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Article abstract

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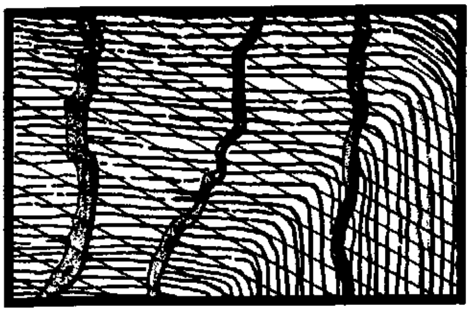

Environmental Marine Geoscience 2.

Multibeam Bathymetry and Backscatter Imaging of the Canadian Continental Shelf

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SUMMARY

High-resolution, multibeam technology has revolutionized the study of marine continental shelf geology in the 1990s. For the first time, complete coverage maps of the seabed are becoming available: the marine equivalent of the aerial photograph. This article reviews the principles that lie behind multibeam bathymetric and backscatter surveying, and also details the mapping platforms available to researchers in Canada. Examples of imagery derived from a wide range of geologic settings, spanning the Cambro-Ordovician through to the present, are presented from sites located on the eastern Canadian continental shelf.

RÉSUMÉ

Au cours des années 1990, la technologie des levés multifaisceaux à haute résolution a révolutionné l'étude de la géologie des plateaux continentaux marins. Pour la première fois dans l'histoire, une couverture cartographique complète des fonds marins est devenue possible; c'est l'équivalent de la photographie aérienne. Le présent article passe en revue les principes des méthodes de levé bathymétriques multifaisceaux et de rétrodiffusion, et présente les particularités des diverses plateformes de cartographie à la disposition des chercheurs au Canada. Le lecteur y trouvera également une large fourchette d'exemples de milieux géologiques différents provenant de divers endroits de la plateforme continentale de l'Est du Canada et allant du Cambro-Ordovicien jusqu'au présent.

INTRODUCTION

In Canada, the majority of the continental shelf has been glaciated, leaving a wonderfully detailed and complex surficial geology. The geology ranges over a wide span of time scales, from the exposure of ancient terrains through to Pleistocene glaciogenic depositional and erosional features which are, in places, overprinted by modern wave- and current-dominated processes. Until recently, only a small fraction of this diversity had been uncovered.

Imagine that a field geologist does his/her mapping at night, with no access to aerial photographs and only a flashlight to illuminate his/her surroundings. This has been essentially the fate of marine geologists for the last 40 years. Data derived from single-channel seismic and sidescan sonar systems, verified by bottom sampling, have formed the basis of most existing surficial marine geologic maps. Although we recognize recent advances in navigation and digital processing, it can be argued that the standard suite of survey tools has not significantly changed during the past 20 years. On Atlantic Canadian shelves, for example, many maps were compiled using single-beam echo sounders and survey lines spaced several kilometres apart (*e.g.*, Fader *et al.*, 1977, 1982). These surveys could not hope to constrain the lateral continuity of features observed along survey lines. Consequently, there existed real limits to the depositional models that have been proposed for continental shelves; one could contend that advances in process understanding were limited by technology.

In the late 1980s the Canadian Hydrographic Service (CHS) invested in high-resolution multibeam technology (Costello *et al.*, 1992) to enhance the quality and accuracy of their navigational charts. A multibeam bathymetry mapping system employs an array of acoustic transducers to form beams of sound pointing over an arc, or swath, under the survey vessel, allowing the measurement of bathymetry and backscatter strength along a wide swath on the seafloor. Before 1990, deep-water systems were in use (*e.g.*, SEABEAM) but their seafloor footprints were too coarse, their swath widths too narrow, and their frequencies too low for shelf seabed mapping. Advances in a range of technologies during the last decade, in particular motion sensing, positioning, and computation, made possible the development of higher-resolution mapping tools.

Although this thrust in multibeam mapping was initiated by the CHS, the information derived from these systems is of great use to marine geologists. For the first time, complete coverage of the seabed topography could be achieved, resulting in maps that resolve the complex micro-relief that is characteristic of Canadian shelves. Although it is difficult to put precise limits on the change of mapping capability offered by these new systems, it can be said that previous to this advancement, few geologic maps of the seabed were valid for scales less than 1:250,000. We now map routinely at scales approaching 1:1000 and consequently a whole range of geologic features and processes, previously unknown in some instances, has become apparent.

Bathymetry and Backscatter

All multibeam sounders work using essentially the same basic principles. Sound is projected toward the seabed in cone-shaped beams formed using an array of piezoelectric transducers mounted on the hull of the survey vessel (Fig. 1). These beams span a fan-shaped sector below and to the sides of the survey vessel. The width and number of beams depends on the multibeam manufacturer and model. The Kongsberg Simrad EM1000 system, for example, projects up to 60 beams over a 150° arc with an effective beam width of approximately 2.5° in the along-track direction. The beam width on the seabed determines the footprint of the mapping system and the footprint expands with the distance

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between the transducer array and the seabed. The Kongsberg Simrad EM1000 system has a footprint between 2 m and 10 m in water depths of less than 100 m, depending on the angle of the beam with respect to nadir.

By measuring the transit time of a pulse projected from the transducer array and reflected from each seafloor footprint back to the array, an estimate of the distance to each seafloor footprint can be calculated. Since the beams are projected at variable angles to nadir, the sound velocity profile of the water column is needed to account for ray-bending effects. As the survey vessel moves along its track, estimates of depth are measured below and to the sides of the vessel. The along-track spacing between successive soundings is determined by the time for sound to return from the outermost beams, the ship's speed and the computational speed of the multibeam processing unit. By running survey lines so that adjacent swaths overlap, a complete coverage high-resolution, digital terrain model (DTM) is assembled over the seabed.

Multibeam systems generally record the mean backscattered signal strength, or mean amplitude, and the time series of related amplitudes returned in each beam. It is tempting to use the backscatter amplitude as a direct proxy for surficial sediment type, but a careful consideration of the physics of the problem presents a more complex picture (*e.g.*, Jackson *et al.*, 1996; Novarini and Caruthers, 1998). The amount of acoustic energy returned in each beam depends on the interaction of the incident energy in the down-going ray with the physical state of the seabed and the shallow subsurface, and it is strongly dependent on the angle of incidence of the beam on the seabed.

Multibeam sounders project sound over a wide range of angles, ranging from 0° for beams pointing directly down from the vessel to as high as 75° for the outermost beams.

For angles of incidence less than approximately 20°, the signal returned from the seabed is largely within the specular zone where a direct and coherent reflection from the seabed is recorded from objects larger than the acoustic wavelength. The amount of energy returned from a specular reflection increases with the acoustic impedance contrast across the seabed boundary (acoustic impedance is the product of density and acoustic velocity). The specular return is conversely diminished as the roughness of the seabed increases. In contrast, the energy returned at wider beam angles arises from constructive interference with roughness on the seabed (Bragg scattering) and this scattered energy increases with increasing surface roughness. There can also be an added contribution to the backscatter energy from volume heterogeneity within the subsurface at these wider angles. The acoustic pulse incident does propagate to a varying extent below the surface or the seabed, moreso in soft, fine-grained sediments, dependent on the frequency of the sounding system.

There exists, then, no direct and simple relationship between the backscatter amplitude and surficial sediment type. Generally for angles outside the specular range, there does exist a general correspondence between backscatter amplitudes and surficial sediment roughness that can be used for cursory mapping and sediment identification. Coarse gravels and cobbles tend to be locally rough and return high-amplitude, wide-angle backscatter signals, whereas sands and fine-grained materials can be locally smooth with a much lower backscatter. Care must be taken to look at the complete angular response of backscatter in some cases. Flat or polished bedrock, for example, is locally smooth and thus can have a very low wide-angle backscatter response, which could be confused with clay or other smooth, fine-grained deposits. The near-nadir response would, in this instance, be needed to differentiate the two possibilities. Coincident seismic data and seabed samples are often collected to aid the backscatter interpretation.

An Integrated Survey Tool

Multibeam mapping demands the integration of many differing technologies. The CHS at present owns and operates three multibeam mapping platforms. These platforms are available to Canadian researchers through the national ship committee for government departments, and through NSERC for universities. Whereas the CHS has chosen Kongsberg Simrad multibeam systems, other manufacturers produce a similar range of products (*e.g.*, Basu and Saxena, 1999).

The Kongsberg Simrad EM100 system mounted on the CCGS *Matthew* is the earliest version of a multibeam shelf-mapping system used in Canada, installed in the 1980s. It operates at 100 kHz and surveys with a 100° arc divided into 32 separate beams. This mapping system can make only a relative measure of backscatter strength, not suitable for quantitative analyses.

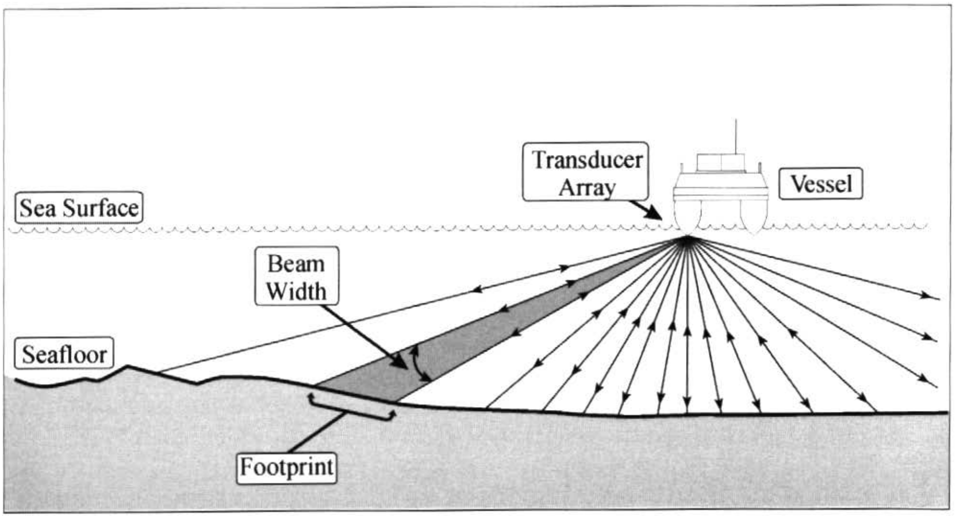

Figure 1 A hull-mounted multibeam system measures a sequence of depths across a fan-shaped arc sweeping to both port and starboard beneath the survey vessel. The arc is divided into a number of distinct and separate beams, which impinge the seabed over an area, or footprint, that expands with the distance between the transducer and the seabed.

The EM1000 system on the CCGS *F.G. Creed*, the next development in the line of Kongsberg Simrad high-resolution multibeam systems, operates at 95 kHz and can form up to 60 beams over an arc of 150°. With this and subsequent Kongsberg Simrad multibeam systems, backscatter coefficients are better calibrated and are more suitable for quantitative modelling. The *Creed* is a 20-m SWATH (Small Waterplane Area Twin Hull) vessel specially designed to afford exceptional stability in moderately rough, open-ocean conditions.

Lastly, three Kongsberg Simrad EM3000 systems are mounted on small hydrographic launches (deployed in eastern, central and western regions of CHS). The EM3000 system operates at 300 kHz with 120° arc and 127 beams. It excels in high-resolution, nearshore/estuarine surveys but is not suitable for open-water shelf operations from the launch-based platform. On more seaworthy vessels, the EM3000 can be used in water depths approaching 200 m.

The accuracy of depth estimates and their derived positions on the seabed depend critically on precise estimates of the position and attitude of the transducer array when the sounding is collected. The CHS mapping platforms use the TSS Applied Analytics Corporation POS-MV 320, to accurately measure the ship's motion, heading, roll, pitch and heave. This position and attitude sensor combines short-period attitudinal estimates from a strap-down inertial motion sensor with positional estimates from dual differential GPS receivers (Dinn *et al.*, 1996).

These multibeam mapping systems collect large amounts of navigational, attitudinal, bathymetric and backscatter data. Without the development and use of computer-aided techniques, it would be impossible to examine or make use of these data. The Geological Survey of Canada (GSC) has focussed on processing multibeam data within a geographic information system (a public domain, raster-based GIS called GRASS), extending the GIS software with specialized in-house developed tools, and the integration of multibeam maps with other types of marine geophysical survey data.

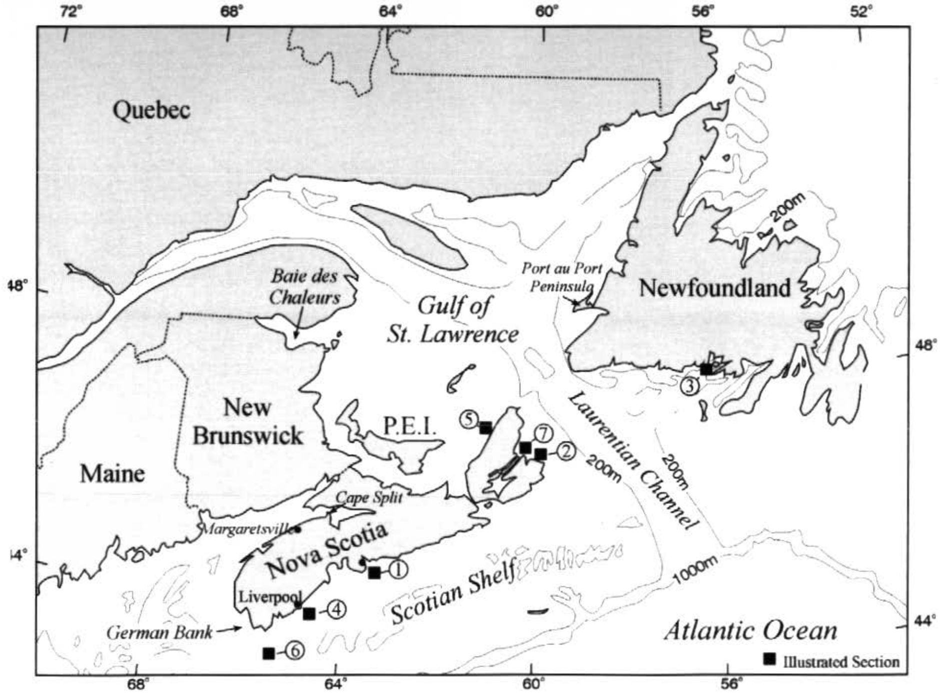

Figure 2 Map of Atlantic Canada with sites of the study areas mentioned in the text. The numbers identify areas for which illustrations are included in this report: (1) approaches to Halifax Harbour, (2) outcropping Carboniferous bedrock over Phalen Colliery, (3) submarine moraine off Bay d'Espoir, (4) ribbed moraines off Liverpool, NS, (5) bifurcating bedforms off Cheticamp, (6) barchan dune fields on Browns Bank, and (7) seabed subsidence over the Prince Colliery, Point Aconi, Cape Breton.

A typical multibeam survey contains hundreds of millions of soundings, which are impossible to comprehend as a table of numbers or as numbers plotted on a chart. Even contouring techniques do not adequately reveal the wealth of information in these new data sets. The information inherent in the digital terrain model (DTM) is, in the authors' opinion, best appreciated by making synthetic images of the seabed with artificial illumination; these techniques had already been standard practice in the display and analysis of other geophysical data. The advent of graphic workstations has made other approaches available. Interactive, 3-D visualization software is now routinely used to examine and understand the DTMs and backscatter mosaics collected during routine surveys.

Principal Advances in Understanding

Previous survey techniques, whether conducted on geometric grids or on irregular tracks planned using hydrographic charts (the so-called chicken-track methodology), generally allowed the scientist to construct 2-D geological cross sections. The missing element was the kind of spatial geomorphic continuity obtainable with aerial photographs or high-resolution contour maps on land. The 100% multibeam coverage now available reveals complex seascapes containing many hitherto unrecognized geomorphological elements. The overlay of backscatter data on the multibeam maps is central to recognizing the seascapes as the integrated results of ancient, recent and modern processes.

It is useful to illustrate some of the advances in scientific understanding that have come about in the past several years through the application of multibeam technology. In the remainder of this article we discuss several case studies representing a variety of geological settings and scientific issues (see Fig. 2 for a location map). Some examples have illustrations included here in black and white; we invite readers to visit the Geological Survey of Canada, Atlantic (GSCA) website (agc.bio.ns.ca) to see colour versions and other examples from a wide range of seascapes on the Canadian Atlantic coast.

BEDROCK MAPPING

Bedrock is widely exposed on the Canadian continental shelf. In many places the unconsolidated overburden has been scraped off during late Quaternary glaciation and the bedrock surface has been further denuded during the postglacial transgression. Unlike the terrain on land, the seabed has minimal vegetation, and the degree of bedrock exposure easily eclipses that observed on land. The bedrock exposed off the Atlantic coast includes geological units from the Cambrian through to the Mesozoic eras.

Approaches to Halifax Harbour

In the approaches to Halifax Harbour (Loncarevic *et al.,* 1994), more than 30% of the underlying bedrock is within a few metres of, or at, the seafloor (Fig. 3). The complete succession of geologic units mapped on land is more clearly defined in the multibeam imagery, including the Cambro-Ordovician Meguma Group, consisting of thickly bedded metasandstones of the Goldenville Formation and the associated overlying slates of the Halifax Formation, overprinted in some areas with the granodiorites and granites of the Devonian Halifax pluton. Loncarevic *et al.* (1994) showed that the bathymetric imagery reveals exceptional information about the fracture patterns within the older host rock and suggests that these faults control the emplacement of the plutonic suite. Fracture patterns that cut all major units show a correlation with Carboniferous motion on the Cobequid-Chedabucto fault, a trend that had not been reported in previous land-based studies. In addition, the existence of west-northwest bounding faults, which were proposed to explain the trend of many harbours in Nova Scotia, has been precluded by these new bathymetric data.

Western Newfoundland Offshore

The Appalachian Front lies offshore of western Newfoundland except where it crosses the Port au Port Peninsula (Stockmal and Waldron, 1993). Knowledge of the geometry and trend of this structure in the proximal offshore had been extrapolated from limited onshore outcrop exposure. Multibeam mapping in 1996 and 1997 (Courtney *et al.,* 1998) examined the near-shore bathymetric expression of the structural front. The imagery reveals a succession of structural elements along the western coast of the peninsula, including exposures of a foreland basin succession and the trace of the Round Head Thrust (the intersection of the Appalachian Front with the seabed). It has been seen in the multibeam data that the Odd Twins magnetic anomaly (Ruffman and Woodside, 1970), a regional, potential field marker of the structural front, coincides

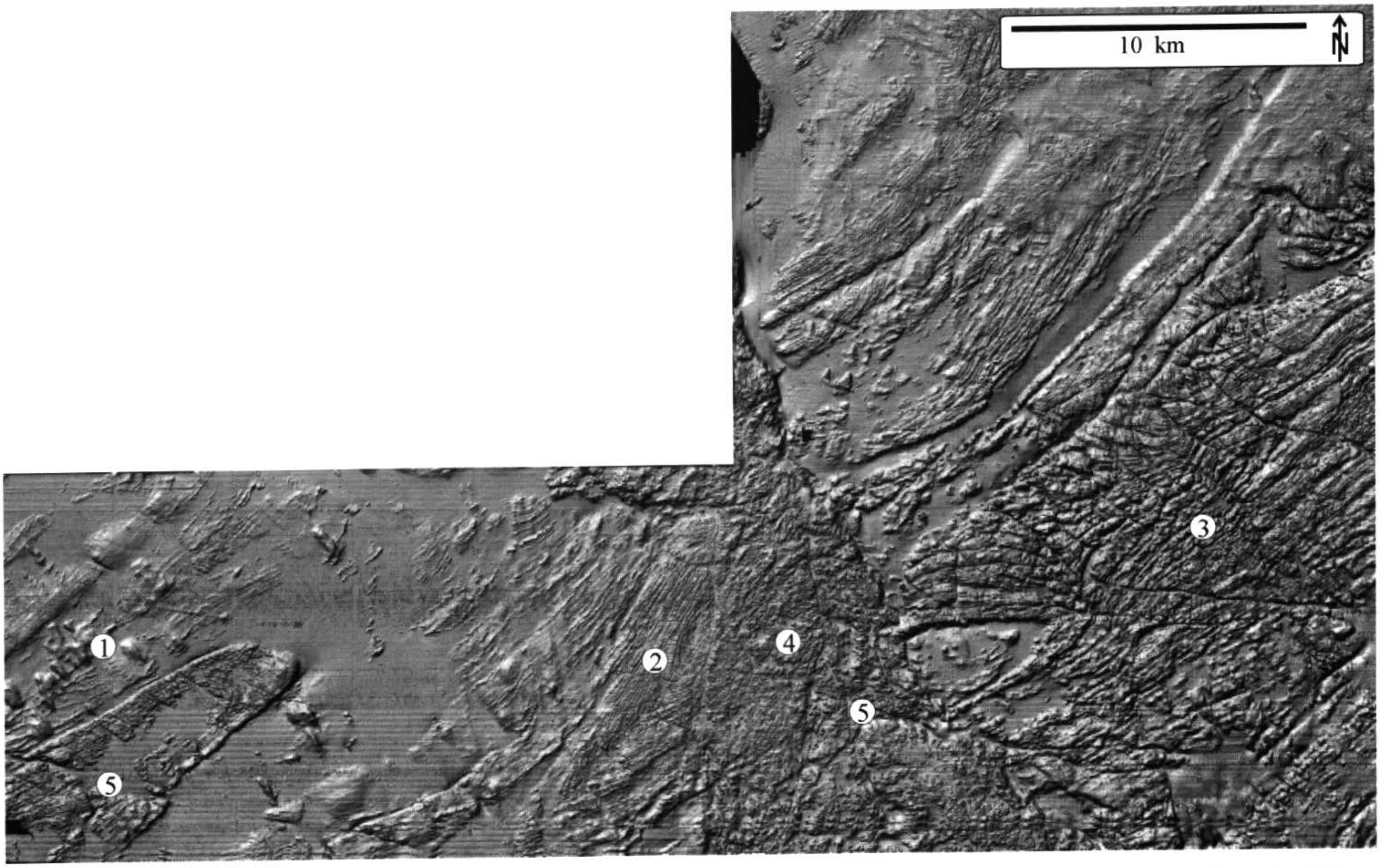

Figure 3 Shaded relief image of the seafloor found off the approaches to Halifax Harbour. Quaternary drumlin fields (1) overlie rocks of the Cambro-Ordovician Meguma Group in the western area of the image. Tightly folded and closely spaced parallel ridges (2) are commonly associated with the slates of the Halifax Formation, while the Goldenville Formation (3), comprising primarily meta-sandstones, has more widely-spaced and discontinuous ridges. Outcrop of intrusive Devonian granites (4) appears in the middle of the image. Faulting (5), parallel to Carboniferous motion on the Cobequid-Cheabucto fault, crosscuts all major groups with a sinistral offset.

with resistant stratigraphy. Terrestrial magnetic observations on Long Point indicate that the lower Twin coincides with the basal contact of the Misty Point Formation, whereas the upper Twin remains offshore immediately west of Long Point. A previous interpretation suggesting a volcanic origin for this feature can now be discounted. Sampling of the structure exposed on land indicates that the magnetic anomaly arises from chromite grains, derived from the proximal Humber Arm Allochthon, which are deposited conformably within the sedimentary strata (J. Waldron, personal communication). The Odd Twins magnetic signal can be traced northward as far as Bonne Bay, Newfoundland, and it can be correlated with dipping reflectors seen in regional industry seismic data collected in the early 1990s. Since there exists no well control in the foreland basin sequence north of the Port au Port Peninsula, the identification of the Odd Twins anomaly, and the use of multibeam data to fill the gap between the onshore geology and offshore seismic data, affords one of the few means of establishing a firm chronological marker within the foreland basin package.

Sydney Basin

The Maritimes basin, formed on the margin of the North American Craton during the late Paleozoic (Gibling *et al.*, 1987), comprises a number of sub-basins including the Sydney Basin, which has been the major source of coal on the east coast of Canada (*e.g.*, Hacquebard, 1983). Most of the coal-bearing strata lie within the Pennsylvanian Morien Group, a sequence of gently dipping interbedded grey mudstones and sandstones that outcrop primarily offshore. There exist only a few exploration wells and little high-quality seismic data over these strata. Most of the detailed knowledge of the Morien Group comes from coal mine workings and analysis of cliff exposures on the shoreline. Previous work has suggested that these units are weakly deformed with no major faulting except near basin boundaries (Gibling *et al.*, 1987). The southern part of the basin near Sydney, Nova Scotia was imaged using a Kongsberg Simrad EM3000 multibeam system during 1998 (Fig. 4). This survey was conducted to investigate stratal structure and deformation overlying the Phalen coal mine, operated by the Cape Breton Development Corporation.

The bathymetric imagery shows a wealth of detail attributable to both ancient and modern processes. Drainage channels, incised during the last glaciation (Grant, 1994), crosscut the outcropping Sydney Mines Formation of the Morien Group. The bedding in the exposed strata can be traced over tens of kilometres; in some instances, the mudstones comprising the bulk of the strata are punctuated with channel fills. The quality and detail of the image has few parallels and affords one of the few continuous, regional exposures of Carboniferous structure on the Atlantic coast of Canada. Tectonic deformation of the strata is indicated by an anticline in the eastern section of the image. A closer examination of the data reveals a whole ensemble of minor compressional, thrust faults, which are present throughout the entire survey area. These faults are so subtle that they cannot be detected in high-resolution seismic data and have not even been mapped in the underlying coal workings. Although the consequence of these faults on the coal mine workings is still a matter of debate, it seems likely that they enhance fluid permeability in the Morien Group, allowing water migration through the sedimentary column, and also facilitate methane gas release from coal seams to the seabed.

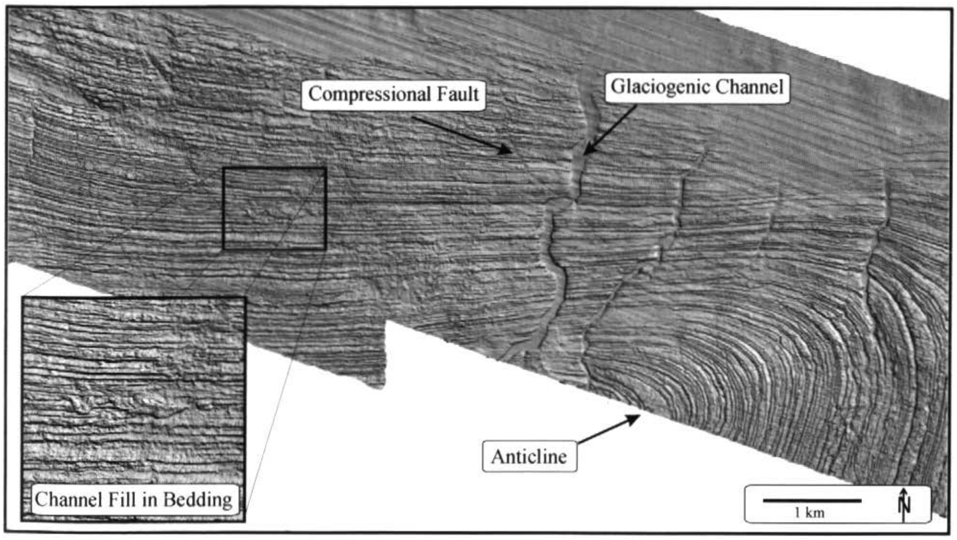

Figure 4 Shaded relief image of the outcropping Sydney Mines Formation imaged over the Phelan Colliery highlights the tightly-spaced, parallel strata of Carboniferous mudstones incised in places by coeval channel fill deposits. Subsequent tectonism induced the formation of minor faulting and anticlines within the sedimentary column. Quaternary drainage channels, formed at the most recent sea-level lowstand, crosscut the older strata.

QUATERNARY STUDIES

The continental shelf off Atlantic Canada bears the imprint of glacial ice advances and retreats during the late Quaternary Epoch. Ice-contact sediments, variously denoted as till or glacial diamict, and sometimes assigned formation names (*e.g.*, Newfoundland Shelf Drift; Fader *et al.*, 1982), commonly occur in extensive sheets of variable thickness, and more rarely in moraines, linear ridges that record periods of ice-margin stability. Multibeam mapping of moraines reveals a more complex morphology than was previously suspected. Some moraines have multiple-lobate form (*e.g.*, off Halifax), whereas others have a beaded appearance (*e.g.*, Brown's Bank, see below) (Todd *et al*, 1999); yet others are "decorated" by superimposed, narrow ridges (as in the Baie des Chaleurs [Shaw *et al*, 1998]). On some of the shallow offshore banks (*e.g.*, German Bank), series of irregularly spaced large ridges record the stepped retreat of grounded ice from the shelf; elsewhere, retreat is registered by fields of closely spaced, equidistant ribbed moraines (Fig. 5) off Liverpool, Nova Scotia (Parrott *et al*, 1999).

A previously little-known series of fjord-mouth submarine moraines has been revealed by multibeam mapping close to the coast of southwest Newfoundland, between Bonne Bay (Great Northern Peninsula) and Argentia (Placentia Bay). The EM100 image in Figure 6 shows a moraine at the mouth of Bay d' Espoir. The morphologic elements of the moraine — an arc comprising several lobes and including transverse curvilinear ridges to the rear — is suggestive of drawdown of glacier ice southward from the Newfoundland ice cap into the deep (~750 m) fiord and out to the calving margin. The trackline for seismic data collected in 1991 has been superimposed on the multibeam imagery. The seismic data show that the ridge is composed of acoustically incoherent ice-contact sediment (equivalent to the Newfoundland Shelf Drift Formation of Fader *et al.,* 1982), and furthermore that the acoustically incoherent unit passes laterally into a drape of acoustically well-stratified sediment (the equivalent of the glaciomarine Downing Silt of Fader *et al.,* 1982).

Similar moraines have been imaged by multibeam systems off nearby fjords, including Bay de Vieux, White Bear Bay, and Facheux Bay. Cores, foraminiferal analyses, and radiocarbon dating show that the moraines were probably coeval, and formed when an ice front stood at the coast between 14 ka and 13 ka. The "pristine" morphology contrasts with horizontal terraces developed on much shallower submarine moraines at Stephenville (Shaw and Courtney, 1997; Shaw *et al.,* 1997) and Argentia (Shaw *et al.,* 1996), revealing that the latter have been beveled by surf-zone erosion during the postglacial sea-level lowstand.

MODERN PROCESSES

The advent of Canadian multibeam mapping has not confirmed existing models of the marine geology of the Atlantic shelf, but rather it has overturned them by revealing seascapes with hitherto unsuspected complexity. This is particularly true with respect to bedforms developed in sand and gravel on the seafloor. These occur over a wide range of wavelengths, ranging from several centimetres to sand ridges with wavelengths of more than 6 km (Amos and King, 1984).

Bedforms resolved on both multibeam bathymetric and backscatter imagery display great complexity and variety, and contain information not available from the use of single beam sounder and seismic systems (Fader *et al,* 1977). An ensemble of bifucating bedforms have been observed in 50 m of water off Cheticamp using an EM1000 multibeam system (Fig. 7). These bedforms show no obvious, preferred direction of migration and they likely arise from a strong, oscillatory tidal flow along the western coast of Cape Breton coupled with peak storm-driven currents. These bedforms are probably quasi-stationary, although a repeat survey over this area would be needed to corroborate this hypothesis. Another instructive example is the sand-wave field on the current-swept seafloor off Cape Split in the Bay of Fundy (Miller and Fader, 1990). EM1000 imagery shows this as consisting of sets of bedforms of varying height and wavelength. The orientation of the bedforms and seabed sampling show the existence of a current gyre that maintains the sand wave field as a submarine island of well-sorted sand surrounded by gravel pavements. Potentially, this information could assist the exploitation of the sand for aggregate purposes and enhancement of the fishery through creation of productive gravel habitat (Fader and Miller, 1994). Yet another bedform style is revealed in EM1000 imagery of the dune field off Margaretsville, Nova Scotia where the seascape comprises a widely dispersed suite of large sand waves. Many of these have become self-immobilized (G.B. Fader, personal communication, 1999) through current scour of the flat surrounding gravel pavement. These large sand waves could potentially be sources of aggregate, easily exploited with accurate positioning of dredging vessels.

EM1000 imagery of Browns Bank (Todd *et al.,* 1999), a shallow (~50 m) bank off southwest Nova Scotia, reveals a population of widely dispersed sand waves, comparable to desert barchan dunes (Fig. 8). Unlike the stranded sand waves in the previous example, these features are probably mobile. The orientation of the barchans (horns pointing in the direction of migration) shows that on the western half of the bank they are moving toward the northwest, whereas on the eastern sector of the image they are moving toward the southeast. The backscatter mosaic (Fig. 9) shows the sand-dominated terrain as light, low-

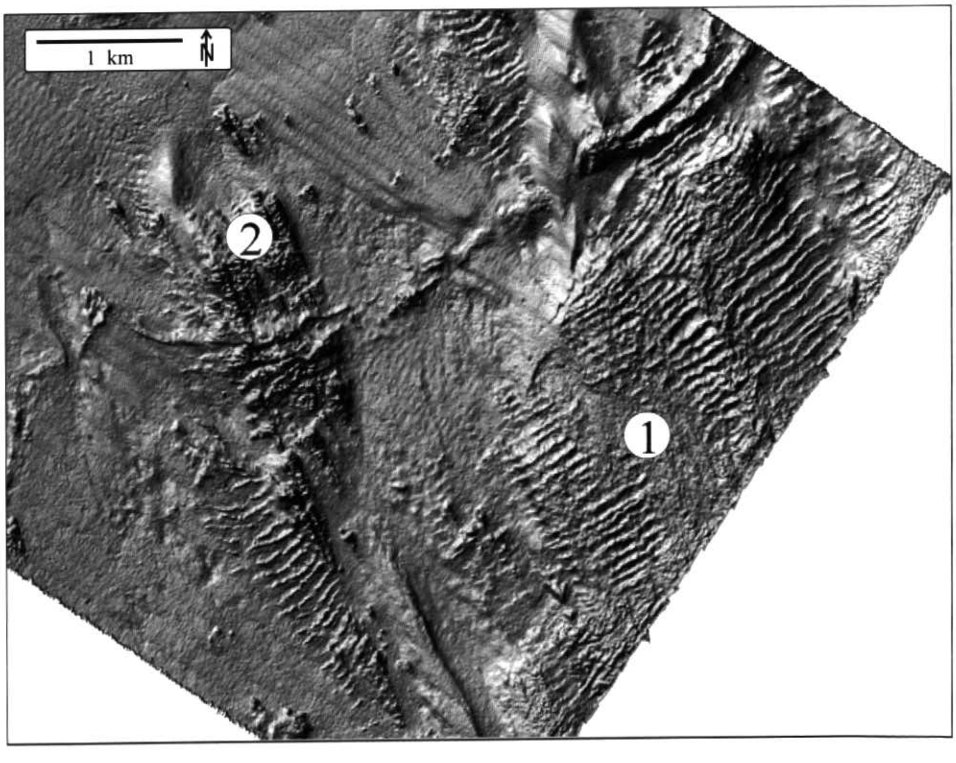

Figure 5 Shaded relief image of closely-spaced, ribbed moraines (1) found near Liverpool, Nova Scotia, with outcropping bedrock (2) draped with flutes of glacial till.

backscatter regions, whereas the coarser-gravel lag deposits show a higher backscatter response. These images reveal a sediment transport gyre that moves sand around the bank in the direction of the mean currents predicted by oceanographic modelling. Multibeam mapping of the bank has proven to be of great use to the fishing industry. It reduces the loss of gear that was common in the past, when gear was inadvertently dragged across bouldery ice-contact sediments. Other areas, previously underused to avoid seabed hazards, can now be exploited. More importantly, however, these new maps will, in future, facilitate a systematic management of the scallop resource on Browns Bank (Todd *et al.*, 1999).

HUMAN IMPACTS

Although multibeam data can be used to define both regional variations and local details of natural geologic processes, the impact of human activity is also recorded on the seabed. There is a range of anthropogenic features recognized in the estuaries and harbours of Atlantic Canada. Imprints of sunken vessels, dredge marks, and anchor drags have been imaged in Halifax Harbour (Courtney and Fader, 1994) and Argentia Bay, Newfoundland (Shaw *et al.*, 1996). Footprints of dry-docks and oil rigs have left a lasting impression in soft Holocene sediments in many of these harbours. In addition to imaging the past effects of human activity on the seabed, these multibeam systems can also be used to monitor the change in the seabed over time. These systems are now being used to monitor seabed dumping and the migration of sand waves. One of the most illustrative examples of human impact on the seabed can be drawn from work completed off Cape Breton Island, Nova Scotia.

Human Impacts off Cape Breton

A series of repeat multibeam surveys over the Prince coal mine, located some 5 km offshore of Point Aconi has been conducted to monitor the change in the depth to the seabed over the active workings (Forrester and Courtney, 1997). The coal has been extracted from the underlying sedimentary section using the longwall mining method, wherein long, rectangular panels of coal are removed from a coal seam. In the Prince Colliery, these panels can approach nearly 200 m in width and 3 km in length. When the coal is removed and the mining machinery moves along within the seam, support from the mined section is removed and the roof is allowed to collapse. The intervening rock between the panel and the seabed acts like a structural beam that supports, to some extent, the void created in the seam. The resultant stresses induce a deformation and a downward bending of the seabed. Quantification of this deformation, in turn, can be used to determine the effective strength of the intervening roof rock, a parameter critical in planning the mine layout and dimensions.

In Figure 10, we show a shaded-relief image of the seabed over the Prince Colliery collected during the initial survey of 1994. There are smooth areas on the image which probably indicate unconsolidated sediment ranging from a drape of Holocene muds in deeper water to fluvial sands and muds deposited in glacially cut channels. The outcrop of the Sydney Mines Formation of the Morien Group manifests as a series of tilted bedding planes. The most striking features, however, are a series of parallel, linear, northwest-trending elongate troughs imprinted on the seascape. These troughs are subtle features with a cross sectional depth anomaly of only a metre, but they are still clearly imaged. An overlay of the mine plan (Forrester and Courtney, 1997) shows that these troughs lie directly over the panels that had been completed in the mine over the seven years previous to 1994. In 1995 and 1997, the same area was resurveyed to study the change in the seabed over time

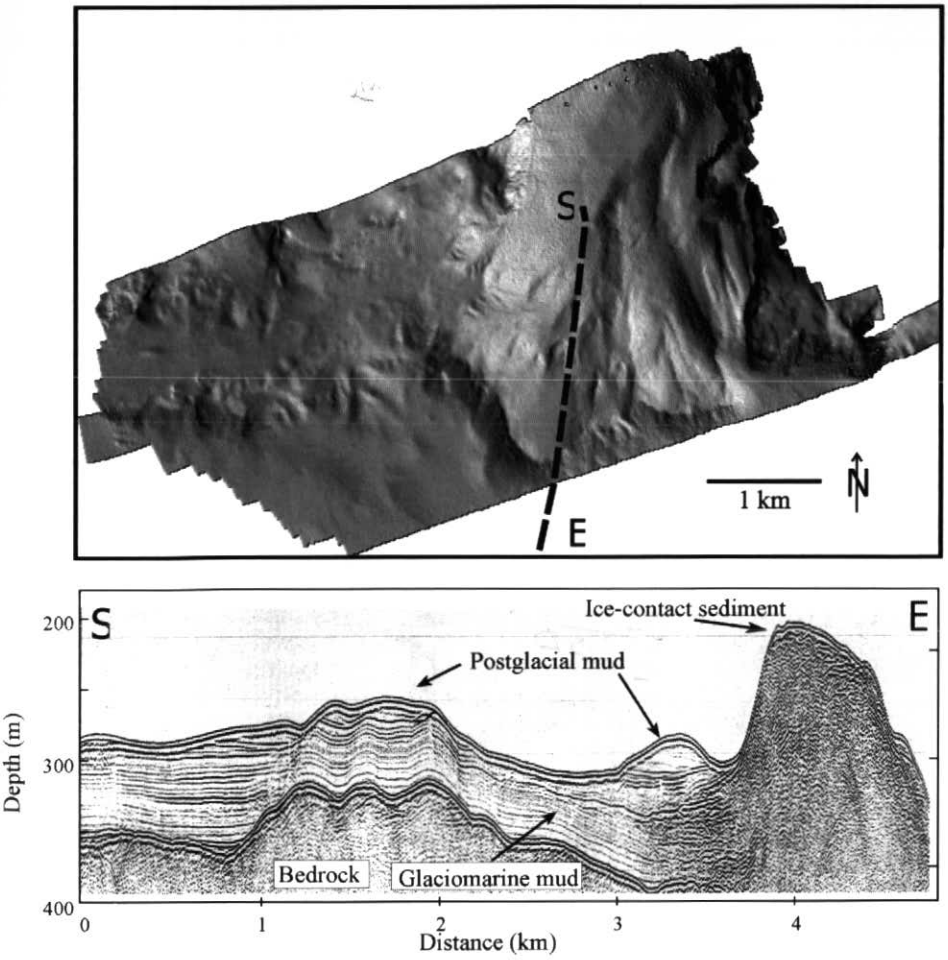

Figure 6 Shaded relief image of a submarine moraine off Bay d'Espoir in the upper panel. The broken line on the shaded relief image marks the position of sleeve gun seismic data shown in the lower panel.

as mining continued and more panels where excavated. Since the survey data from each year are geo-referenced and stored conveniently in a gridded format within a GIS, the change in depth to the seabed over the new and old workings from year to year can be easily computed. In Figure 11, the difference in seabed depths between 1995 and 1994 is shown in a shaded relief representation. The difference reveals the subsidence over the 13 West panel that had been removed during the period between the two surveys. In addition to providing important structural data on the roof rock within the mine, these data have also demonstrated that the roof collapse over the panel is immediate, indicating an elastic/plastic deformation. Suggestions that there may have been a significant creep component in the deformation are not supported.

THE FUTURE

Multibeam systems continue to evolve and narrower beam, deep-water systems are now available (*e.g.,* the 30-kHz Kongsberg Simrad EM300). During the last decade, most of the GSC's effort has so far been focussed on the continental shelf, but now a burgeoning oil industry on the Atlantic continental slope seems likely. These new systems will be used to help identify the geo-hazards that may present obstacles to development in frontier areas.

Much of the effort in processing repeat surveys arises from the need to remove systematic errors in the data. A vertical datum on a moving vessel is very difficult to establish, but advances in kinematic GPS methods seem poised to solve this problem. Variations in water column sound velocity likewise induce errors in depth estimates. A moving vessel sound velocity profiler (MVSP), which will give a continually renewed estimate of the sound velocity profile, has been developed by Brooke Ocean Technology of Dartmouth, Nova Scotia.

Although multibeam technology has clearly changed the face of marine geological surveying, it is no panacea, and older, more conventional technologies remain important research tools. Multibeam images give an exceptional mesoscale view of the seabed with wavelengths greater than a couple of metres. Sidescan sonars still give superior short-wavelength information that can be used to better identify objects on the seabed and to delineate geological features such as submetre-scale sand ripples. In progressively deeper water, hull-mounted multibeam systems return increasingly blurred images of the seabed because the footprint increases with distance from the source to receiver. Sidescan sonar systems can be lowered to within tens of metres of the seabed, and thus maintain image fidelity. Problems remain in the positioning of the sidescan, the effective georeferencing, and calibration of the sidescan sonar data. Seismic systems will always be needed to extend geological models to the third dimension. Current projects at the GSCA include work on optimizing the positioning and dynamics of towed instrument platforms that will carry high frequency multibeam, sidescan and seismic systems.

Multibeam data represent the marine equivalent of aerial photographs used widely in terrestrial geologic studies. Other countries, including the United States, Australia and New Zealand, have already recognized the value of these data and have planned systematic mapping programs. Even the Republic of Ireland, a small nation, has just announced a $40 million program to map the seabed in their territorial waters. In contrast, while our country has been completely photographed from the air, the Canadian continental shelves are still largely uncharted using modern methods. Much of the coast off Newfoundland and Labrador has not even been surveyed since the 1800s. The total area of the Canadian shelf surveyed with multibeam methods still amounts to little more than an illustrative vignette. This is a regrettable commentary on the national apathy toward the 35% of the Canadian landmass found on our continental shelf. Decades of effort and support are required to complete the task. An aggressive, forward-looking, cross-institutional, national vision is needed to focus and serve our country's long-term needs in this area.

Many of the new phenomena revealed in these images lie at the boundaries between scientific disciplines. Although we have now recognized a myriad of bedforms, co-operative work with physical oceanographers and researchers in non-linear dynamics is required to understand why these bedforms exist,

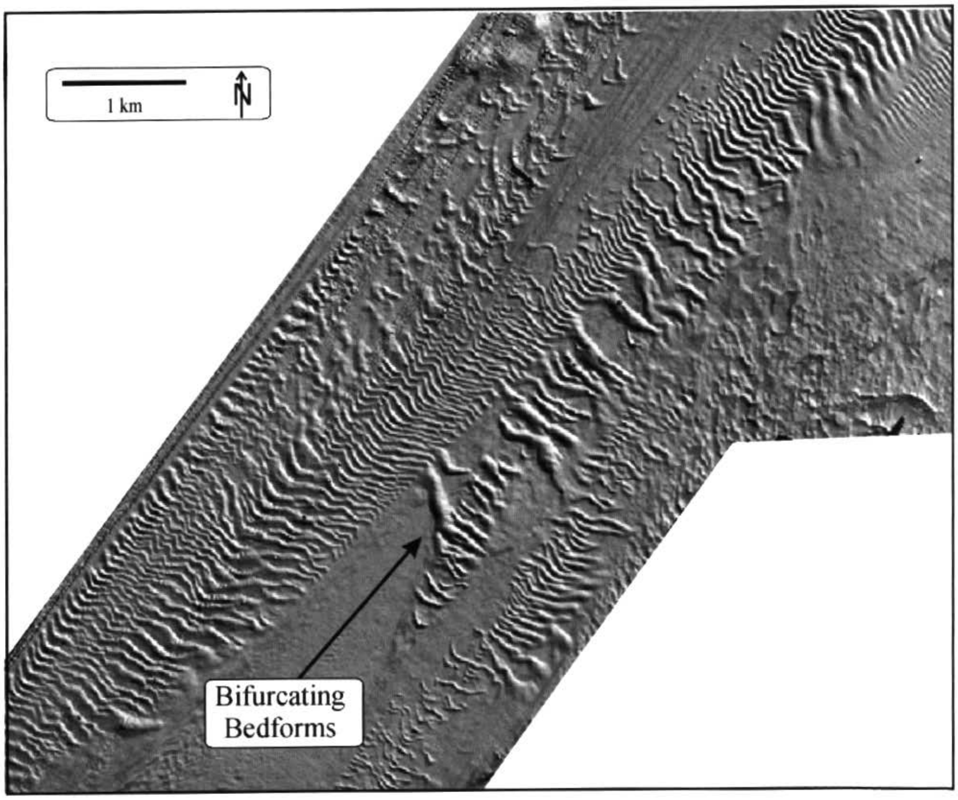

Figure 7 Shaded relief image of bifurcating bedforms observed offshore near Cheticamp, Nova Scotia.

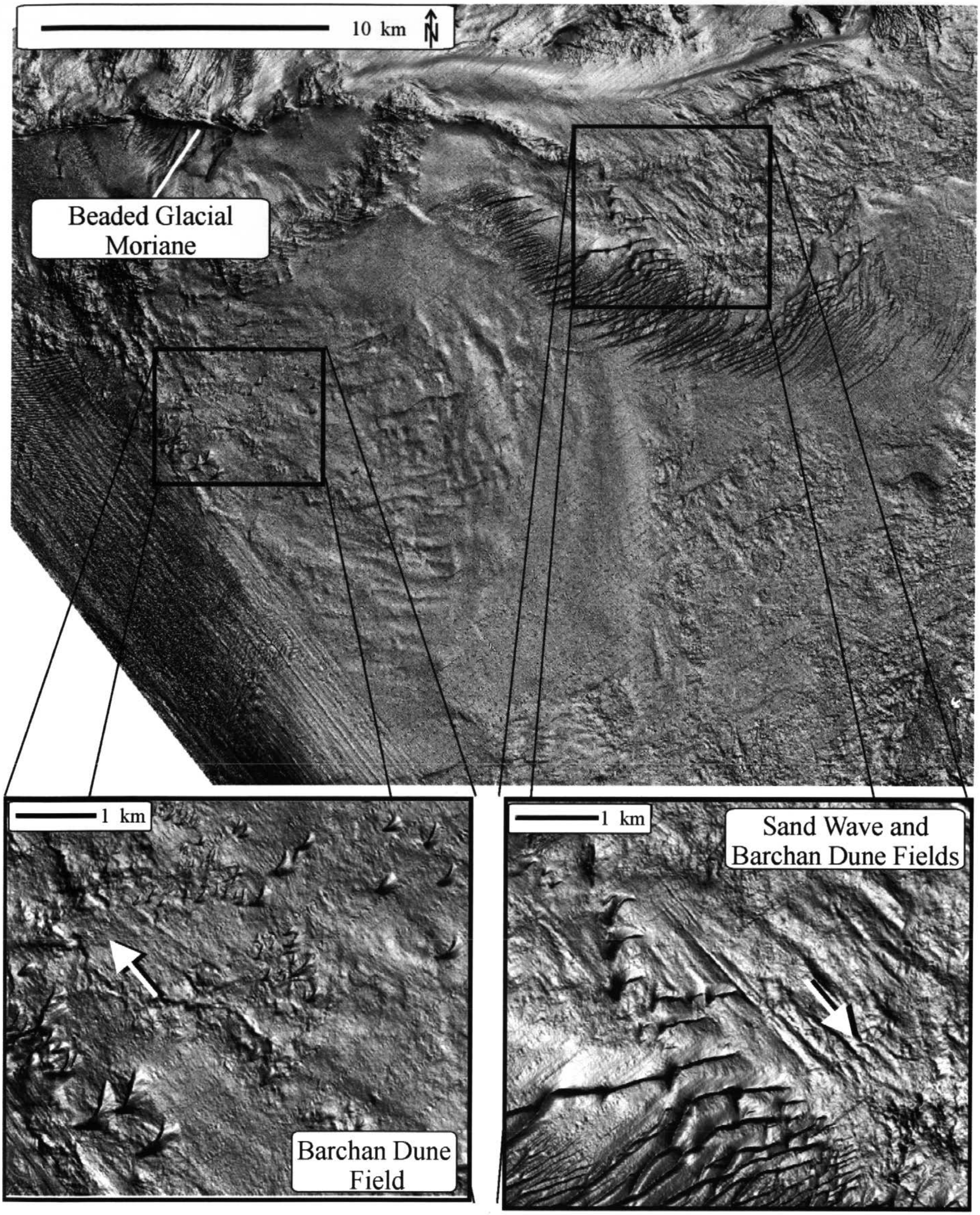

Figure 8 A shaded relief image of a northern section of Browns Bank. The left inset shows barchan dunes migrating to the northwest, in the direction of the arrow. The right inset shows barchan dunes propagating to the southeast, in the direction of the arrow.

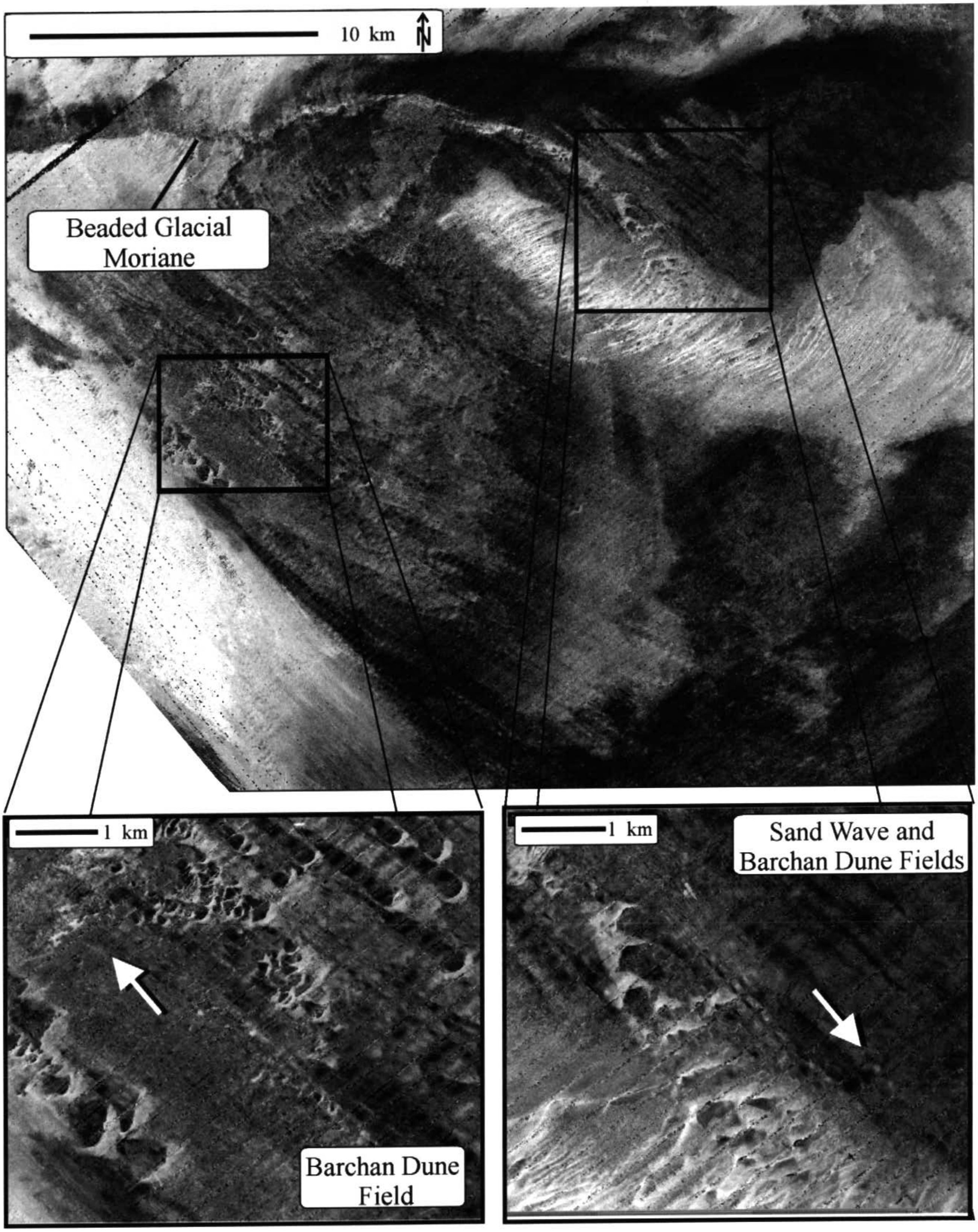

Figure 9 Backscatter mosaic on a section of Browns Bank is plotted with low-amplitude backscatter shown as lighter tones. The barchan dunes and sand wave field show up as zones of low backscatter. Less obvious on the shaded relief image (Fig. 8), the backscatter mosaic suggests a more subtle drape of low backscatter material, likely caused by thin layers of sand overlying a gravel lag, distributed in wispy and patchy patterns aligned in a general clockwise gyre pattern. The seabed found between the horns of the barchan dunes shows a relatively higher backscatter signature, attributable to turbulent scouring of the seabed as currents flow over the bedform, exposing a gravel lag.

how they evolve, and what they tell us about the conditions in the overlying water mass and the proximal landmass.

Our new maps of the seabed are undoubtedly important to benthic biologists and ecologists. Can we step away from the hunter-gatherer model of fishing and use these new mapping systems to provide quantitative information for the systematic management of marine benthic resources? In this light, we cannot continue the style of marine geoscience as practiced in the past. Each of these issues (among many others) necessitates a broader interconnection of science, and the mandates of government agencies, universities and industry have to evolve to embrace these new challenges.

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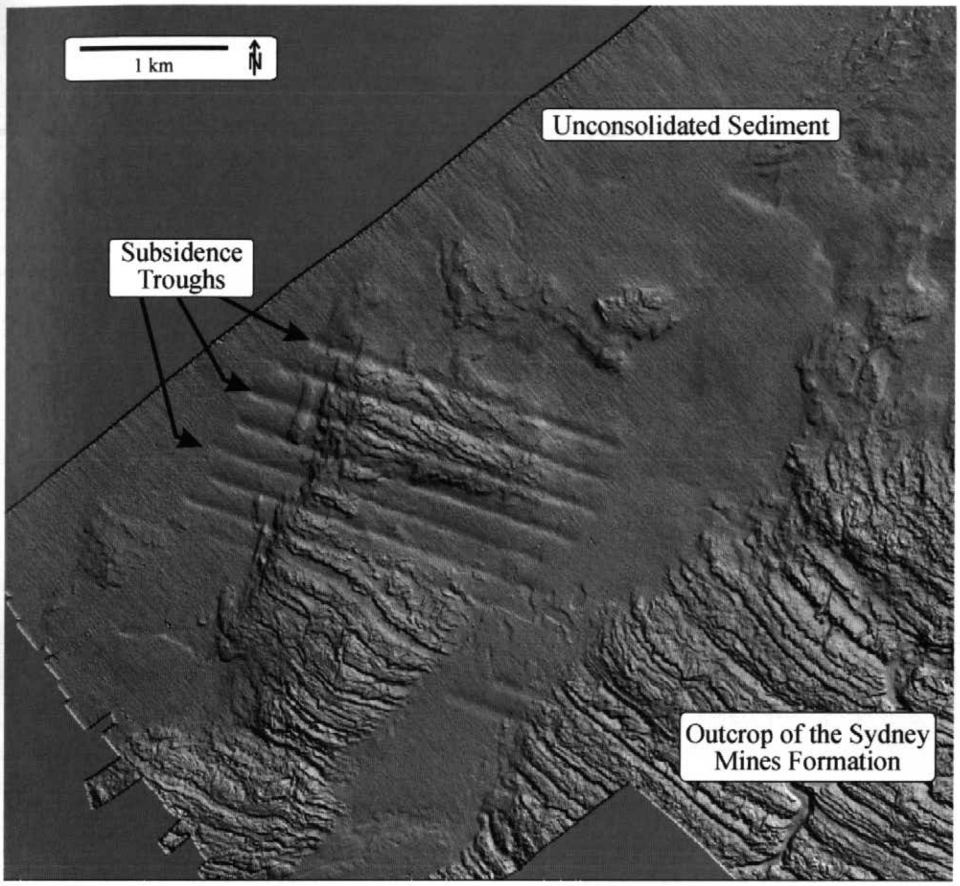

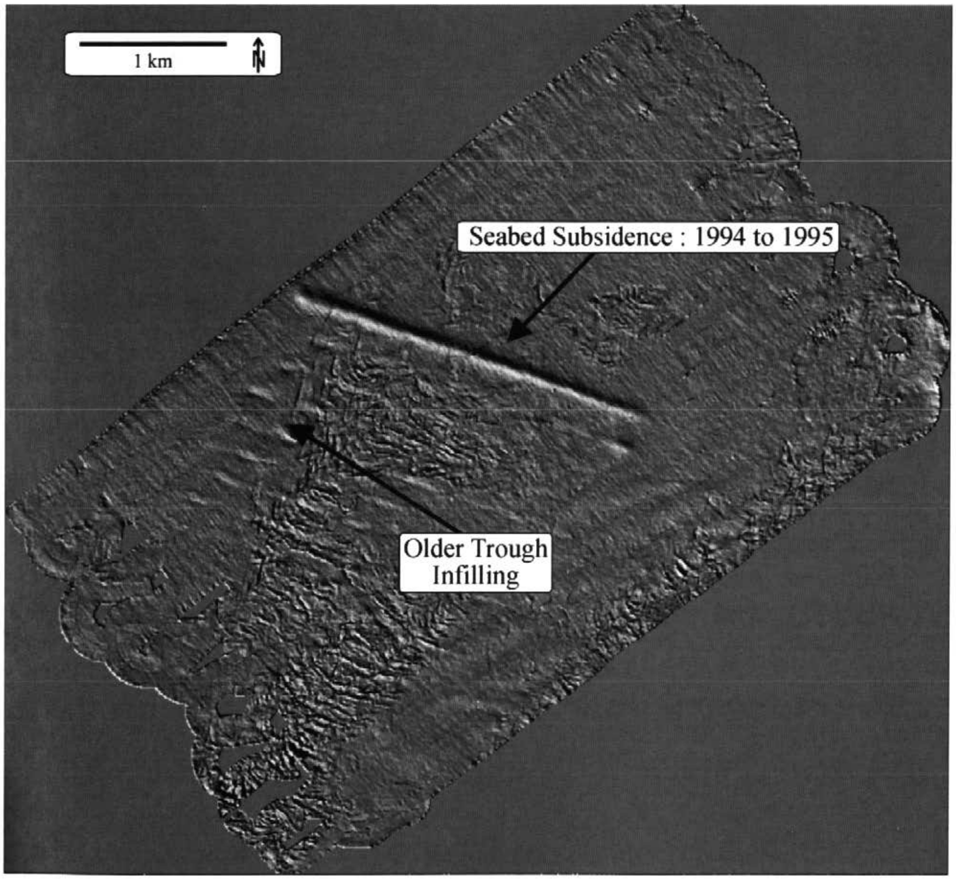

Figure 10 (**top**) Shaded relief image showing outcrop of the Sydney Mines Formation and subsidence troughs over the Prince Colliery observed during the 1994 survey.

Figure 11 (**bottom**) Shaded-relief image of the difference in bathymetry between the 1995 and 1994 surveys. The main feature is a large subsidence trough formed over the 13 West panel, which had been worked during the interval between the two surveys. There is some evidence for minor infilling of older subsidence troughs, likely from sediment resuspended during storms.

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