a mariner entrusted with piloting a ship safely to its destination is the knowledge of where to steer the ship (*i.e.*, what course to take). His interest in positional accuracy at any moment is secondary, except that each fix represents a new point of departure from which to lay a course. Once he has passed a point safely, he has no further interest in his past track. In contrast, for the geologist, hydrographer and other users of the oceans, the accuracy of all navigational fixes is of great importance since there is a need to refer shipboard observations to their position on the surface of the Earth.

The earliest navigational aid was a sounding rod or line, already mentioned above. Herodotus has a clear description of this method as practised five centuries before our era.

> "On approaching Egypt by sea when you are still a day's sail from the land, if you let down a sounding line you will bring up mud, and find yourself in 11 fathoms of water, which shows that the soil washed down by the stream extends that distance" [in Taylor, 1971, p. 35]

When this account was written, conning the ship by determining the depth and feeling the nature of the seabottom was already a thousand-year-old practice, as can be seen in old Egyptian paintings.

Feeling one's way along the seabottom is impractical for ships underway or in deeper water and so, to aid them in finding their way, sailors turned to the night sky. The convenient seasonal winds in the Red Sea established long-range navigation across 20 degrees of latitude. The observations of stars under a clear cloudless sky established the first principles of navigation. The practice was well established by the time of Homer (VIIth century B.C.) who could write that on leaving Calypso's island, Odysseus

> "... never closed his eyes in sleep, but kept them on Pleiades, or watched the late-setting Arcturus and the Great Bear ... It was this constellation that the wise Goddess Calypso had told him to keep on his left hand as he made across the sea."
> [*in* Taylor, 1971, p. 40].

These instructions directed Odysseus to sail east.

The accumulated knowledge of the stars, their positions and motions, served mariners for several thousand years and enabled them to undertake ambitious voyages. The challenges of navigation stimulated significant developments in mathematics and astronomy. The magnetic compass, introduced sometime after 1100 AD, enabled the mariner to know steering direction throughout a voyage. With a compass, he could estimate position by dead-reckoning, as knowledge of ocean currents, magnetic compass deviation and the distance travelled (from a variety of devices known as speed-logs) was built up. For the determination of absolute position, the mariner still depended on the complex calculations based on time and positions of the stars above the horizon. Various instruments were devised to estimate the elevation of stars (astrolabe, quadrant, sextant), but they all depended on the navigator's eye and skill, and cloudless skies.

By the time James Cook completed his great voyages, all the elements of celestial navigation were in place. For the following two hundred years, the accuracy of position fixes at sea out of sight of land was limited by the accuracy of the ship's chronometer, the quality of observations of selected stars at dawn and dusk, and the care with which the tedious computations were performed. The best accuracy of position was of the order of one nautical mile when a good fix was obtained, but position knowledge degraded with the passage of time if the sky was cloudy and the star fixes impossible.

The art of navigation was revolutionized by the use of radio navigation aids introduced after 1940, during the Second World War. The rapid progress in the accuracy of positioning since then is shown in Figure 1. The Luftwaffe was first with a practical radio navigation aid in the form of X-waves (Jones, 1978), which guided their bombers toward

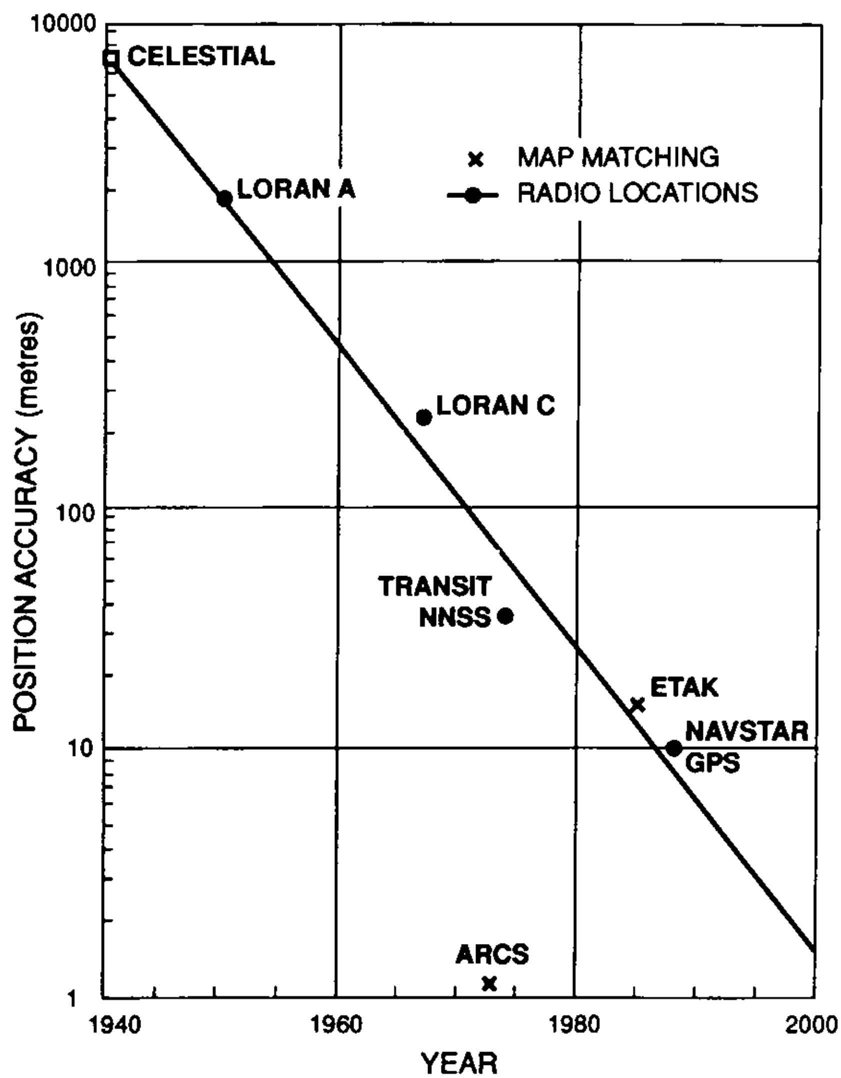

Figure 1 *Improvements in the accuracy of navigation since 1940. The graph indicates an order of magnitude (ten-fold) improvement in accuracy every 15 years. (After French, 1989, p. 102).*

the industrial heartland of the United Kingdom. After the war, this was followed by a civilian development of DECCA in the United Kingdom and LORAN in the United States. These systems depended on a "master" and several "slave" transmitters setting up a low-frequency radio pattern; the intersections of the pattern "lanes" gave a position. These systems were distributed widely, covering many areas of congested sea traffic. Their limitation was a range of less than 100 km and decreasing accuracy with range (from a few hundred metres to a few kilometres).

LORAN-C, a more powerful and accurate system, replaced LORAN-A in the mid-1960s. It is still in use, and may continue until the end of the century. Under good conditions, LORAN-C has an accuracy of 100-200 m. Off eastern Canada, it covers all of the Scotian Shelf, most of the Grand Banks of Newfoundland and the Gulf of St. Lawrence, and a significant portion of the Labrador Shelf. The speed of propagation of radio waves is different over land and water. The accuracy of the system is affected by the land-path. In nearshore areas, this may require empirical corrections and frequent adjustments of shipboard receivers.

In addition to these "public" radio navigation aids, special purpose, local radio positioning systems can be set up to support specific surveys. Offshore oil exploration is particularly dependent on these systems, which are marketed under commercial names as MINI-RANGER, SYLIDAS, TORAN, *etc.* While limited in range, these systems can pinpoint position with an accuracy of a few metres. This is adequate for all marine investigations, but there are two constraints which limit their wider application. Transmitters must be established on land, carefully surveyed in and operated during the survey; this is expensive. Second, most systems operate on high-frequency bands (to achieve the desired accuracy) and are thus limited to "line-of-sight" range, extending not more than 40-50 km offshore.

Ship positioning in the open ocean was revolutionized in the late 1960s with the launching of the first generation of navigational satellites (Project TRANSIT). This was the most significant development in seafaring since the invention of the mariner's compass, 900 years earlier. Suddenly, everywhere in all the oceans, every vessel equipped with a suitable radio receiver could plot its position with an accuracy of 150-300 m once every 1-2 hours. The second generation of navigational satellites presently being implemented, Global Positioning System (GPS) and its (ex-)Soviet counterpart GLONASS (Global Navigation Satellite System), will give continuous position fixes with a potential accuracy of 10 m or better. A long-standing goal for several millennia, of finding a safe method of navigating a ship to a distant port, has been reached. At least in principle, the positional accuracy of marine observations is no longer a constraint.

DEVELOPMENT AND MANIPULATION OF LARGE DATA BASES

In early hydrographic surveys, when the number of soundings in any given area was small, the data were presented as isolated numbers on a chart, giving spot depths. These numbers gave investigators an idea of the average sea depth and its variability (or "roughness") from the scatter of the values. As surveying techniques and instrumentation improved, the density of soundings along ships' tracks increased. Thus, it became possible to connect the numbers of the same magnitude with contour lines (called isobaths). The contours provided important additional insight by indicating significant slope changes, and features such as depressions, ridges, hills, *etc.*

As the number of soundings continued to increase during the past 30 years, the visualization of sea-bed features from a large number of postings on a chart became impossible and it was necessary to turn to computers for help. Several requirements must be met in order to use computers effectively for this purpose. Data must be in a computer-readable (digital) form; digital data must be ordered in the file so that a selection can be made within an area, or a time period, or source of data; computers must have a sufficient storage capacity for hundreds of thousands of data points; efficient software must be implemented and it must be running on a computer that is fast enough to process data files within a reasonable time (preferably

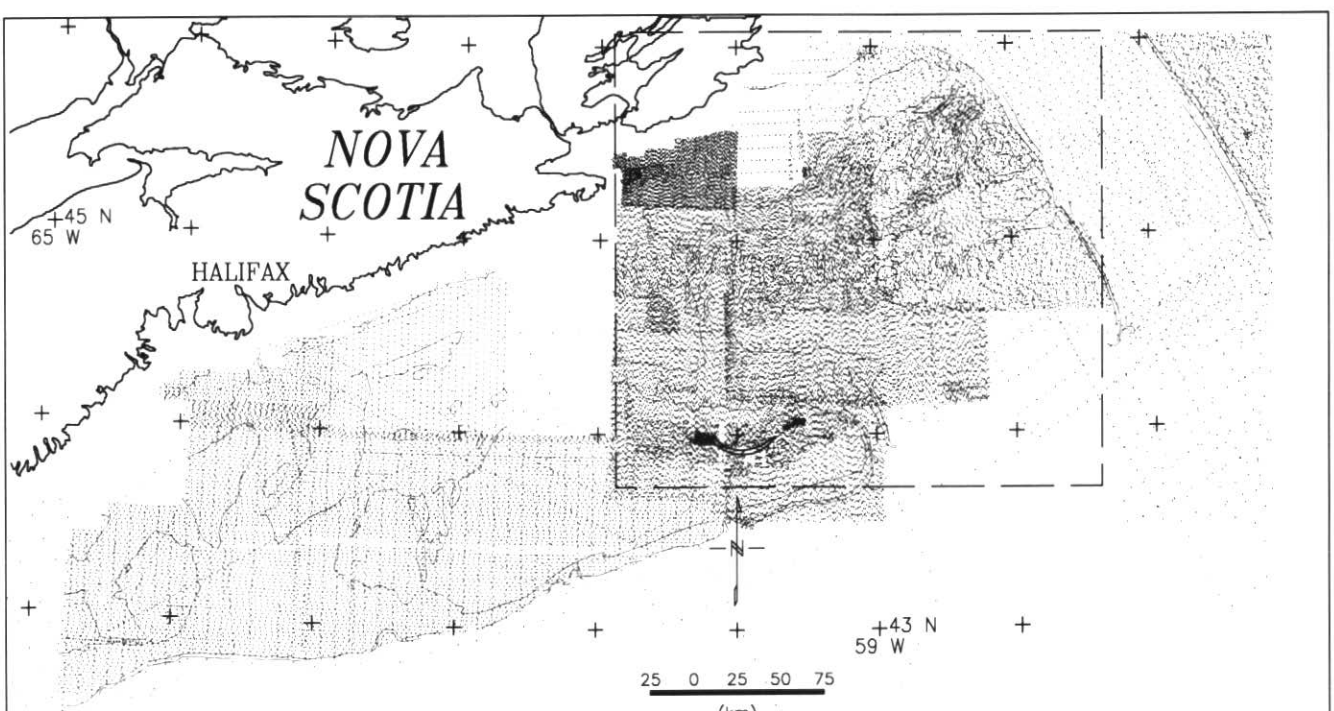

Figure 2 *The area of the continental shelf off Nova Scotia covered by the Canadian Hydrographic Survey between 1979 and 1990 employing* CSS BAFFIN *and 35 launch survey parties. There are more than half a million soundings in the data file. In the above diagram, the position of every tenth sounding is shown to preserve legibility. In the vicinity of Sable Island, the sounding tracks are about 100 m apart. In the western sector, the tracks are 2000 m apart, but there are plans to increase the density of the coverage. The area outlined within dashed rectangle is shown in Figures 4 and 5.*

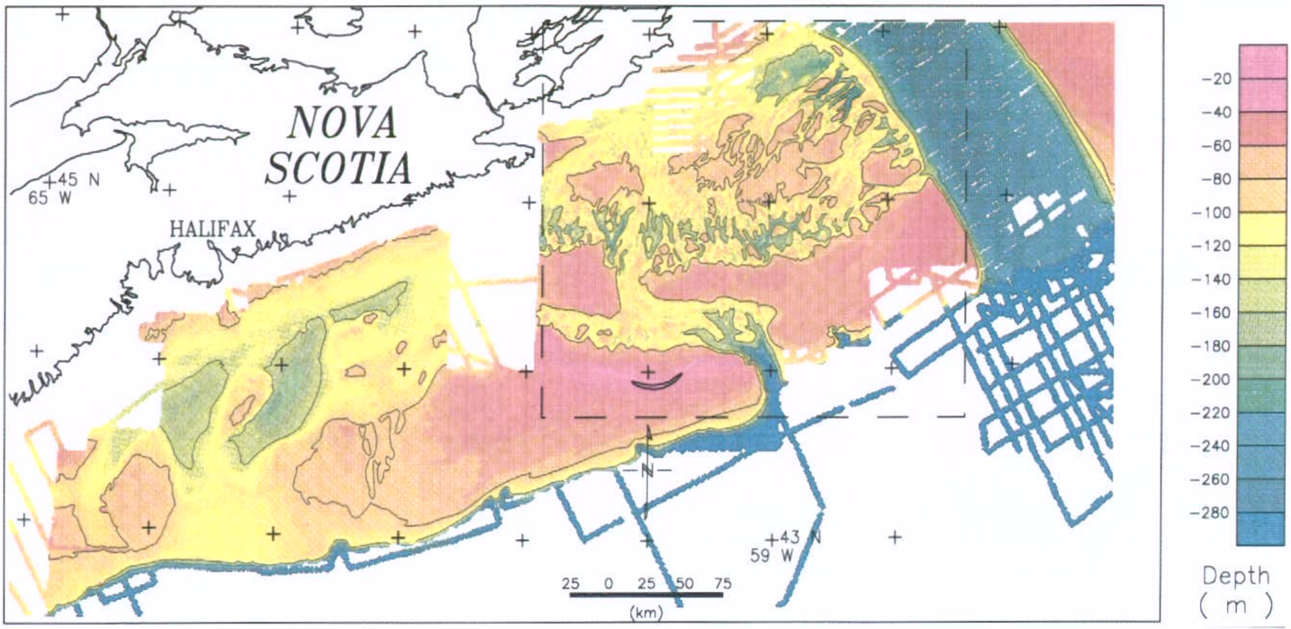

Figure 3 *The sea-floor morphology of the continental shelf off Nova Scotia. The depths of the ocean are indicated by coloured banding at 20 m intervals, with 100 m contour lines added for emphasis. This contoured map was produced from a 1000 m × 1000 m gridded data set. At this grid size, the near-shore areas of rapid topography change are not well depicted.*

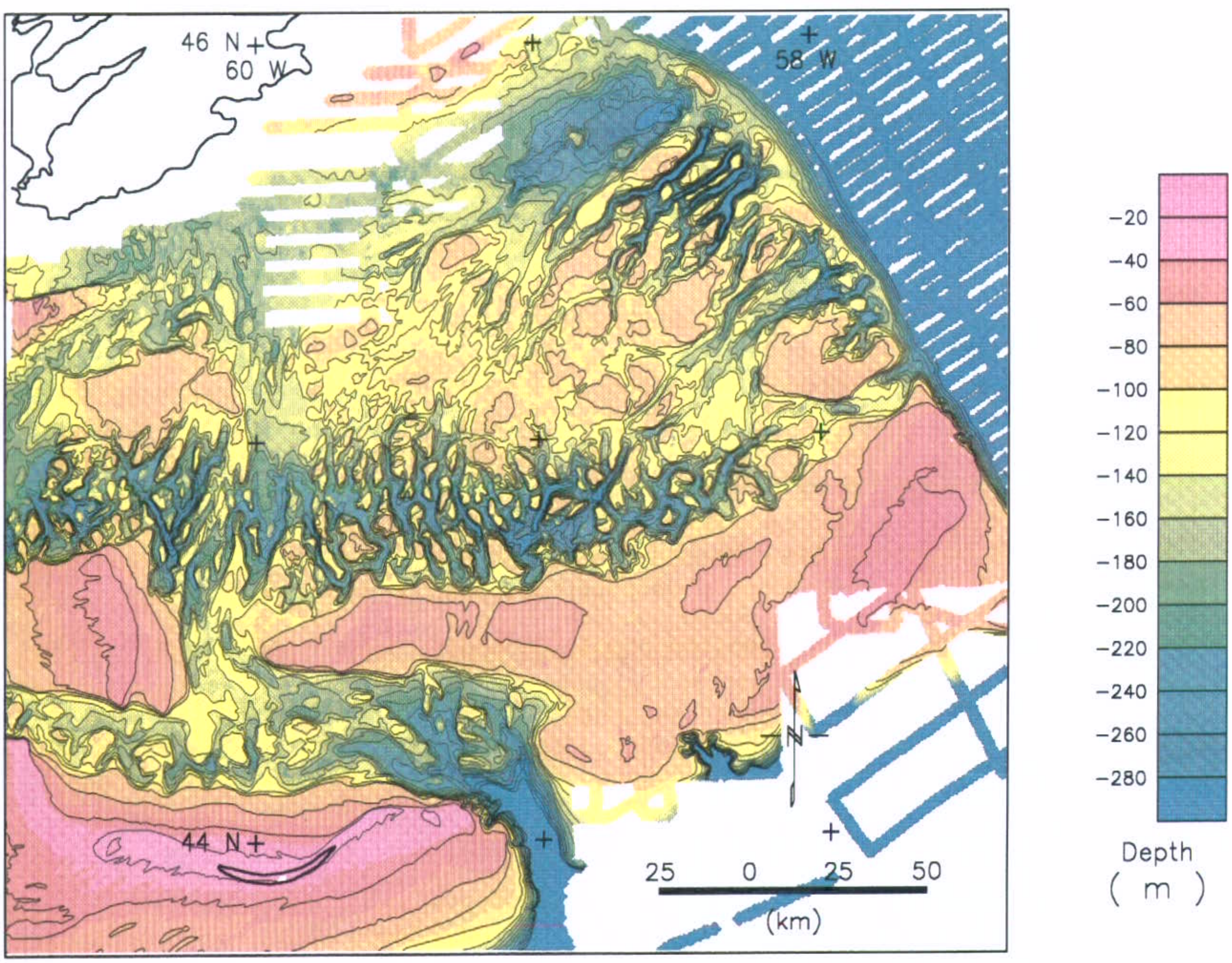

Figure 4 *The area of detailed surveys between Sable Island and Cape Breton, discussed in this paper. The colour contouring is the same as in Figure 3, but the contours were derived from 400 m × 400 m grid to show more detail. The figure suggests a complex sea-floor morphology north of the Sable Island Bank (Fig. 6), but the interconnected web of valleys is not clearly evident in this presentation.*

minutes, certainly not days); and finally, computer output (on a video screen or as a hard copy plot) must be available for quick examination and for later study in detail.

By the late 1980s, all the above requirements were met. Between 1979 and 1990, *CSS BAFFIN*, and up to five accompanying launches, collected slightly less than one half million soundings, covering the area from LaHave to St. Pierre Banks, but concentrating near Sable Island. The area covered and the density of soundings are shown in Figure 2. This huge volume of data was processed, "cleaned up" and made available to us through the Canadian Hydrographic Service (CHS) data base (Varma *et al.*, 1990). Efficient software was developed by GEOSOFT, Inc. of Toronto, and adapted by them for operation on PC-compatible desktop computers.

CHS data were gridded using a minimum curvature algorithm (Briggs, 1974) with tension factors of 0.5 (Smith and Wessel, 1990). Gridding is an interpolation procedure, and plotted data must be interpreted with care, paying particular attention to the density of original data points since a computer can blindly carry on inventing values where no data are available. We have used a 400 m × 400 m grid for the presentation of our data as the best compromise. Using large-grid spacing (low-pass filter) smooths the appearance of the bottom, while using a grid spacing that is too small allows the computer to invent too many values.

The gridded data were processed in two ways. The grids were machine contoured and the depth range between the contours was colour coded. This gave a conventional representation of the bottom topography, although in greater detail than available before (Figs. 3 and 4). In order to enhance irregular bottom features, the gridded data were further manipulated to produce a shadowgram (Broome, 1990; Macnab *et al.*, 1987) which was superimposed on the coloured topography to obtain a three-dimensional or relief model (Fig. 5). Shadowgrams give a reflectance of grid elements relative to an illumination source positioned at an arbitrary inclination and azimuth. By altering those two parameters, different aspects of bottom morphology can

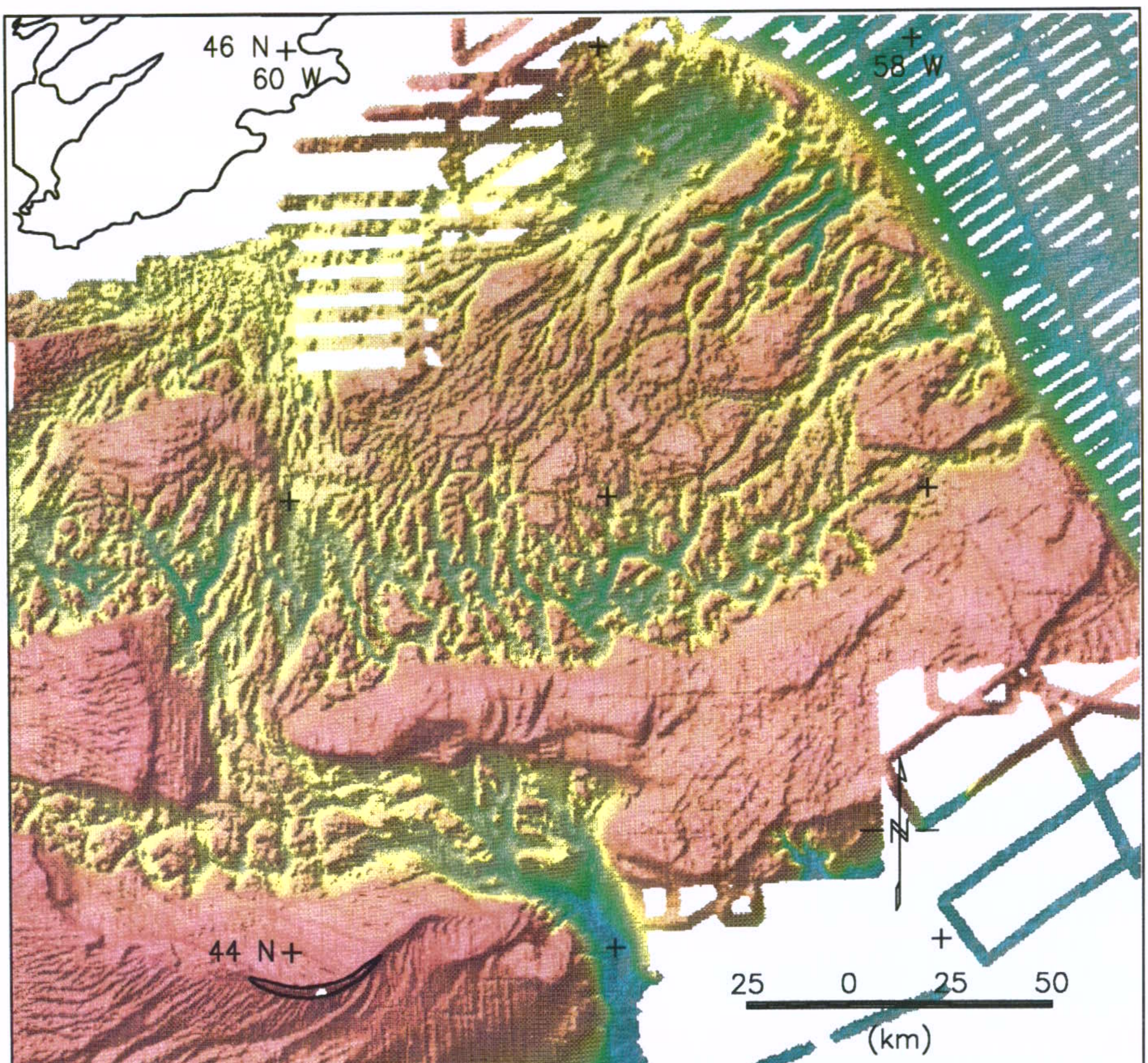

Figure 5 *Same area as shown in Figure 4 with a shadowgram superimposed. The illumination direction is from the northwest at an elevation of 45°. In this presentation, the continuity of deeply incised valleys can be traced across the whole survey area.*

be emphasized. The lower inclinations emphasize surface ruggedness (higher frequencies) while higher inclinations emphasize more regional topographic variations. The azimuth highlights the linear features which strike in a direction perpendicular to the illumination direction. After some experimentation, we have chosen to illuminate our study area with a source at inclination I=60° and azimuth D=135° (*i.e.*, from the southeast).

THE SCIENTIFIC APPLICATIONS OF THE BATHYMETRIC COMPILATION

The area of the eastern Scotian Shelf for which we have produced the bathymetric maps (Figs. 4 and 5) was covered by glacial ice at times during the Quaternary, and preserves glacial morphologic features (Shepard, 1931; King *et al.*, 1972, 1974; King and Fader, 1986), with only deeper basins filled with later sediment masking the glacial features (Fig. 6). Thus, our high-quality bathymetric data can be used in a manner similar to the use of good topographic maps on land by geomorphologists. We have selected an area of particularly dense soundings for detailed examination and further discussion.

The map extends from Banquereau in the south to close to the southern coast of Cape Breton Island in the north (Figs. 4 and 5). Banquereau (Amos and Knoll, 1987) is one of a series of large shallow fishing banks on the outer Scotian Shelf, separated from the coast by deeper waters of the middle shelf (Piper and Fader, 1990). The northern parts of these banks are built on Tertiary strata that were eroded during low stands of sea level in the Pliocene and Early Quaternary and by glacial ice in the Late Quaternary. The steep northern margins of the banks are commonly cuestas formed by resistant Tertiary strata. The seaward sides of the banks have been built up by deposition of up to 200 m thickness of Quaternary glacial sediments. North of Banquereau, the topography of the shelf is very complex, with several belts of linear depressions reaching maximum depths of 360 m. These depressions extend from the northern edge of Banquereau, across Misaine Bank, to the flanks of the Laurentian Channel (the main outlet for both Appalachian and Laurentide ice in southeastern Canada).

These depressions were interpreted by King *et al.* (1974) as remnants of a Late Tertiary subaerial drainage system later modified by glacial erosion. Valleys on the inner shelf with an irregular talweg were interpreted to be subglacial tunnel valleys (Barnes and Piper, 1978). Boyd *et al.* (1988) showed that buried valleys beneath Sable Island Bank have an anastomosing pattern and their floors extend far below sea level, also indicating a sub-glacial origin. Similar buried tunnel valleys occur on Banquereau (Amos and Knoll, 1987), on the Grand Banks (Fader and Miller, 1986), and in southwest Newfoundland (Shaw and Forbes, 1990).

The relief model bathymetric map of the eastern Scotian Shelf (Fig. 5) clearly illustrates and enhances both seabed and buried features. The dominant characteristic of the map is the presence of the large shelf edge, and shallow bank areas with intervening, highly dissected zones. The latter are linear, generally parallel, depressions reaching considerable depth. Unlike the other banks, Misaine Bank, in the north central area of the map, has the linear dissected pattern cutting its surface. The dissected deeper zones can be clearly seen to have different orientations to their linear elements. Those north of Banquereau trend more or less north-south, while those beneath Misaine Bank and to the east trend northeast-southwest and are similar in width. Less clearly defined features on Banquereau and Sable Island Bank are large-scale bedforms and sand ridges. The western edge of Banquereau is deeply incised by a channel, which provides an outflow route from glacial channels through the Gully cut into the Continental Margin, to the deep sea.

Generally, tunnel valleys are not expressed as surface features on Banquereau. Buried channels are less frequent than in the area to the north (Amos and Knoll, 1987), but are of similar dimensions, as are buried tunnel valleys beneath Sable Island (Boyd *et al.*, 1988). Some tunnel valleys lead to heads of submarine canyons (Amos and Knoll, 1987; McLaren, 1988). Post-Miocene channels at the eastern margin of Laurentian Channel reach depths as great as 1300 m below present sea level (Wade and MacLean, 1990, fig. 5.46), far deeper than known Pliocene or Quaternary sea-level lowerings (Gradstein and Agterberg, 1982; Piper and Normark, 1989) and therefore could not have resulted from fluvial erosion. The youngest tunnel valleys on Sable Island Bank are at least early Wisconsinan in age (Boyd *et al.*, 1988).

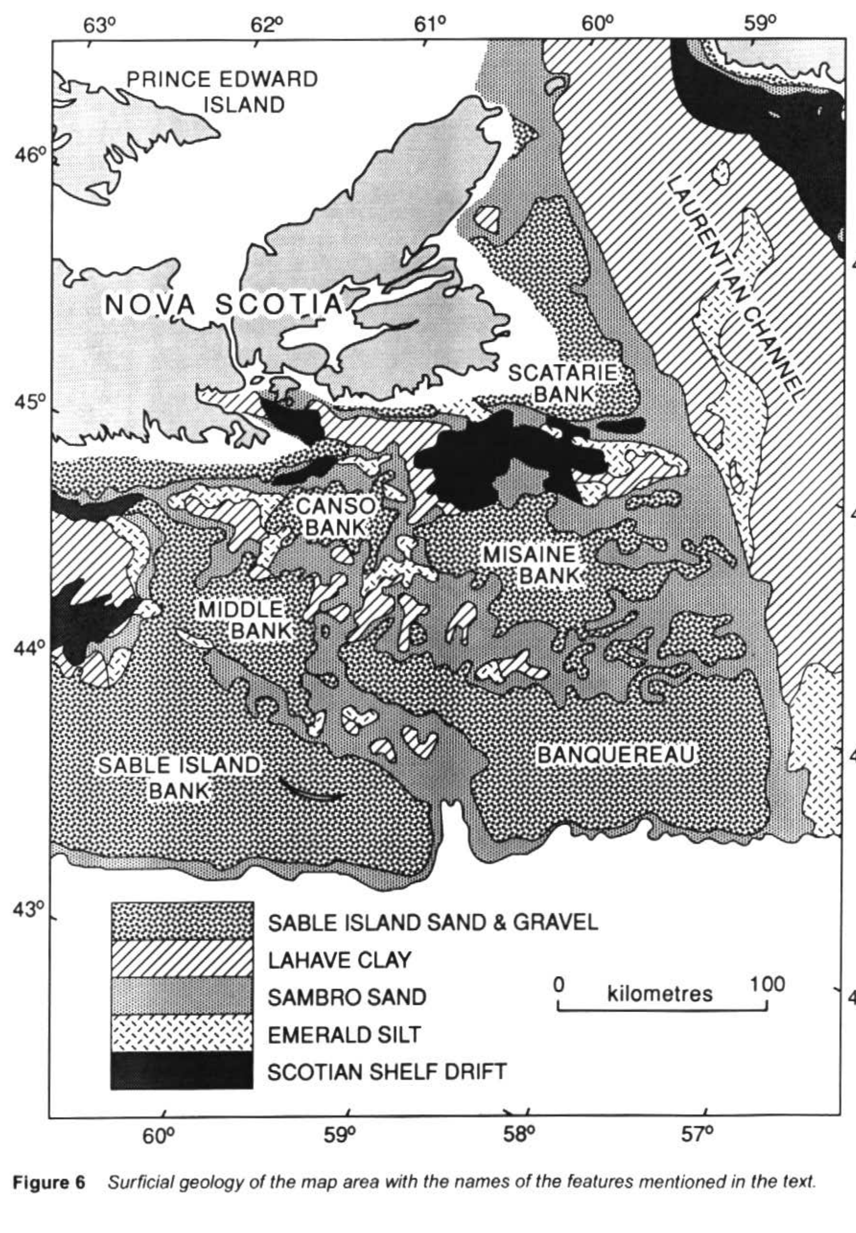

Figure 6 *Surficial geology of the map area with the names of the features mentioned in the text.*

The most complete descriptions of similar valleys are from the North Sea (Long and Stoker, 1986; Wingfield, 1990) and North German Plain (Ehlers and Linke, 1989): characteristic are the anastomosing pattern and irregular talweg, with local overdeepening of several hundred metres. Three main stratigraphic levels of tunnel valley incision (isotopic stages 2-4, 6 and 12) are seen in the North Sea (Cameron *et al.*, 1987).

Several models have been proposed for the origin of tunnel valleys. Most authors regard them as cut by sub-glacial meltwater streams under high pressure. It is unclear whether this was a gradual process beneath a stagnating ice sheet (Boulton and Hindmarsh, 1987; Jeffery, 1991; King and Fader, 1992) or a catastrophic process beneath active ice (Shaw, 1985; Boyd *et al.*, 1988). Deeply incised valley segments have even been interpreted as ice marginal (Wingfield, 1990). Resolution of these issues requires a detailed knowledge of the stratigraphic setting, age and the character of the fill tunnel valleys, information that is not available from bathymetric surveys.

However, bathymetric surveys reveal the surface expression of unburied or partially buried tunnel valleys more clearly than spaced seismic reflection profiles or boreholes. The southern margin of the prominent tunnel valleys on the eastern Scotian Shelf corresponds approximately to a late Wisconsinan ice margin at the northern edge of Banquereau and Sable Island Bank (Boyd, in McLaren, 1988). The local cross-cutting patterns of valleys suggest several tunnel-valley-cutting events, probably under different configurations of glacial ice. Two types of tunnel-valley fill sequence are observed on high-resolution seismic profiles north of Banquereau (Fig. 7). Some contain a thick sedimentary fill above Tertiary bedrock, including the typical basin fill sequence on the Scotian Shelf (King and Fader, 1986), namely Scotian Shelf Drift (largely till), Emerald Silt (proglacial sediment) and LaHave Clay (post-glacial muds). Others contain a simpler sedimentary sequence of a lower irregularly stratified unit resting directly on Tertiary bedrock, overlain by LaHave Clay. In both types of valley, thickness of LaHave Clay is highly variable and apparently influenced by tidal currents. In many places, gas in the sediments forms an acoustic mask.

The valleys with the thick sedimentary fill may predate the late Wisconsinan glacial advance, which reached the northern edge of Banquereau and Sable Island Bank

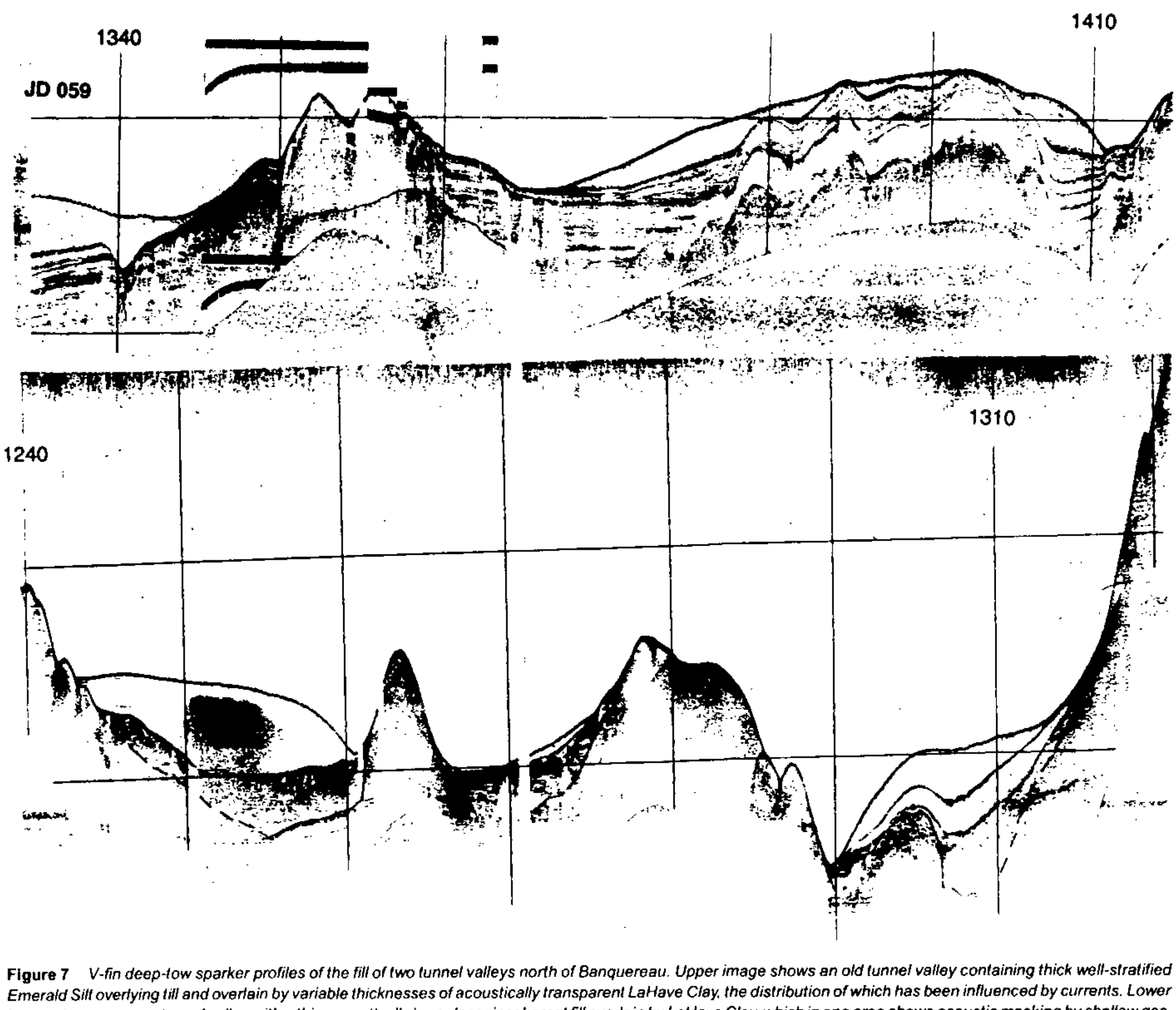

Figure 7 *V-fin deep-tow sparker profiles of the fill of two tunnel valleys north of Banquereau. Upper image shows an old tunnel valley containing thick well-stratified Emerald Silt overlying till and overlain by variable thicknesses of acoustically transparent LaHave Clay, the distribution of which has been influenced by currents. Lower image shows a young tunnel valley with a thin acoustically irregular or incoherent fill overlain by LaHave Clay, which in one area shows acoustic masking by shallow gas.*

(McLaren, 1988). These valleys may correlate with buried tunnel valleys on Banquereau and Sable Island Bank, which are of pre-late Wisconsinan age (Boyd *et al.*, 1988). Off the south shore of Nova Scotia, tunnel valleys, which cut bedrock, are also of pre-late Wisconsinan age (Piper *et al.*, 1986; Piper and Fehr, 1991).

Valleys with the thin sedimentary fill were probably flushed out during the late Wisconsinan, perhaps after deposition of part or all of the Emerald Silt sequence in the other valleys. The chaotic fill (irregular stratified fill) may represent final ice-contact deposition, followed by rapid ice retreat and postglacial mud deposition. The exact chronology is not at present established, but the inferred stratigraphic position of these young tunnel valleys suggests that they might correlate with a late ice advance postulated by King and Fader (1988) at about 10 ka, immediately prior to final ice retreat on the Scotian Shelf.

If tunnel valleys on the shelf are formed through catastrophic outbursts of subglacial meltwater, then the effects should be visible in deep-water areas seaward of the continental shelf. Two lines of evidence suggest that catastrophic discharges may have flowed down the Laurentian Fan, seaward of the Laurentian Channel. The morphology of the valley, revealed by Seabeam surveys (Hughes Clarke *et al.*, 1990), is remarkably similar to that of glacial spillover channels between ice dammed lakes on the southern margin of the Laurentide ice sheet (Kehew and Lord, 1986), with a straight unusually wide valley, downflow distributary valleys with similar geometry, and lemniscate erosional residuals of former valley wall sediments. Cores on the Sohm Abyssal Plain have recovered a mid-Wisconsinan sand bed (Vilks *et al.*, 1985) interbedded with distal turbidite muds, indicating a flow far more powerful (Wang *et al.*, 1982) than the 1929 turbidity current (which transported 200 km^3 of sediment at velocities of 65 km/hr). This sand bed may record a catastrophic outburst of turbid glacial meltwater down the Laurentian Channel and fan.

CONCLUSIONS

In the past, the bulk of information concerning sea-bed morphology came from hydrographic surveys and hydrographic maps. The objective of these maps was to ensure safe navigation and, therefore, they emphasized shallow peaks, often shown as isolated contours. The maps were further limited by the spacing of the data points and the bias of the cartographer who contoured the data. The almost total areal coverage of modern surveys, together with digital techniques for enhancement and presentation of the data, provide marine geologists with new insights for the interpretation of processes which have affected the seabed. This will lead to the development of new models to explain the observed morphology and provide a new level of understanding of marine processes which shape the sea floor.

ACKNOWLEDGEMENTS

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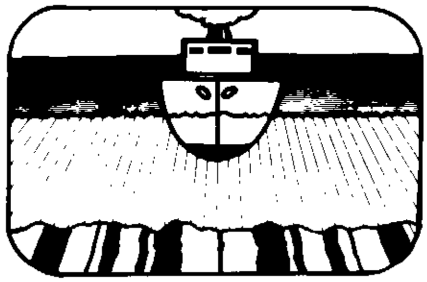

The Seasonal Distribution of Suspended Particles and Their Iron and Manganese Loading in a Glacial Runoff Fiord

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SUMMARY

Three mechanisms are responsible for the distribution of inorganic suspended particulate matter in a glacially influenced fiord such as Knight Inlet, British Columbia. The most important is the influx of sediment from rivers draining hinterland ice fields, with maximum input levels reached in the summer melt season and during the autumn period of flash floods. Sediment can also enter a fiord from the sea: 1) within the return flow of estuarine circulation that is fully developed during the late spring through early autumn, and 2) as part of deep shelf water that exchanges and flushes out the deep water of the fiord basin, particularly during the winter season. The third mechanism for sediment accumulating on the sea floor is through the action of episodic turbidity currents. These sediment gravity flows carry coarse delta-front sediments to the otherwise muddy basin floor. The relative abundance of particulate iron within the suspended sediment load directly relates to higher levels of iron in glacially derived particles issuing from river mouths at the head of the fiord. Elevated levels of particulate manganese may be a result of turbidity currents. They are observed in the water column nearest the sea floor where circulation and geochemical conditions would normally preclude their existence.

INTRODUCTION

A fiord is a deep high-latitude estuary which has been (or is presently being) excavated or modified by land-based ice (Syvitski *et al.*, 1987). Since fiords are at least partially ice scoured, the typical configuration is a long narrow deep and steep-sided inlet, which is frequently branched and sinuous, but may be remarkably straight in whole or in part where the ice has followed major fault zones. Fiords usually, but not inevitably, contain one or more submarine sills: bathymetric highs that separate the deep water of basins. The internal basins defined by these sills are characteristic features of fiords, which determine many of their distinctive physical and biogeochemical characteristics. Except for some polar inlets during the winter, all fiords are estuaries. Major freshwater inflow is likely to be at the head, and the brackish water typically flows toward the mouth as a surface plume. As with all estuaries, fiords are therefore transition regions between the land and the open ocean, regions of strong physical and chemical gradients where fresh and salt waters mix and react.

Fiords encompass a number of distinctive oceanographic environments, which make them particularly exciting for estuarine research. The near-surface "estuarine zone", basically common to all estuaries, is underlain by marine water which, in silled fiords, may be physically restrained in basin enclosures. Such coastal-zone, mini-ocean basins offer unique opportunities for studying terrestrial input into quasi-closed marine systems. Often the circulation above and below the top of the sill is poorly coupled, and, in deep fiords, processes and reactions within the basins may be spatially and temporally separated from those occurring in the upper-zone estuarine environment.

Fiords receive water from land *via* rivers that drain the hinterland mountains and ice fields, and as deep water circulation from the open ocean. These water pathways carry sediment in suspension, most of which settles to the sea floor creating a sedimentary cover characteristic of fiord environments. The character and distribution of suspended particles within fiords receiving glacier meltwater is influenced strongly by the seasonality of fluvial discharge, the largest source of sediment, and the production of biological detritus. From the work of Syvitski and Murray (1981), we know that the turbid plume issuing from a river mouth carries sediment down the length of the fiord quickly, while this fresh water slowly mixes with sea water.

Flocculation is the process that holds particles together in spite of repulsive electrostatic forces that are part of the natural chemical makeup of soil particles. Ions within a saline solution neutralize the repulsive forces, allowing Van der Waals binding to occur. Once particles have joined, the resultant settling velocity of the flocs is usually greater than that of the individual components. Although flocculation occurs within the brackish waters of a fiord plume, mixing