Bedford Institute of Oceanography

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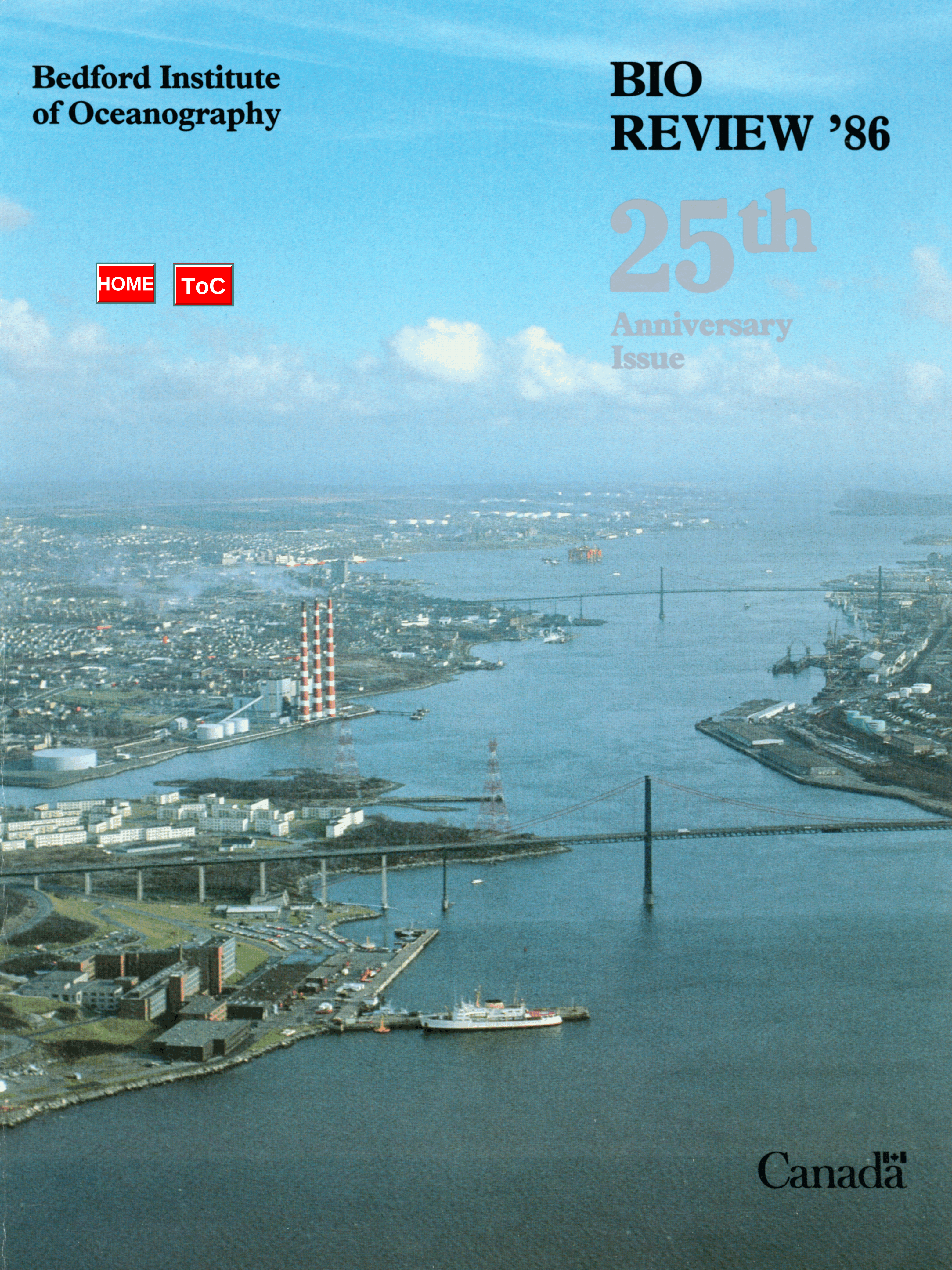
BIO REVIEW '86

25th Anniversary Issue



Canada

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The Bedford Institute of Oceanography (BIO) is the principal oceanographic institution in Canada; it is operated within the framework of several federal government departments; its staff, therefore, are public servants.

BIO facilities (buildings, ships, computers, library, workshops, etc.) u-e operated by the Department of Fisheries and Oceans. The principal laboratories and departments located at BIO are:

Department of Fisheries and Oceans (DFO)
- Canadian Hydrographic Service (Atlantic)
- Physical and Chemical Sciences Branch
- Biological Sciences Branch

Department of Energy, Mines and Resources (DEMR)
- Atlantic Geoscience Centre

Department of the Environment (DOE)
- Seabird Research Unit

DFO operates a fleet of research vessels, together with several smaller craft out of BIO. The two larger scientific ships, *Hudson* and *Baffin*, have global capability, extremely long endurance, and are Lloyds Ice Class I vessels able to work throughout the Canadian Arctic. BIO has four objectives:

(1) To perform applied research leading to the provision of advice on the management of our marine environment including its fisheries and offshore hydrocarbon resources.

(2) To perform fundamental long-term research in accordance wit the mandates of the resident departments.

(3) To perform necessary surveys and cartographic work to ensue a supply of suitable navigational charts for the region from George's Bank to the Northwest Passage in the Canadian Arctic

(4) To respond with all relevant expertise and assistance to any major marine emergency within the same region.

J .A. Elliott - *Director, Physical and Chemical Sciences Branch, DFO*
E.H. J. Hisock - *Seabird Research Unit, Canadian Wildlife Service, DOE*
M.J. Keen - *Director, Atlantic Geoscience Centre, DEMR*
A. J. Kerr - *Director, Atlantic Region, Canadian Hydrographic Services, DFO*
J.E. Stewart - *Director, Biological Sciences Branch, DFO*

Front cover:
An aerial view of Halifax Harbour showing BIO with CSS Baffin *in the foreground, and the cities of Dartmouth and Halifax beyond.*

Roger Belanger

Inside front cover:
BIO as it looked in 1962.

Unknown

Back cover:
An aerial view of the jetty and the research vessel fleet at BIO.

Roger Belanger

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On helping to make a revolution

THE BEDFORD INSTITUTE OF OCEANOGRAPHY was established in 1962 by the Government of Canada to respond to what was perceived as a high probability that many sectors of the Canadian economy would, in the years to come, require research and services from all disciplines of marine science. Coincidentally, the early sixties was a time when a renaissance of marine science was occurring everywhere, principally because of the new tools becoming available from the introduction of solid state electronics. Electronic sensors and computers enabled information to be obtained from the ocean, processed, and interpreted with a precision and rapidity that was undreamed of in the earlier, exploratory days of marine science.

BIO was endowed from the start with splendid seagoing ships whose operational capability has seldom been matched even today, and the newly recruited scientific teams were quickly able to go to sea wherever and whenever their research required. An ability to work in the high arctic under moderately severe ice conditions, and to continue precision scientific work in the North Atlantic under winter conditions that would be impossible for most ocean-going scientific vessels, has characterized BIO research through the years. Much is owed to the foresight of those who commissioned ***Hudson*** and ***Baffin,*** and the crews who have operated them: even as these lines are being written, ***Hudson*** is returning the crew of a large bulk-carrier to St. John's, having rescued them from their foundering ship off the Grand Banks in appalling conditions of 10 m seas and hurricane-force winds.

BIO has also been different, as we hope to show in this 25th anniversary review, from most other marine science institutes in a rather special way. The range of disciplines included in a single corporate institution has been extraordinarily wide, right from the start, and this has given us unusual opportunities for cross-fertilization and collaboration. As the reviews that follow will show, the physical, chemical, and biological oceanography research groups have worked alongside teams of marine geologists, metrologists, fishery biologists, ornithologists, and

Bedford Institute of Oceanography in 1962 ...

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hydrographers and cartographers. Many research projects, and more voyages than not, have involved collaboration between several of these groups irrespective of their funding and affiliation. Most voyages have also accomodated research projects of Canadian and foreign university scientists.

There is no doubt that the 25 years since the establishment of BIO has been a period of extremely rapid development of new understanding in all the marine sciences and the application of the new findings to the needs of society. If BIO had not been an active participant in all of this, and a leader in some of it, this introduction would have been headed "On living through a revolution". So much has changed in marine science, and so rapidly and fundamentally, that it is not easy to remember the concepts and models that were current only 25 years ago in 1962. In these reviews of the first quarter-century of BIO, we have tried to illustrate some of the conceptual revolutions that have occurred during that period, and how we think we have contributed to them.

There is no question that the most revolutionary changes have occurred in the earth sciences, at least comparable to the Darwinian revolution in biology, and at least as important economically; it is hard to visualize today that when BIO was founded the concepts of sea-floor spreading and continental drift were just beginning to be talked about on the basis of the first hard data to support them, and that in the intervening 25 years the whole science of global plate tectonics has become established as the cornerstone, not only of marine but of all geological sciences. As we shall discuss, the BIO shoulder was applied to this wheel as to others perhaps no less revolutionary in ocean circulation, biological production, management of commercial sea fisheries, and techniques of charting the sea for navigation. In all these, and other fields, the contributions of BIO to the global activity have been novel and significant: like all major oceanographic research institutes during this period, we have done our share of leading, and our share of filling-in behind.

We might have chosen to celebrate, in this report, not

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BIO's role in the scientific revolution of the last 25 years, but how we have, in Atlantic Canada, carried the mandate of several federal departments in the application of scientific solutions to the economic revolution that has occurred in the same period at sea, for the benefit or survival of several sectors of the Canadian economy. Though not foreseen in detail by the federal government departments that established BIO, there have been deep economic changes in the fishing, shipping, and offshore energy industries that have confirmed the wisdom of the decision of the early sixties to establish a Canadian oceanographic program.

In the years since then, there has been an ever-increasing demand for new surveys, new information, and new services that could have been satisfied in no other way. In the last quarter-century, the fishing industry and fishery managers have weathered the crisis in fuel prices, the establishment of a 200-mile fishing zone, the economic restructuring of the industry, and rapidly changing international markets. The energy industry has undertaken major offshore exploration in Atlantic and Arctic Canada, and found engineering solutions to deep water and unstable sediments, bergs and pack-ice, and extreme wind and sea conditions, all in waters more exposed than any other offshore exploration area. The highest tidal regime in the world required extensive evaluation of the consequences of its utilization as a regional energy source. The shipping industry continually uses fewer, larger, deeper-draft, and faster ships on new routes and to new ports and demands a more rapid evolution of navigation charts and aids than ever previously. This period has also brought unexpected new knowledge of how dramatically year-to-year weather patterns can be disrupted by changes in ocean circulation, and of the importance of the ocean in mediating longer-time-scale climate changes: the agriculture, transport and energy sectors of the Canadian economy are now known to have been seriously impacted by such processes.

To all these, and other practical matters, unforeseen in detail 25 years ago, scientific solutions, services, or data have been required from the scientific community at BIO by several federal and provincial departments and by many Canadian industrial enterprises. If BIO had not existed during this period of great change in the Canadian economic sectors that 'have their business in great waters', it would have had to be invented rather rapidly. . .

- ***A.R. Longhurst***
Director General
Bedford Institute of Oceanography
Department of Fisheries and Oceans
- 1 April 1986

- ***B.S. Muir***
Regional Director Science
Scotia-Fundy Region
Department of Fisheries and Oceans
1 April 1986 - 19 May 1987

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Department of Fisheries and Oceans
19 May 1987 -

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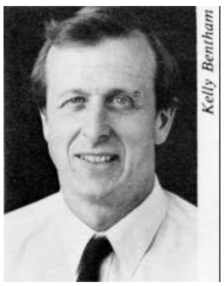
Biological sensors: The search for spatial pattern

Alex Herman and Alan Longhurst



Alex Herman.

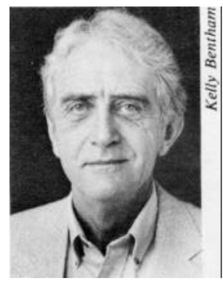
THE earliest investigators quickly discovered that plankton is not uniformly distributed even in what appears to be a uniform water mass and rapidly encountered the statistical problem of obtaining plankton data that could confidently represent a whole region. By the turn of the century they had already developed simple opening-closing nets to try to measure plankton patchiness. From about 1920 to 1950, observations were made of the size and coherence of patches of diatoms in the North Sea and of zooplankton in the Southern Ocean, and the basic patterns of daily and seasonal vertical migration had been worked out, though profiles were based on very poor depth resolution. The most noteworthy special equipment of this era was Alister Hardy's Continuous Plankton Recorder designed to be towed behind merchant ships over long sea routes, describing plankton patchiness as it changed seasonally with the resolution of about ten miles.

The fifties saw a number of major advances and by 1962, when BIO began its work, others had already begun to study the statistical significance of plankton patchiness and had demonstrated its occurrence down to the metre scale with the use of near-surface pump techniques; this was also the period when the significance of 'deep scattering layers' on shipboard echo-sounding records was investigated, with the result that the existence of dense subsurface layers of plankton right across major ocean basins was first recognized to dominate plankton spatial pattern.

The establishment of BIO in 1962 coincided fortuitously with the development of an ability by marine scientists to deploy electronic sensing and control equipment in their subsurface instrumentation in a major way. 'From the start, it was BIO policy that engineers and applied physicists should be an important and integral part of scientific groups. This policy, and the solid-state electronic revolution in marine science rapidly led, both at BIO and elsewhere, to the development of new ways of measuring spatial pattern in open waters. Rapid progress was made in understanding the significance of the patterns and such studies dominated much of marine ecology for the next several decades.

Phytoplankton abundance can, with certain constraints, be very conveniently measured as chlorophyll and one of the earliest applications of opto-electronics was to apply fluorometry to enable measurement of chlorophyll to be made in near-surface water from a ship underway, together with temperature and salinity. This was first achieved by Lorenzen (1966) at Scripps by the mid-sixties and rapidly became a standard technique in many oceanographic laboratories including BIO. In retrospect, this was the first fruit of the electronic revolution for biological oceanography.

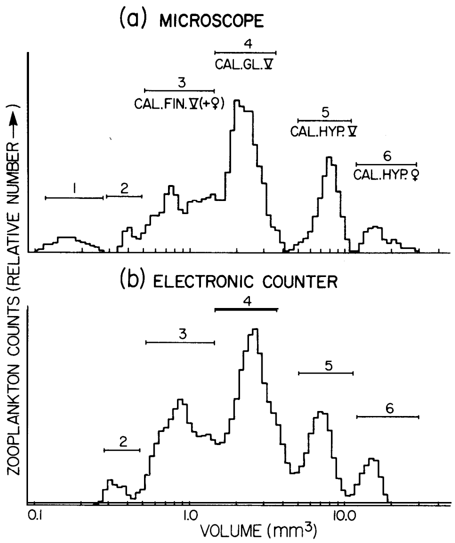
It also now became possible to attempt to sample zooplankton and micronekton with a much finer spatial discrimination than was possible with simple opening-closing nets. The new ability to deploy subsurface electronic



Alan Longhurst.

packages to control mechanical sampling gear and simultaneously record data on the ambient environment led during the sixties to the development of a range of multiple-serial plankton samplers able to produce vertical profiles of much greater resolution than did earlier mechanical opening-closing nets controlled by simple weights ('messengers') slid down the towing wire at what was judged the right moment.

The first of these new samplers, the LHPR, was developed by Longhurst (1966) at Scripps and was able to resolve zooplantkon profiles to about 5-m depth intervals and to obtain limited salinity and temperature data. Later, significant advances were made in the development of multiple opening-closing nets able to obtain larger samples than the LHPR while providing an effective resolution of about 20 m on vertical profiles. Foxton of Wormley developed acoustic telemetry to control a series of NIO net systems, while Wiebe (1976) of Woods Hole and Sameoto (1980) of BIO opted for electronic control using conducting cables for their multiple net systems, known as MOCNESS and BIONESS respectively. Recently, engineers at BIO have succeeded in developing a microprocessor-based subsurface control unit for BIONESS to complete an integrated system now sold widely by a Nova Scotia company and which is compatible



1. A comparison of copepod size distributions measured by the electronic counter (bottom) and those measured under a microscope (top). The same sample was used in both cases and originated from Baffin Bay.

with the current generation of LHPR, also developed by BIO engineers.

In parallel with this development of more sophisticated nets, and in an attempt to obtain an even finer vertical resolution, Strickland at Scripps tried to develop pumping systems in the early sixties capable of reaching down through the seasonal thermocline; there are many mechanical difficulties in this technique and one of the most successful solutions has been developed by Herman *et al.* (1981) of BIO. The BIO system is now operated routinely at sea and is supported by an 'intelligent' microprocessor-controlled winch, which adjusts to the heave of the ship so as to maintain the pumping orifice at constant depth. Biological sensing and sampling can be performed with this system with a vertical discrimination of one metre to about 100 m depth.

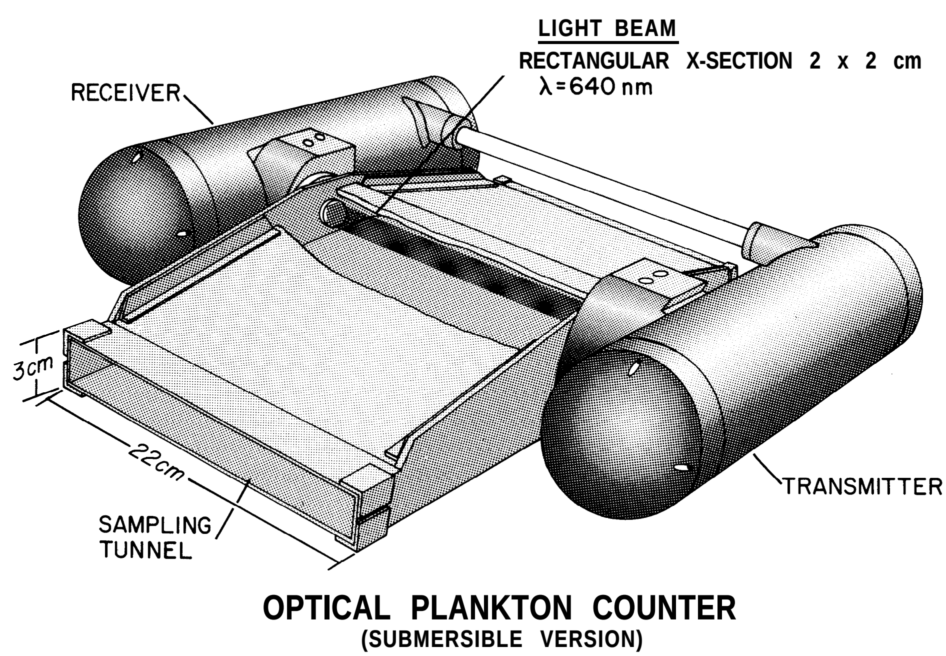
The highest resolution capabilities for zooplankton profiles were to come from electronic zooplankton counters that adapted Coulter's conductivity cell into a subsurface towed unit. Early attempts by Maddux and Kanwisher of Woods Hole were not very successful and this technique produced little more than engineering data for more than the next decade, though Boyd and Johnson (1961) of Dalhousie were able to obtain data on both vertical and horizontal distributions with a further development of the conductivity cell. As we shall discuss, this particular technique was finally exploited successfully here at BIO, so that it became possible to transfer production of a new generation of electronic plankton counters to a commercial company.

One of the keys to BIO's successful participation in this global development of a new discipline was our engineering of effective electronic sensors that finally gave us the ability to produce profiles of zooplankton with as fine a vertical discrimination as the phytoplankton profiles obtained with fluorometry, and hence to study plant-herbivore interactions in great detail. In the mid-seventies, a joint program between DFO at BIO and the National Research Council of Canada was undertaken to develop an electronic zooplankton counter that biologists could easily use at sea.

Conductivity cells used in salinity measurements and for zooplankton counters up to this time were subject to large electric current drift caused by polarisation in the cells. These instruments used high frequency AC circuitry, but the BIO/NRCC counter was to use DC circuitry based on the 'square-wave' conductance system used in the Canadian CTD already developed at NRCC and manufactured by Guildline Instruments of Ontario. This meant that we could use state-of-the-art digital electronics, and low power integrated circuits, resulting in a sensor that was electronically stable, noise-free, and used little power.

The electronic counter (Herman and Dauphinee, 1980) can be mounted on a BIO BATFISH vehicle, and towed in a vertical sawtooth pattern, to produce a series of quasi-vertical profiles separated by l-2 km. A CTD mounted on the BATFISH can provide environmental data, while an in *situ* fluorometer provides chlorophyll profiles. Over a 4-year period from 1977, this configuration of the 'biological BATFISH' was used by BIO to study plankton ecology in the North Atlantic and over the Scotian Shelf, in the eastern Canadian Arctic, the eastern tropical Pacific, and on the coast of Peru on behalf of CIDA.

We found that the electronic counter was capable of identifying the dominant species in a sample solely on the basis of size discrimination. An example of a



2. The operational design of the submersible version of the optical plankton counter.

size frequency distribution representing a BATFISH profile from Baffin Bay (Herman, 1983) is shown in Fig. 1 where the dominant peaks correspond to copepod species and growth stages, checked with microscope measurements on the same samples. The latter procedure is laborious and expensive; however, once the comparison has been made for an area and season, the plankton counter can be used routinely to count and identify species, and thus generate cheap, accurate data unobtainable any other way.

However, there was one serious problem: the counter was not easily used at sea by biological technicians. The sampling and pre-filter net needed continual cleaning, so towing periods were short, of less than 3 hours. Moreover, the counter could not measure animals longer than 3 mm, such as euphausiids and fish larvae, because of its necessarily small cell diameter. About the time that this was realized, new advances in optical technology were being made, and low power/high intensity light-emitting diodes and rectilinear photodiodes became available.

A project was then undertaken at BIO to develop an optical plankton counter that could avoid, finally, the operational difficulties inherent in conductivity cell counters. The new counter relies on the formation a parallel light beam of square cross-section, oriented normal to the tow direction. A zooplankter crossing the beam interrupts it, and the magnitude of the 'shadow' corresponds to the size of the animal. Using an opto-electronic principle now patented by BIO, the same light beam is also used to measure the light attenuance of the water and so provide a simultaneous measurement of phytoplankton biomass. The same light beam is thus used to measure zooplankton simultaneously with their food source, on spatial scales of centimetres.

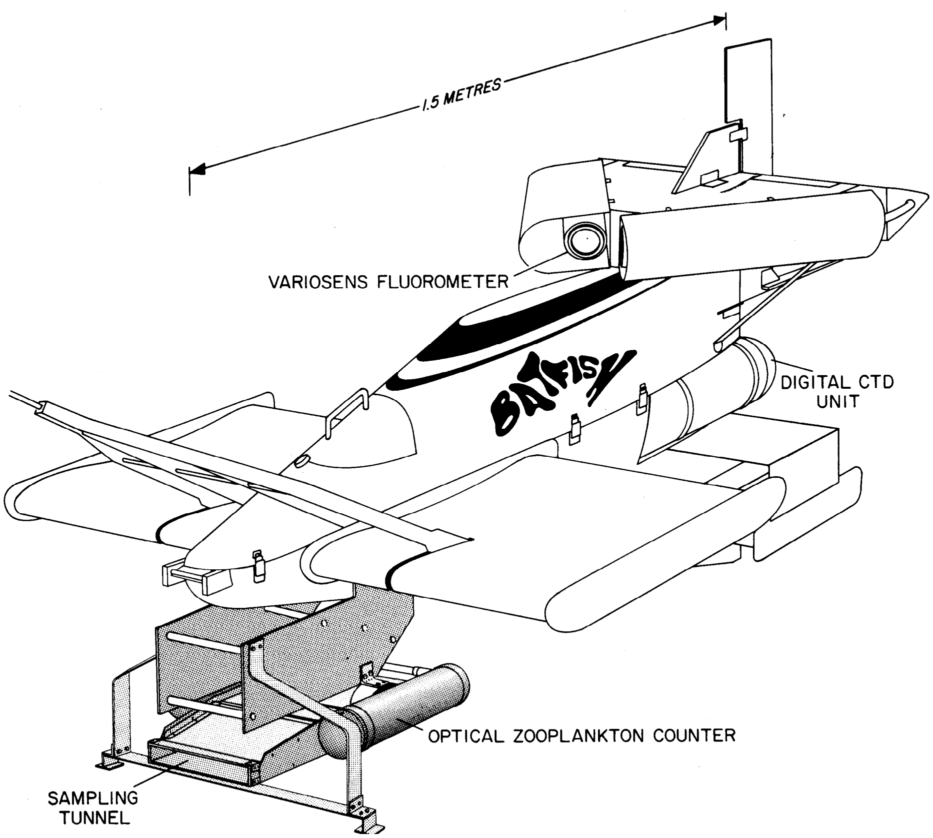
The operational design of the optical plankton counter is presented in Fig. 2, which shows the sampling tunnel used to house the light beam and transport the sample. The tunnel aperture is large enough to accommodate animals of up to 3-4 cm, so extending the upper size limit by an order of magnitude. The optical plankton counter, mounted on the BATFISH (Fig. 3), can be towed at speeds of up to 10 knots, and because of the large tunnel-diameter, sampling statistics are vastly improved at such a speed and a concentrating net is not required. Tows are therefore unlimited in time and space. An example of NO-km-long tows through the Emerald Basin is shown in Fig. 4 where we observed dense copepod layers (5000/m^3) in the bottom 60 m of water.

We also a needed a deck-mounted or laboratory electronic particle counter. Much of our underway surface sampling, or station profiling, is accomplished not with a BATFISH, but by pumping, so that a deck-mounted counter can be employed to process the pump effluent arriving on deck. A laboratory version of the optical counter has now been developed at BIO and is shown in Fig. 5. This has several advantages over conductivity cell counters. The large size of the light beam allows the use of a large-flow cuvette (2-cm cross section) and a high flow rate of 25 litres/minute with much improved sampling statistics. Such flow rates were impossible with the previous conductivity cell models with their small 3 mm orifices.

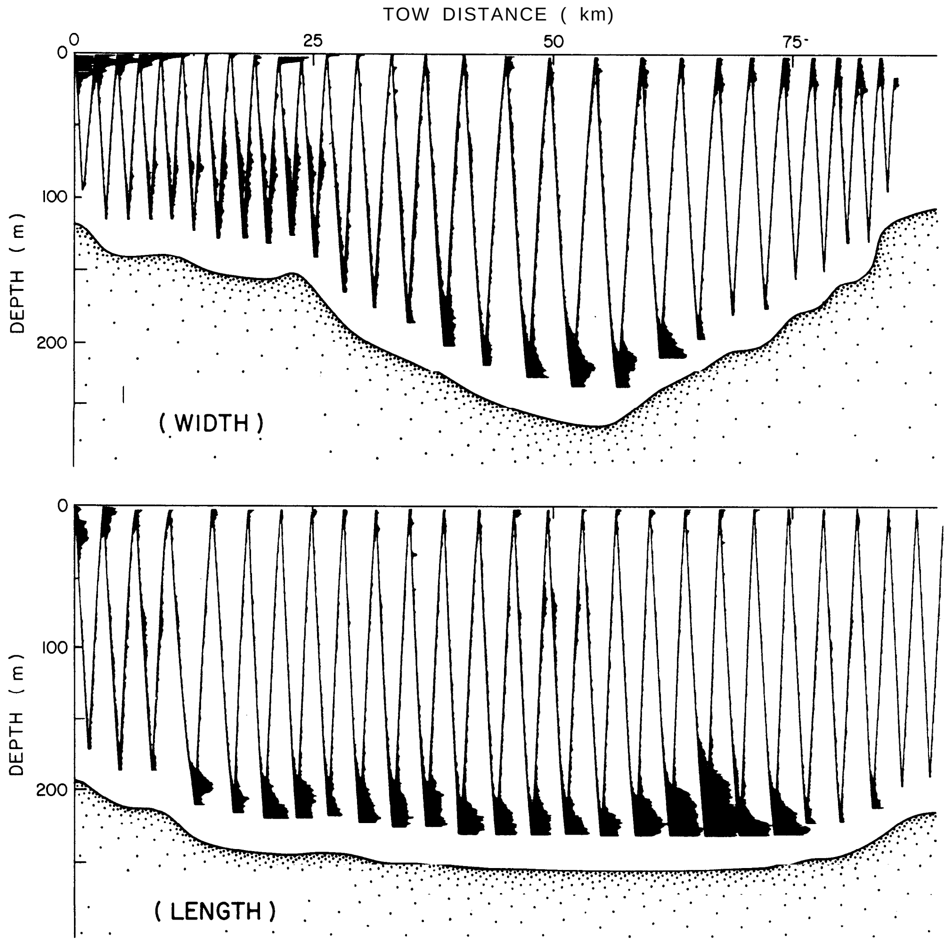
The laboratory version of the optical counter is now used routinely to process seawater samples from the BIO pump profiling system. An example of a pumped profile is presented in Fig. 6 which shows zooplankton layers and light attenuance measured with the zooplankton counter and chlorophyll fluorescence measured with a Turner fluorometer.

Other applications of the laboratory version of the optical counter are the processing of the large numbers of formalin-preserved zooplankton samples that await analysis in most oceanographic laboratories. However, even though their microscopic analysis is labour-intensive and expensive, the optical counter will never fully replace this procedure but will enable relatively simple analyses to be made very quickly and cheaply.

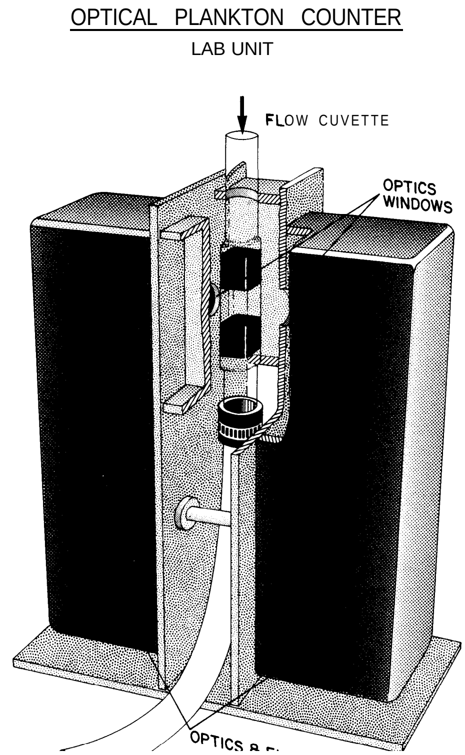
The new BIO optical particle counter has proved to be both versatile and practical in studies of the spatial patterns of plankton, and is in demand both inter-



3. The Batfish vehicle mounted with the optical plankton counter.



4. Batfish transects through the width and length ***of*** *Emerald Basin. Dark bands indicate the presence* ***of*** *copepod layers in the bottom 60 m.*



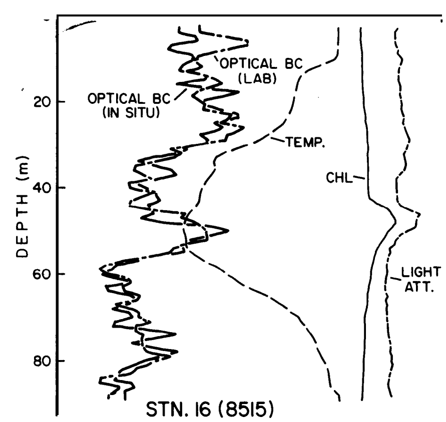
5. The laboratory version of the optical plankton counter. The large diameter cuvette allows sampling of high flow rates of about 25 litres per minute.

nationally and by other parts of the DFO Science Branch. As a result, its technology has been transferred successfully by BIO to a Canadian company, and it is currently in commercial production and is already used by institutes other than BIO.

How far have all the technical strides made at BIO and in other oceanographic institutions during the last 20 years taken us in biological oceanography? Certainly, the current concepts of the functioning of the planktonic ecosystem are a great advance on those of 25 years ago, and a real ability to measure spatial relations with some precision has made an important contribution to that advance.

An ability to obtain data on the distribution of plankton with a spatial resolution on the metre scale led to the use of formal dimensional analysis, by means of which we can now separate the spatial scales of phytoplankton patchiness due to biological processes from those due to turbulent mixing; the application of spectral analysis to these problems by Platt and Denman (1975) of BIO, using fluorometry, was a notable contribution to this field. The interaction between horizontal patchiness in the mixed layer with internal waves at the thermocline to produce false patches in the data series was demonstrated for phytoplankton by Denman and Platt (1975), and for zooplankton by Haury and others (1977) of Woods Hole using multiple-serial plankton samplers.

The general nature of the layered biological structure of the upper water column is now clear for many marine habitats, and significant contributions have been made by BIO scientists in developing the current concepts because



6. A plankton profile obtained with the BIO pumping system. The profile obtained with the laboratory counter shows good agreement with the in situ *counter mounted on the profiler. The light attenuance profile also measured by the counter agrees with the chlorophyll profile sampled with a Turner fluorometer.*

of the support given them by engineers and applied physicists since BIO was established. The vertical interactions between plants, herbivores, and predators, and the vertical gradients of turbulent mixing, light, and nutrients are now well understood and central to any models of pelagic ecosystems and their application to practical problems. The production of plant material throughout the water column can now not only be measured, but also modelled satisfactorily, as Herman and Platt (1986) of BIO have shown. The interaction between the deep chlorophyll maximum and the physical structure of the upper water column has been examined closely, and in a wide range of marine habitats from the arctic to the tropics, by BATFISH bearing the sensors described above.

What of the future? Biological oceanographers are now in a position to contribute seriously to important practical problems such as the variable recruitment of commercial fish and the role of marine phytoplankton in the exchange of carbon dioxide between ocean and atmosphere. The major thrust in biological oceanography worldwide in the coming decade will certainly be an attempt to integrate budgets of organic carbon, and other variables, on a global or at least ocean-basin scale. It is fortuitous that an ability to contemplate such a task, because of our ability to model production in the upper ocean, coincides with the urgent need to better understand and predict changing global climates.

In this context, two developments at BIO in biological remote sensing are noteworthy because of their relevance to these global studies as we attempt to integrate budgets of biological production and consumption for whole oceans, based on our new understanding of pelagic ecosystems. Platt and Topliss of BIO are investigating the optical properties of the upper ocean and developing algorithms to relate integrated water column production to satellite images of sea-surface chlorophyll, not only to indirectly estimate whole ocean production rates but also to infer regional estimates of variance of mixed-layer chlorophyll, a critical parameter in extrapolation from direct oxygen- or radiocarbon-based measurements of plant production profiles. Meanwhile, Sameoto and Cochrane at BIO, with support from other federal government departments, are planning to work with a Canadian acoustic engineering company (SeaStar of Halifax) to develop a multi-frequency acoustic system for the quantification of zooplankton and micronekton in biological oceanography, which will be capable of acquiring data even more extensively than the optical zooplankton counter.

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Photosynthetic picoplankton: Creatures small and great

Trevor Platt and William K.W. Li

A partial list of the topics of interest to researchers on phytoplankton ecology in 1962 would have included the following:

(i) The magnitude of primary production in the ocean;
(ii) The distribution of primary production among the various size-classes of photosynthetic cells;
(iii) Development of a formalism to describe nutrient dynamics in phytoplanton;
(iv) The relationship between photosynthesis and light; and
(v) The value to oceanography of the embryonic technology of remote sensing.

Of these, only the first could be considered as a real "problem", as epitomised by the celebrated controversy between Riley and Steeman Nielsen, and even then its problematical side would be ignored by most workers in the field. The issue of the absolute magnitude of primary production in the world's ocean remains as contentious now as it was then, but in the intervening 25 years we have gained a much better understanding of why it is a problem. The evolution of thinking on these five themes has depended on the perception of their interrelatedness, and on the conceptual development of marine ecology in general. Scientists in the Biological Oceanography Division of the Marine Ecology Laboratory have made important contributions to each of the topics. Here, we address mainly the second of them (size fractionation of primary production), in particular the discovery of the fascinating role of picoplankton in the ocean. The presence of the other four issues, however, will be felt throughout.

Within the last decade our perception of the structure and function of the pelagic ecosystem has undergone a profound change. The essence of the revolution that has taken place is the recognition of the importance and diversity of very small organisms in the pelagic food web of the ocean. Here ‘very small’ means, say, less than 10 µm in the largest dimension. It is now believed that these organisms, the ‘microplankton’, are responsible for about 90% of the metabolism of the ocean.

Bill Li and Trevor Platt observe output from a flow cytometer, an instrument used to analyze phytoplankton distributions.

For the photosynthetic part of the pelagic ecosystem, the most striking discovery of recent years has been that of the so-called picoplankton community. These are organisms <2 µm in width. They occur everyhere in the upper layers of the world’s oceans. The first members of the picoplankton to be discovered were prokaryotic cells belonging to the cyanobacteria (genus *Synechococcus)* (Johnson and Sieburth, 1979; Waterbury *et al.,* 1979). The extremely small-size of the cells, their prokaryotic nature, and their unusual photosynthetic pigments were all characteristics that set them apart from the stereotypic phytoplankter, a large cell of a diatom or dinoflagellate. Later, it was realized that eukaryotic cells belonging to several taxonomic groups were also important members of the photosynthetic picoplankton community. It quickly became apparent that, under certain circumstances, picoplankton could be responsible for a substantial fraction of the primary production of the ocean ecosystem. The Biological Oceanography Division was at the leading edge of these developments on voyages of CSS *Hudson* to the eastern tropical Pacific (Li *et al.,* 1983) and the subtropical North Atlantic (Platt *et al.,* 1983).

In general, the relative importance of photosynthetic picoplankton increases from inshore to offshore; from high latitudes to low latitudes; from winter to summer; and from the top to the bottom of the photic zone. In fact these generalizations are based on rather few observations and it remains to be seen how robust they are.

A recent review by Joint (1986) examined data obtained on picoplankton from different regions of the world’s oceans. The abundance of cyanobacterial picoplankton in the ocean is typically about 10,000 cells/ml. The limited data on eukaryotic picoplankton suggest a typical abundance about an order of magnitude less in ocean water, higher in coastal water. These numbers will be smaller in high latitudes, or in temperate latitudes during winter. In Lake Ontario, the abundance of cyanobacterial picoplankton varied through four orders of magnitude during the year with a peak (600,000 cells/ml) at the time of maximum water temperature (22°C). In the coastal waters off Southern California, cyanobacterial numbers varied over two orders of magnitude during the year with a minimum (1,000 cells/ml) in February. During the arctic summer (temperature about 0°C) some 1,000 cyanobacteria/ml have been reported. The effect of temperature on the abundance of picoplankton is therefore modulated by other local factors.

It appears that picoplankton contribute relatively less to total phytoplankton production in winter and during the spring bloom, and relatively more immediately afterwards and during the summer months (both times of low ambient nitrate concentrations). A study in the Celtic Sea indicated that picoplankton accounted for 22% of the annual total carbon fixation. In other areas, from non-seasonal studies, picoplankton contributes from 20% (at the surface) to 80% (at 70 m) of total primary production in the eastern tropical Pacific, 60% in the subtropical north Atlantic, 80% off Hawaii, 27% off southern Africa, and from 10% to 25% in the eastern Canadian Arctic (summer). Clearly, picoplankton are rarely an insignificant factor in the photosynthetic community, and can often dominate it, especially in subtropical, oceanic regimes.

Microscopic detection and enumeration of photosynthetic picoplankton is aided greatly by the fluorescent emission of visible light when these cells are excited by light of a shorter wavelength. Algae (and cyanobacteria) belonging to

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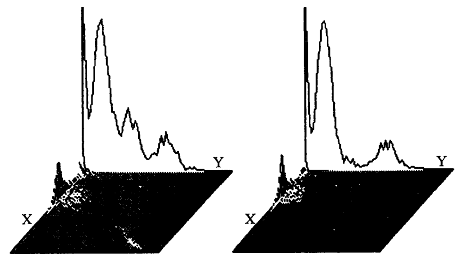
different taxonomic groups possess different suites of photosynthetic pigments. Each pigment differs in the wavelength ranges over which fluorescent excitation and emission are maximal. Thus when pigments occur in particular suites as they do in each taxonomic group, it is possible to attempt taxonomic characterization from particular so-called spectral ‘signatures’, ‘fingerprints’, or ‘excitation-emission matrices’. The most common application of this principle is the enumeration by epifluroescence microscopy of phycoerythrin-rich cyanobacteria and the distinction of these cells from algae without phycoerythrin whose emitted fluorescence is due mainly to chlorophyll *a*.

In microscopy, human eyes are used to detect the emitted fluorescence from cells moved about the microscope stage by human hands. In an automated method based on the same principle of detection by pigment autofluorescence, electronic photomultiplier tubes quantify the relative fluorescence from cells made to flow past a region of excitation. This method is known as flow cytometry. The use of flow cytometers to detect and enumerate living cells according to their autofluorescent characteristics represents only a most rudimentary application of such instruments to phytoplankton research. Even so, such a use already affords several advantages over microscopy. These include the capability of analysing many more cells in a short time, the characterization of living cells according to relative fluorescence intensity, and the ability to characterize each cell by more than one variable (e.g., fluorescence emissions at different wavelength ranges, light scatter at different angles) at the same time (Fig. 1). The Biological Oceanography Division is fortunate to possess one of these sophisticated instruments.



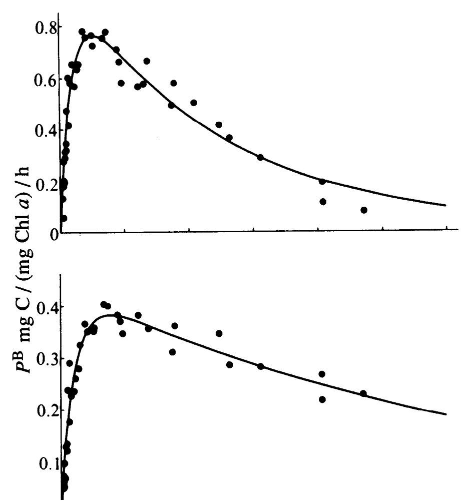
1. Flow cytometric analysis of phytoplankton from Bedford Basin. The X-axis indicates the intensity of fluorescence originating mainly from phycoerythrin, while the Y-axis indicates that mainly from chlorophyll a. The height above the X-Y plane is a measure of the frequency of occurrence. Left panel: plankton filtered through a 50 µm mesh. Right panel: plankton filtered through a 3 µm membrane.

One of the tools employed by phytoplankton ecologists is measurement of the response of photosynthesis to increasing light. The result, the so-called light-saturation curve, can be described by a general equation for which particular parameter values characterize a given experiment. The parameters of interest are the slope of the light-saturation curve near the origin (a measure of the efficiency of photon utilization at low photon flux densities) and the height of the plateau (the so-called assimilation number, a measure of the capacity of the dark reactions of photosynthesis). Light-saturation curves can be measured routinely at sea, and the mathematically extracted parameters used to characterize the phytoplankton communities under different circumstances. Furthermore, by differential filtration, it is possible to characterize different size-fractions of the same community (Fig. 2).

The initial slope of the light-saturation curve depends on both the quantum yield of photosynthesis and the optical absorption coefficient of the cells. Absorption cross-section, all other things being equal, varies inversely with cell size. Picoplankton cells are small enough to be commensurate with the wavelength of available light in the sea. They can be expected to enjoy an advantage, relative to larger cells, in their efficiency of utilization of the available light.

In cultures, it is found that *Synechococcus* grows best at low light intensities (± 45 µE/m/s). In natural picoplankton from the subtropical north Atlantic, the optimal light intensity for photosynthesis was lower for picoplankton (±125 µE/m/s) than it was for the larger fraction. Picoplankton cells were also more susceptible to photoinhibition. At first sight then, it appears that picoplankton are adapted to live in low light conditions, and indeed there is often a pronounced peak in their vertical distribution at the level of the deep chlorophyll maximum, typically found at about the 75 m depth in the open ocean. At this depth, photosynthesis by picoplankton is strongly light-limited, and enhanced efficiency of light-utilization would be advantageous to the cells. In fact, the initial slope of the light-saturation curve is higher for the picoplankton fraction than for the rest of the community.

These results have to be interpreted with caution, however. The reason is that, in stably-stratified water columns, phytoplankton are known to adjust their photosynthesis characteristics to the prevailing conditions (photoadaptation). Therefore, populations living in the deep chlorophyll maximum of the open ocean, where the ambient light levels are low, would be expected to adjust in the direction of increasing photosynthetic efficiency and decreasing light level for optimal photosynthesis, regardless of their taxonomic (genotypic) status. In this context, results from the Porcupine Sea Bight and the Celtic-Sea, where populations adapted to three quite different light levels



2. Photosynthesis-light curves for phytoplankton from the Mid-Atlantic Ridge. Upper panel: plankton filtered through a I µm membrane. Lower panel: plankton filtered onto a 1 µm membrane.

could be sampled from the same stably-stratified water column, are of particular interest. Light-saturation curves for these samples provided no clear evidence that the picoplankton were more adapted to low light levels than the larger size-fraction of the phytoplankton.

As well as light intensity, light quality is also an important ecophysiological factor. The reason is that cells can absorb light only to the extent that they have pigments suitable for the wavelengths available.

$$I_{abs} = \int_{\lambda} I(\lambda)\, k(\lambda)\, d\lambda$$

where I_{abs} is the light absorbed, I(A) is the light available and *k* is the optical attenuation coefficient at wavelength A and the integration is taken over the photosynthetically-active range of the visible spectrum (roughly 400-700 nm). Seawater is a powerful optical filter and, in the open ocean, the spectral distribution of light is strongly-peaked in the blue at the depth of the deep chlorophyll maximum. The pigments of cyanobacteria absorb best in the region from 500 to 550 nm and by the absorption criterion are therefore suited for life in the deep, blue ocean. There is another, and more important, criterion: the photosynthetic action spectrum (relative photosynthetic efficiency at low light for light of different colours). The initial slope of the light-saturation curve can be measured in monochromatic light of different wavelengths to construct the action spectrum. For culture populations of both prokaryotic and eukaryotic picoplankton, the action spectrum is a more-or-less faithful reflection of the absorption spectrum, the phycobilin peak being the most characteristic feature of the cyanobacterial spectra.

In the field populations tested so far, however, photosynthetic action spectra show no peaks at the phycobilipigment wavelengths, even for size-fractionated samples, and even for samples containing proteins with a strong response for immunofluorescent antibodies against phycoerythrin (i.e., samples containing cyanobacteria).

Nitrogen is a major essential nutrient of all cells. To date, it has been thought that marine phytoplankton are able to acquire the element only in combined forms (e.g., ammonium, nitrite, nitrate, organic compounds.) The rate of supply of these nutrients to the phytoplankton may be a key determinant in the rate of oceanic primary productivity. Recent studies indicate that certain cyanobacteria of the picoplankton possess mechanisms allowing them to deal with the possible problem of nitrogen limitation.

Recent studies on the phycoerythrin-rich picoplanktonic marine cyanobacterium *Synechococcus* strain WH7803 show a high yield of phycoerythrin autofluorescence, which indicates that much of the light absorbed by this pigment is unavailable for photosynthesis. Furthermore, over a range of growth conditions, a poor correlation exists between the autofluorescence and the amount of phycoerythrin in the cells, implying a variable proportion of the pigment dedicated to photosynthesis. Wyman *et al.* (1985) subsequently demonstrated that in WH7803 the relative loss of energy through phycoerythrin autofluorescence is higher for nitrogen-sufficient cells than it is for nitrogen-limited ones, an observation supporting the hypothesis that WH7803 phycoerythrin serves as both a nitrogen store and a collector of quanta for photosynthesis. Lewis *et al.* (1986) have also shown that the absorption of light in the wavelength range characteristic of phycobiliprotein absorption is much less for nutrient-deficient cells compared to nutrient-sufficient cells. The ecological implication is that these cyanobacteria might be able to outcompete others during times of nutrient scarcity by utilizing intracellular pools of nitrogen stored as phycobiliproteins.

There is also some indirect evidence from measurements made on natural phytoplankton in the ocean for the inefficiency of energy transfer from phycoerythrin to the reaction Centre for photosynthesis. In the Sargasso Sea, Lewis *et al.* (1985) measured the efficiency of photosynthesis over twelve 25 nm wavebands spanning the visible light spectrum and found the value to be relatively low in the green wavebands expected for phycoerythrin absorption. This was in spite of the fact that the presence of phycoerythrin-rich cyanobacteria in the samples was confirmed by independent means. In contrast, the photosynthetic efficiency in green light is high for these cells in logarithmic phase cultures.

A restricted number of unicellular marine cyanobacterial species appear to have another way of obtaining the nitrogen they require. They are able to reduce the dinitrogen molecule to ammonia utilizing a multi-component enzyme system called nitrogenase. A simple indication that they can do so is that they are able to grow in a medium that does not contain any form of combined nitrogen. It has been shown recently (Mitsui *et al.*, 1986) that picoplanktonic cyanobacteria can carry out both nitrogen fixation (which is inhibited by oxygen) and photosynthesis (which evolves oxygen) by restricting the one to the night period and the other to the day period.

Measuring the incorporation of ^{15}N (whether supplied in combined form or as dinitrogen) in field samples of phytoplankton forms a crucial part of the study of nitrogen nutrition in the sea. For photosynthetic picoplankton, such measurements are difficult to make because the ability to take up many of the common nitrogenous compounds is shared by other members of the picoplankton community. Although data exist for nitrogen uptake by picoplankton isolated by size-fractionation (W .G. Harrison, unpublished compilation), there is no distinction made between uptake by phototrophs versus non-phototrophs. A recent attempt to partition the uptake of nitrogen by picoplankton relied on selective inhibition of prokaryotes and eukaryotes: about 78% of total ammonium uptake was by prokaryotes and other considerations suggested that a significant portion of this was due to heterotrophic bacteria. In light of results such as this, we can see that it will be difficult to study the nitrogen nutrition of photosynthetic picoplankton in the sea.

Phytoplankton may be detected, and their abundance estimated, from optical instruments carried on satellites. An example is the Coastal Zone Colour Scanner (CZCS) carried on the Nimbus-7 satellite since 1978. It collects light from the sea in six channels, including

443 nm (absorption maximum of chlorophyll) and 550 nm (absorption minimum). Because the ultimate source for this light is the sun, the procedure belongs to the passive remote sensing class. The ratio of collected light at 443 nm to that at 550 nm is a measure of chlorophyll concentration and therefore an index of phytoplankton abundance. The question then arises whether prokaryotic autotrophic picoplankton, with their unusual pigment complement, interfere significantly with this method of estimating phytoplankton. The prominent absorption peak of phycoerythrin in the green might militate against the use of the A_{443}:A_{550} ratio as an index of chlorophyll concentration. On the other hand, little or no evidence of the effect of the phycobilipigments characteristic of cyanobacteria has been found in natural situations on the submarine light field, on the spectral absorption of light by filterable material, or on the photosynthetic action spectrum. The remote sensing algorithms for chlorophyll are therefore robust.

The fluorescence of chlorophyll, excited by the sun, can also be detected in the underwater light field, and in the light leaving the sea that is collectible in remote sensing, for example by the Fluorescence Line Imager developed in Canada. Because photosynthesis and fluorescence are reciprocal processes with respect to the photons absorbed, the relative fluorescence contains potential information about the rate of photosynthesis in the water column. Although the passive fluorescence of phycobilin pigment is also detectable in the submarine light field, it is unlikely, for the same reasons as with the estimation of chlorophyll, to interfere with algorithms that might be developed to estimate primary production.

In the ocean, under low nutrient conditions, it seems that cyanobacteria may not develop such high intracellular concentrations of phycobilin pigments as are seen in nutrient-replete cultures. If this is the case, chlorophyll-like pigments will dominate the submarine light field and the light leaving the ocean that is useful for remote sensing.

The discovery that a community of minute, pigmented cells can be responsible for more than half of the total primary productivity in a given area has been a great stimulus to research in biological oceanography. Although the community is widely distributed, its best development is seen in the blue-water ocean far from shore. This is the stereotypical, low-nutrient environment and members of the prokaryotic picoplankton have been found to have at least two important adaptations to life in a nitrogen-limited regime: the ability to store nitrogen in pigment-membrane complexes and the ability to fix molecular nitrogen. Further, their ability to photosynthesize with high efficiency at very low light levels means that they are adapted to live near to the major external source of nitrogen supply to the photic pelagic ocean - the vertical flux of nitrate through the base of the mixed layer.

The extremely small size of picoplankton cells has tested the ingenuity of researchers to develop suitable methodology, a problem compounded by the heterotrophic community occupying the same size range. On the other hand, the wide range of pigment types means that recent developments in fluorescence microscopy, especially high-speed cell sorting, can be exploited to the full. Picoplankton studies have already presented several clear examples of the principle that results found in culture populations cannot be generalized without considering conditions in the real ocean.

The role of picoplankton as a food organism in the pelagic food web remains an open question. For very small cells, fluid mechanical forces determine which organisms are able to ingest them. For the organisms able to ingest the photosynthetic picoplankton, there is yet the consideration of which among them are able to digest their prey. Ciliates have a feeding apparatus with the right size-characteristic, but the abundance of the prey is thought to be too low for the feeding link to be viable in natural conditions. Again, because of their very small size, direct loss from the photic zone by sinking would be insignificant without considerable aggregation or flocculation. On the other hand, strong growth implies an equally strong removal rate in the quasi-steady state. The two most likely types of organisms responsible are thought to be heterotrophic protozoan microflagellates and the mucous-net feeding forms. The so-called 'microbial-loop' involving bacteria (either heterotrophic, growing at the expense of phytoplankton exudates, or photosynthetic cyanobacteria) and heterotrophic microplankton is an element of the pelagic food web whose importance remains to be quantified. Photosynthetic picoplankton have played a major role in revolutionizing our thinking about the structure and function of the pelagic ecosystem in the ocean. But many questions are still unanswered: exciting times lie ahead. Meanwhile, the present state of knowledge is accessible in a volume edited by the authors and published by the Department of Fisheries and Oceans (Platt and Li, 1986).

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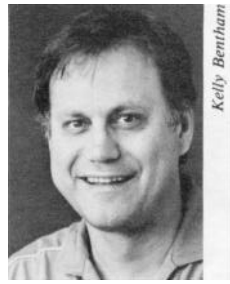
The management of marine fisheries: An historical perspective

Robert N. O'Boyle and Peter A. Koeller

Bob O'Boyle.



Peter Koeller.

BIOLOGISTS have, since its inception at the turn of the century, played a central role in fisheries management. This role has changed considerably over time, paralleling changes in management objectives.

There are three key elements to any fishery management system: (1) objectives, which define the goals of society in biological, economic, social, and political terms; (2) management action designed to move the system toward the objectives; and (3) monitoring activity designed to, on an ongoing basis, assess the success of managerial actions in achieving the objectives - the biologist's domain. This article looks at the development of fisheries management systems in the Northwest Atlantic since the establishment of BIO in 1962 and the Institute's role in this evolution, from a biologist's perspective.

The situation in 1962

The International Commission for the Northwest Atlantic Fisheries (ICNAF) was established in 1949 by an international convention of countries then fishing in the Northwest Atlantic. ICNAF directed and oversaw the orderly exploitation of marine resources by the European nations during the post-war era of expanding harvesting capacity. Consequently the objectives of fisheries management at the time focused on conservation. In 1962, biological models already played a central role in defining management actions by ICNAF.

Then, as now, data availability defined the sophistication of biological input into the management process. Interactions among species, although generally acknowledged, could not be quantified. Thus, single species/stock models prevailed. Two broad categories of these models existed, each having evolved along parallel paths since the turn of the century.

The first, referred to here as the Beverton-Holt approach, reduced a fish population to a linked set of biomass pools, each consisting of a different age group. Biomass entered the first pool in the form of recruitment. As this pool moved through the population, it increased due to growth and decreased due to natural and fishing mortality. In theory, one could change the recruitment, growth, and natural and fishing mortality to examine the system's behaviour. In practice, the data were lacking for all but the simplest assumptions. Beverton and Holt (1957), in their classic work detailing this approach, point out that they were primarily concerned with determining the effects of regulations such as mesh size in the North Sea, rather than with developing a general population model.

The second approach, pioneered by Schaefer and described in Schaefer and Beverton (1962), considered the population as an aggregate pool, with no age structure, governed by logistic growth curve dynamics. Assumptions on stock dynamics are made more directly than in the Beverton-Holt approach. The Schaefer Surplus Production Model was developed to determine harvesting levels for the Pacific tuna fishery. Tuna, like many tropical species, are difficult to age thus precluding an age-structured model.. However, contrary to the situation in the North Sea encountered by Beverton and Holt, the time series of catch and effort data was long and thus suitable for the Schaefer Approach.

Thus, in 1962, two basic models existed to describe the dynamics of fish populations. Originally both had the same intent - to provide a biological basis for management of specific fisheries - but they differed due to the data limitations encountered. As will be discussed below, both the models and the management objectives developed and changed during the 1962-1976 period.

The period of transition - 1962 to 1976

ICNAF was the forum within which regionally developed biological expertise was channelled into the management process. Scientific exchange between ICNAF and its European sister, the International Council for the Exploration of the Sea (ICES), resulted in the parallel development of fisheries management on both sides of the Atlantic.

It was obvious by the mid sixties that the mesh-size regulation first introduced in 1957 by ICNAF was ineffective at limiting fishing mortality and thus conserving the resources. More direct limitations were needed. These came in the form of stock-specific Total Allowable Catches (TAC) in 1970, based on the Maximum Sustainable Yield (MSY) concept of the Schaefer model. This represented the first time in the world that an international fisheries management organization had employed TACs to limit fishing effort. By 1973, TACs were established for all stocks harvested in the ICNAF Convention area.

It was soon realized that the Schaefer approach, although appropriate in providing long-term estimates of yield, could not provide the reliable estimates demanded by annual TACs. Annual fluctuation in growth and recruitment needed to be taken into account. An extension of the Beverton-Holt

Roger Belanger

Staff from Marine Ecology Laboratory (Fisheries Oceanography Group) in 1967 aboard the chartered MV Acadian Snowbird *test the acoustic fish counting system prior to departing for the Scotian Shelf.*

approach called Cohort Analysis ‘was introduced by Pope in 1972. It provided a computationally simple way of keeping track of year-class sizes as they move through a population. Used in conjunction with independent estimates of abundance, it provided current estimates of stock size that could be used to set a TAC for the coming year.

While the regulations were changing so too were the objectives of the system. The catch levels based on Maximum Sustainable Yield (MSY) or F_{max} (the equivalent output from the Beverton-Holt Approach) proved to be too high for effective conservation. The concept of a Maximum Economic Yield (MEY) also surfaced during this period. A number of authors (e.g., Doubleday, 1976), observed that the MEY level could be approached by setting fishing effort at a more conservative level than at the MSY level. Such a level was eventually adopted by ICNAF. Termed “F_{01}”, it represents a specific fishing level that attempts to conserve the stock while optimizing gains for fishermen.

Canadian participation in the development of fisheries management by ICNAF mainly involved staff at the St. Andrews Biological Station. Part of this component was moved to BIO in 1977. From 1962-1976, the Marine Ecology Laboratory (MEL) at BIO was undertaking more fundamental research into fish production processes.

The Marine Ecology Laboratory was established in 1965 to study the processes underlying marine production. Research deliberately focused on the multi-species interactions in an ecosystem to evaluate long-term- changes caused by fishing and environmental influences. Trophic interactions were defined (e.g., Kerr and Ryder, 1977) and the underlying size relationships were documented (Sheldon et *al.,* 1977). Efforts to model these complex interactions are exemplified in the Top-Down Modeling approach of Silvert (1982).

In addition to the system behaviour studies, MEL undertook an active research program on recruitment processes. In his classic paper on the topic, Ware (1980) described how food energy is partitioned between somatic and gonadal growth in an individual. His results have implications for the stock-recruitment questions long posed by fisheries biologists.

Sutcliffe *et al.* (1977) studied the relationship between environment (in this case Gulf of St. Lawrence river runoff) and recruitment, and found strong linkages. This work was among the first of many demonstrating the influence of large scale environmental factors on fish populations evident throughout the world’s oceans.

Finally, MEL has developed the direct estimation of fish abundance using acoustic methods. Initiated during the mid-sixties, this program is now co-operating with Marine Fish Division’s (MFD) trawl survey program to provide more precise estimates of groundfish populations. The dual-beam system, designed to provide estimates of fish size as well as abundance, is currently being developed for commercial sale.

1977 to the present

Extension of jurisdiction - Canada extended its jurisdiction to 200 nautical miles on January lst, 1977. This provided new opportunities for the effective management of fish resources on our continental shelf. Funding was provided under the Extended Jurisdiction Program (EJP) to conduct new research initiatives. Staff at the St. Andrews Biological Station involved in management issues were moved to BIO to create a nucleus for growth. This component of the newly created Marine Fish Division had as its prime mandate the provision of biological advice to managers on the optimal harvesting of fish resources on the Scotian Shelf. Over a three-year period, its staff and funding grew dramatically.

A complete change in the management bureaucracy accompanied the new reality of the 200-mile limit. ICNAF was disbanded and replaced by the Northwest Atlantic Fisheries Organization (NAFO). Its mandate now only covered resources outside 200 miles as well as those resources predominantly of interest to foreign nations (e.g., silver hake, argentine, squid). Canada established organizations to handle resources of domestic interest. The Canadian Atlantic Fisheries Scientific Advisory Committee (CAFSAC) became the forum within which Atlantic coast scientists could discuss the current status of the stocks and consider the implications of alternate management strategies. Advice generated by CAFSAC is passed to the management advisory committees, industry/government groups that establish the management plans for the coming year. Here, MFD scientists must explain, elaborate, and sometimes vigorously defend their advice.

Advances since 1977 - In single stock models like Beverton-Holt and Schaefer, the identification and delineation of the stock is a prerequisite. Prior to 1977, stocks were defined by ICNAF scientists using tagging studies and distribution patterns from research vessel surveys. In 1978, MFD initiated the Scotian Shelf Ichthyoplankton Program

Kelly Bentham

Final adjustment being made to the Tucker trawl, a 2m x 2.5m opening and closing mid-water trawl used for capture of evasive large fish larvae, juvenile fishes and lobster larvae, prior to deployment from CSS Dawson.

(SSIP) to define the major spawning grounds in the area. By 1982, these grounds had been identified (O'Boyle et *al.*, 1984), confirming the previous stock definitions. New tagging programs for cod, haddock, and pollock were also conducted to provide further information on stock migrations and interactions. These studies have added significantly to our understanding of the fish population complex on the Scotian Shelf.

Most Divisional resources are expended on stock size estimation and associated research. Since Pope's Cohort Analysis requires accurate catch age/size information, much of this research involves the development of appropriate sampling designs and efficient analysis methods for commercial catch statistics (e.g., McGlade and Smith, 1983). Similar work is conducted on research vessel surveys, which provide independent estimates of stock size and are used to calibrate the Cohort Analyses. In addition to improving the accuracy of existing adult fish surveys, recent work has examined the juvenile phase of various species, with a view to developing pre-recruit surveys (Koeller *et al., 1986).*

Cohort Analysis calibration has received much attention in MFD. Historically, geometric regressions were used. Current work focuses on more sophisticated statistical procedures (e.g., Smith, 1987). Similar work is being conducted by ICES scientists who employ similar assessment techniques. On the west coast of North America, however, a "modelling" approach to population estimation has been taken. Contrary to Cohort Analysis, which is a simple accounting of the year-classes by age, the west coast models (e.g., Fournier and Archibald, 1982) involve a set of equations that completely describe stock dynamics and can be solved using the existing data. Current MFD efforts are directed at integrating the best features of the "Accounting" and "Modelling" approach.

The International Observer Program (IOP) is managed by MFD staff at BIO. In addition to supplementing the domestic sampling program, it provides essential at-sea information on foreign fishing activity and samples catches not landed in Canada. These data are routinely consulted by representatives outside the fishing industry - for example, in the formulation of Environmental Impact Statements (EIS).

In 1982, MFD initiated the Southwest Nova Scotia Fisheries Ecology Program (FEP). This study involves the cooperative efforts of several BIO laboratories and outside agencies. It was designed to describe the population dynamics of the 4X haddock stock, from recruitment to fishing processes. The project is similar to MEL's St. Margaret's Bay study (see article by Lloyd M. Dickie) in its holistic approach to ecosystem research, but it is unique in focussing on a fish stock. Consequently, results will be applied within the management forum reasonably quickly. The project is to be completed in 1987.

MFD has also been active in research on the fish-man interaction. Staff members were involved in evaluating fishing capacity in the troubled Southwest Nova Scotia fishing area. New ground had to be broken in defining capacity and allowable harvesting levels. Fleet distribution in relation to fish distribution on the Scotian Shelf has been well documented (Sinclair, 1985) allowing development and evaluation of area and/or seasonal closures in lieu of TACs to control fishing effort. Work on gear conflicts has also been undertaken, again with implications for the regulatory process. Finally, modelling exercises have been undertaken to describe fleet interactions in time and space and provide a basis for more fundamental changes to management strategies (Allen and McGlade, 1986).

In parallel to the efforts of MFD, MEL has continued its more fundamental research on ecosystem processes. Through the Dalhousie University Ocean Studies Program, it undertook a thorough examination of the bio-economic aspects of a fishery. Published in 1977, this work represents a significant contribution to the field.

In summary, the years following

extended jurisdiction were marked by a significant enhancement at BIO of research in support of the Beverton and Holt approach to fisheries management. The required databases were established and are now readily accessible for both assessment and research purposes. This has resulted in greater understanding of the organisms involved and increased our ability to respond to new management initiatives.

The future

The management system currently in place on Canada's East Coast is based on Beverton-Holt's single species model. The ecosystem research of MEL, MFD, and others suggests that a multi-species approach is more appropriate in principle. Work currently being conducted in ICES has shown that the inclusion of biological interactions into existing models is complex and requires data not available under the present system. However, as recommended in a recent CAFSAC workshop, inclusion of gear or technological interactions is well within current data constraints and should be given serious consideration. Current management objectives emphasize socio-economic issues, including the efficiency and distribution of harvesting. Increasing demands are being made on biologists to provide advice on how best to regulate harvesting by conflicting fishing interests. The challenge of the future is to extend the accumulated knowledge of the past 25 years in order to provide this advice.

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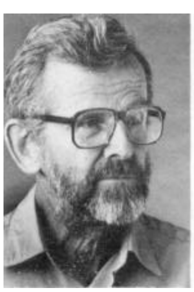
The physiological energetics of fish: Controls on production

Lloyd M. Dickie



Kelly Bentham

Lloyd Dickie.

I T is a fact, not widely enough recognized, that scientists are products of their intellectual and social environments in exactly the same way that poets, historians, or industrialists reflect the influences of their own times. Ideas and attitudes that initially seem to bear little relationship to what has gone before suddenly appear at the same time in the literature or in action, apparently as resonances of the tones already ringing there.

The growth of Canadian fisheries during the early sixties marked an unprecedented expansion in this natural resource industry that was matched by a sense of self-assurance and limitless horizons in the biological sciences. The year of the founding of the Bedford Institute of Oceanography saw a surge of interest in measurement of biological production and its underlying physiological energetics that, in retrospect, makes 1962 a pivotal year. Publications that appeared mark a turning away from an earlier preoccupation with the physiology of individual organisms to a newfound recognition of the need and the possibility of translating this 'basic' science into an applied population energetics that would index the control of production, hence yields, of the growing fisheries. In industry and management, old attitudes of conservatism in exploitation were perceived as a blanket of economic and social habit patterns that could at last be thrown off. On all sides was the sense that more yield was available from the natural stock. The question was only, How much more? Expansion of the sciences would provide the new knowledge required.

The confident background on individual physiologies from which new understanding was expected is exemplified in major scientific publications of the year. J.R. Brett in his important paper, "Some considerations in the study of respiratory metabolism of fish, particularly salmon", consolidated the ideas of F.E.J. Fry on the classification of environmental factors on fish physiology and set the stage for his own future work on energy costs of fish locomotion. At the same time, the American Fisheries Society greeted the release by the Fisheries Research Board of Canada (FRB) of its translation of Winberg's epic "Rate of Metabolism and Food Requirements of Fishes" and the appearance of the first FRB Bulletin by John Strickland entitled, "Measuring the production of marine phytoplankton". Yale University Press released its important, if inadequate, translation of Ivlev's classic work "Experimental Ecology of the Feeding of Fishes", and Blaxter and Holliday published their extensive work on "The Behaviour and Physiology of Herring and other Clupeoids". 1962 was also the date of publication of one of the last of the scientific papers by the retired but active Dr. A.G. Huntsman, entitled "Method in ecology-ectology", in which he tried once again with his aphoristic approach in "How Water makes Fisheries" to direct younger scientists towards an applied fisheries science in which physiological and environmental study deserved equal attention - something not often achieved in the earlier research. The scientific world of 1962 was sure of its capacity to describe both physiology and environments of individual fish and confident that the problem of converting this information into knowledge of how much energy was available to support the increasing fish yield was virtually solved.

There were also indications of how the new scientific endeavours were to translate the basic science into population studies. 1962 saw the publication by John Teal of his pace setting "Energy flow in the salt-marsh ecosystem of Georgia", and Slobodkin's important review "Energy in animal ecology" clarified the appropriate usages of individual physiological efficiencies for the measurement of production at the level of populations and communities. The shape of the body of knowledge needed for practical fisheries advice seemed not much in question. The fact that the cost, complexity, or time required to fill out this body were only dimly discerned, and were quite unrelated to the rate of change in an industry looking for guidance, seemed unable to disturb the general mood of optimism and progress.

As is often true in the growth of human understanding, this time of expansion and great expectations failed to notice that several key elements were still missing. Ironically, one of the ideas now recognized as essential was identified that year but lay virtually unnoticed and unappreciated in what was, for fisheries, the relative obscurity of the *Bulletin of Mathematical Biophysics.* It was there that Robert Rosen, in 1962, published his modest and apparently simple paper called by the unlikely title "The derivation of D'Arcy Thompson's theory of transformation from the theory of optimal design". It would take nearly two more decades of scientific effort and development before his exposition of dimensional analysis would be recognized as the method necessary to bring the physiology and energetics of organisms at different levels of evolution and aggregation onto a common population scale. He pointed out how D'Arcy Thompson's fascinating rules for transforming one animal form into another gave a basis for a truly comparative study of physiology and ecology. But before this could be seen as a generalization important to fisheries science, other key elements had to be found and fished out of the sea of possibilities.

It required nearly three years after the initial opening of BIO for the Fisheries Research Board of Canada to match its

Jeff McRuer hauls a fine-mesh vertical plankton net aboard CSS Dawson at a station on Browns Bank.

vision with its resources and to join fully in the Institute's development. By 1965, under the guidance and encouragement of its chairman, F. Ronald Hayes, it set up the Marine Ecology Laboratory. In keeping with the mood of the times, the laboratory was given a mandate that was a new experiment in Canadian biological sciences. For the first time, one laboratory was expected to integrate study of the physiology of fish production with study of processes of production in the food chains leading to the fish. The ensuing years in many ways have borne out the promise of this broader approach to understanding controls on fish production, justifying the faith of the founders of the laboratory that there was need for it. In fact, as will be evident in what follows, some of the main features of the development of knowledge of physiological energetics of fish populations over the following 20 years are identical with the history of science at the laboratory.

Biological research at BIO in the sixties was influenced by the general spirit of adventure and expansion that affected its Nova Scotian setting. However, scientific research maintains a connection and flow of thoughts, questions, and sense of purpose with a community that transcends local, national, or political borders. Studies of the physiological energetics of fish populations thus began at BIO in much the style of enquiry of the times. The studies by Teal of the salt-marsh ecosystem of the southern USA had been a development of earlier work by Steele in the North Sea, and these examples, among others, guided MEL scientists studying energy flows on the Scotian Shelf and in the St. Margaret's Bay microcosm they had chosen as an ecological laboratory. Their early results were exemplified by the papers of Brodie (1975) on the energetics of whales or of MacKinnon (1973) on the energetics of plaice. The problems seen there also stimulated Mann's (1969) review of methods of measurement of production, and Kerr's demonstration (1970) of the trade-offs between food size and food-chain length in natural ecosystems as well as his discoveries (1971, 1977) of the orderly sequences of production efficiencies in both simple and complex fish communities.

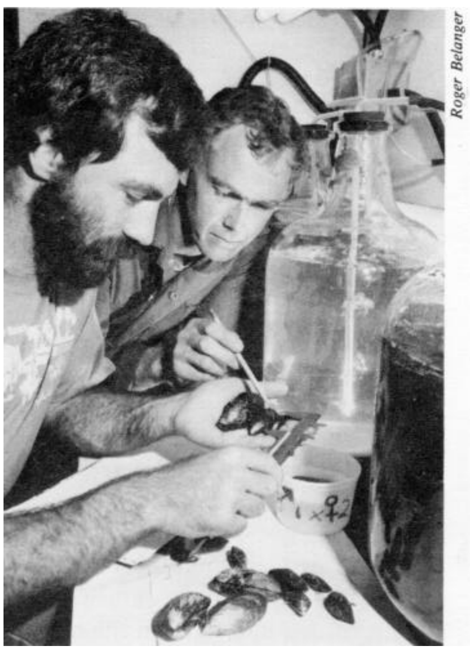
By the early seventies, the staff at MEL began to adopt a point of view in research that diverged somewhat from the popular view. In the world at large, there seemed to be a consensus that population energetics should be simply quantifiable in terms of aggregations of the properties of individuals. When this became linked with the almost explosive expansion of computer science it drew many scientists into the realm of gigantic and complex computer simulation models. The movement swept up much of biological science in the great hopes of the International Biological Program. But while Brylinski and Mann (1973) made their contributions to IBP by generalizing productivities of worldwide fresh water systems, two important but different currents of thought were developing in the lab. The first, which resulted directly from research activity developed during the HUDSON 70 Expedition was reflected in the publication by Sheldon *et al.* (1972) on the size distribution of living "particles" in the seas, based on observations in both the Atlantic and Pacific oceans. The threads of this study are picked up below because it provided the main impetus for much of the production study to follow. Meanwhile, the intuition of Sutcliffe, another scientist in the laboratory, had led him to puzzle over a second feature of ecosystem productivity in a style which was out of keeping with the popular mode of massive computer models. The biomass and turnover rate of the populations in St. Margaret's Bay had been measured by the scientific staff working there. Sutcliffe himself felt that the nitrogen budget was critical to making sense of what was taking place. But when he applied his methods of measurement to the Bay, he found that only half of the required amount of nitrogen could be accounted for. The missing amount must be advected to the system by a combination of wind and surface runoff, drawing nitrogen-rich deep water into the Bay from the shelf outside. That is, the level of productivity and its fluctuations must be largely determined by weather patterns. How general could such a situation be and how could such a theory be tested?

At about this time scientists in the Institute had become interested in the large climatic heat-engine represented by the Gulf of St. Lawrence. The possibilities of local climatic alteration by hydroelectric development seemed significant and there was a developing consensus that this system required special study (Dickie and Trites, 1984). Despite the failure of the scientific community to persuade the Minister of Fisheries and Environment that there should be a priority for special funding of Gulf research, the scientific reviews suggested to Sutcliffe the possibility that the region might represent a large estuarial circulation much like the smaller St. Margaret's Bay over which he had puzzled. In science, theories developed in one situation must be tested in another. The Gulf of St. Lawrence appeared as a place in which to test the extent to which environment, through advection of nitrogen, might control fluctuations of productivity in biological systems leading to fish.

It was the special ingenuity of Sutcliffe, and his associate Drinkwater, to see how weather parameters reflected in the outflow of the St. Lawrence River might be used to index the deep water input of nitrogen into the production system. They. also determined that an index of biological production of a particular year might best be provided by projecting the apparent abundance of fished species back to the years in which they were produced. These refinements of the origins of the theory were however, almost lost sight of in the shock waves created by the high correlation resulting when the two laboriously compiled data series were finally brought together. From the relationships, it was clear that they had found an apparently simple key to the measurement of the impact of environment on production. The precise mechanisms acting on the populations were not clear. Nor were the reasons for evident differences in the effects of the environmental parameters on different species. It was the strength of the relationship of this single index to production fluctuations throughout a large oceanographic basin that made the results too important to be dismissed.

The remarkable results that seemed to flow from this work on the relation of production to environment attracted immediate attention, which in some ways obscured one of the important generalizations underlying it: the success of their endeavour supported the principle followed by other laboratory scientists that insight in ecology depends more on a proper conception of the controlling mechanisms, linked with an intelligent handling of the scales of aggregation on which the variables operate, than it does on complex simulation models of the sort undertaken in IBP. This is not to say that detailed information combined with more sophisticated analyses will not give more knowledge. Welch (1986) showed in elegant fashion that the apparent strength of the stock-recruitment relationship could be much enhanced, if appropriate methods were used with available data series to remove the strong environmental signals operating at the low frequencies. But the approach of Sutcliffe and his associates made it clear that, for useful fisheries science, insights into system operation need to be discovered and independently put into the models in what Silvert (1981) called "top-down" modelling. With the perspective of only a few years, the expectations of IBP that useful results would come as the output from massive and complex simulations based on a mountain of sound details were beginning to seem very naive.

The work of Sheldon *et al.* (1972) had illustrated the same principles. From their curves of particle concentrations at sizes ranging from bacteria to zooplankton, in areas as far apart as the equator and the polar seas, they had begun to see characteristic patterns. Perhaps subliminally influenced by Gordon Riley's (1963) exposition of the "Theory of food chain relations in the ocean", and what he called "potential tuna", they imaginatively extrapolated and projected their observed patterns into the realm of fish and whales, developing them into what became a biomass size-spectrum for oceanic waters. The observations and the justification for their extrapolation were widely accepted, but this acceptance left scientists with the uncomfortable feeling that always accompanies a scientific fact without a supporting theory. The obvious gap was a natural target for further research.



Dr. Andre Mallet and Ken Freeman measure mussels representing genetically identified stocks living in different Nova Scotia inlets. Their productivity parameters have helped identify general size-dependent relations in marine organisms.

The magical currents of creativity generated by this simple but global view of the structure of biological communities in the sea injected new vigour into considerations of the physiological energetics of fish, one that has persisted for 15 years since its original announcement in *Limnology and Oceanography.* It was Kerr (1974) who initially pointed the way to understanding it. He showed that the constancy of body-size relations must depend on the underlying metabolic rates coupled with typical predator-prey size ratios and growth efficiencies. The implication that the relationship depended on a kind of stability of the allometric size relations in a dimensional analysis can in retrospect be seen as an echo of the theme struck by Rosen over 10 years earlier. But despite a growing interest in allometry and dimensional analysis, as shown in the work of Gunther (1975) and Calder (1976, 1981), its power to permit comparisons of data from different sources was still not clearly recognized. Even the perception of Ware (1978) that the bioenergetics of the stock-recruitment problem in relation to environment could be understood as a problem of dimensional analysis in relation to fish size seemed to fall on deaf or uncomprehending ears.

By the late seventies, these first tentative soundings of dimensional analysis had begun to ring more strongly with publications by Platt and Denman (1977, 1978), Silvert and Platt (1978), and Platt and Silvert (1981), though still with little relation to the work of either Kerr or Rosen. Finally the separate perceptions began to form a virtual chorus, with publications at almost the same time, but from various unrelated sources by Humphreys (1979, 1981), Banse and Mosher (1980), and Bamsted and Skjoldal (1980), quickly echoed in the work of Schwinghamer (1981, 1986), Petersen and Wroblewski (1984), and McGurk (1986).

All these papers agreed on one central theme - there is a strong allometric dependance of the production parameters on body size, a fact that had originally been shown by Kerr (1974) to be the basis for the biomass size-spectrum. The wealth of data appearing from many sources left no doubt of the generality of these physiological energetics relationships. Banse and Mosher (1980) had even found a value for their allometric exponent that was identical to one proposed by Dickie (1972) in a tentative early consideration of size-dependance in the ecological relations of food-chains leading to fish production. Two further steps were quickly taken: first, Sprules and his co-workers (1980, 1986) showed that when the biomass size-spectrum was normalized as suggested by Platt and Denman (1978), the resulting curves appeared to be stable and characteristic of certain large bodies of water. Secondly, Dickie *et al.* (in press, a), showed that when the body-size relationships were resolved into two separate scales, one reflecting the physiological influence of metabolic rate and one reflecting the ecological influence of animal spacing in relation to food requirements, the resulting models would allow estimation of production with a precision not previously possible.

We seem once again to be poised at the edge of new practical perceptions of the factors controlling fisheries yields. The balance of factors in physiology and environment foreseen by Huntsman are there, even if in unexpected forms, and there is renewed interest in application to fisheries. It is too early to accurately gauge the extent of progress. A recent attempt to use the new methodology on the Great Lakes (Leach ***et al.,*** in press) shows that it gives better estimates of yield and its relation to fishing than is afforded by any other method. Dickie ***et al.*** (in press, b) have suggested how the same ideas can be used to begin a new methodology of assessment. These early results provide considerable encouragement for future research.

It is an adage of science that when a need for new scientific information is perceived, it is already too late to set about getting it. As if to prove a point, while the foregoing scientific development was taking place, the industry, as well as the general attitude that gave the initial impetus to the science, had undergone extreme vicissitudes, from new highs, followed by near economic disaster, to more recent recovery and a new sense of vitality. The chaos that concluded in the late seventies with the collapse of the management system embodied in the International Commission for the Northwest Atlantic Fisheries has however taught us serious lessons. Gone is the naive belief that a knowledge of the potential catch is sufficient to enable orderly industry development. The delays between plans and their results, coupled with many social and economic interactions, should be enough to convince us that we are dealing with complex systems that exhibit their own special behaviour (Allen and McGlade, 1986). Management information required in the modern context consists of a combination of long-term and short-term projections and a sensitivity to exchange of information and objectives that was not dreamt of 25 years ago. What is most encouraging about the present situation is that the sophistication of the science at both the production and control system levels has kept pace with that of its potential "clients". At the present time, industry and science appear to be in a position to undertake joint development of management information, confident that on the scientific side, the models have been tested in ecological theory to an extent exceeding anything that has gone before. It remains to be seen whether this is a strong enough base from which each aspect of the management system can bear its rightful order of responsibility for foresight.

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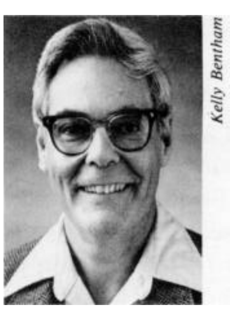
A history of ocean moorings at BIO

Clive Mason

R & D to the point of basic invention constitutes but a relatively short distance along that long and hazardous path, from concept to market place, which we call the innovative process.

Pierre L. Bourgault (1972)



Clive Mason.

DURING the winter of 1985/86, the joint Canadian Atlantic Storms Program was carried out. As part of this interdisciplinary study, which involved AOL, AGC, the Atmospheric Environment Service (DOE), and several universities, an array of moored instruments was positioned on the Scotian Shelf. During the five-month long data-collection phase, we had in place strings of in situ current meters, bottom mounted tide gauges and wind speed sensors, and moored surface buoys to measure both winds and waves.

The replacement cost of the array was approximately $1.5 million; we lost $21,000 worth of equipment or 1.4%. During the experiment, data were not only recorded internally in the moored instruments, but much information was telemetered in near real time via satellite and HF radio link to a shore-based recording system and thence transferred to the BIO central computer for processing. We achieved recovery of usable data in excess of 80% of all possible measurements; by October 1986, the processing of the data sets gathered during CASP was complete and data of known accuracy and resolution were available for analysis (Anderson, 1986).

Since 1983, as part of our deep-sea program, we have deployed a total of 36 moorings for durations of one year or longer. The average current meter record now exceeds 100 days.

Scientific investigators have available a mature technology to design, deploy, recover, and process the data needed for their studies. Engineering specifications are prepared for each individual deployment, based on many years of recorded experience and many design tests. A quality control program ensures careful inspection of every component in a moored array against a known standard. A detailed description of our present procedures, including project planning, instrument check sheets and logs, mechanical design of moorings, and post-deployment performance review, is provided by Hartling (1986). Data processing is quick and efficient using well-proven automated data processing systems, and the processed data are added to the DFO archive within one or two years of being collected.

Development of a system to provide long term in-situ moored instrumentation services has been a continuous part of the Institute's program over the past 25 years, as it has been in every other major oceanographic institute throughout the world (Fig. 1). Technology exchange between institutes is often informal and results of the developments of BIO and elsewhere are most easily tracked by the record of accomplishments rather than formal reporting. However BIO has had a consistent and careful program to develop mooring technology and data processing and series of unpublished Institute reports exist that chronicle the innovations needed to accomplish a CASP experimental plan.

Table 1 summarizes the data days [number of days for which one current meter record is available] since 1963. During 1963, we added the first 715 days of current meter data to the BIO archive: by 1985 we had accumulated a total of 154,000 data days and today our annual rate of data acquisition is about 16 times that of 1963.

A review paper by Bohnecke (1955) described the variety of current meters and current measuring techniques in use 31 years ago. Reliable self-recording electronic instruments with automated data processing were unavailable then, and the stable of instruments was restricted to a few ingenious electromechanical devices that were difficult to use and unreliable. Long-term moorings were not possible and indeed the author cautioned at that time against the high cost of the technology and doubted whether many institutes could afford it.

By 1963 the future was clearer; BIO had a mooring program using internally recording instruments, which was based on earlier work by DFO's Biological Station in St. Andrew's, New Brunswick, and also by the Canadian Hydrographic Service's Tides and Currents group recently arrived at BIO from their previous headquarters in Ottawa (Farquarson and Longford, 1961). The first internally recording current meters had been acquired for Canadian east coast studies in 1957, and by 1963 they were used for BIO's annual surveys. Our program was restricted to continental shelf depths; the technology used at BIO for these shallow water moorings is described by Hugget and Dobson (1965) who report that, during a season, 15 to 19 meters were laid and each was recovered some 8 times; they noted that losses were "gratifyingly small". A recent re-examination of early mooring log books by D. Dobson at BIO has shown that, from 1958 through 1965, the average annual loss rate was 14% and the data recovery rate was 82% of all possible data days.

Up to 1963 no deep-water moorings had been attempted by BIO although the development and data acquisition from deep-water moored internally recording current meters was being actively pursued elsewhere. Richardson *et al.* (1963)

Table 1. Summary of current meter usage: 1963-1985.

Year	Total data days	Average days/record	Number of records	AAND	BRCN	HW	VACM	OTH
1963	715	17	41	0	0	32	0	9
1964	361	17	21	0	0	21	0	0
1965	785	13	60	0	32	28	0	0
1966	1442	24	60	0	38	22	0	0
1967	2761	29	93	0	51	42	0	0
1968	3346	30	108	0	43	50	0	15
1969	3023	29	102	0	46	53	0	3
1970	2658	20	127	0	53	70	0	4
1971	2518	24	101	1	65	32	0	3
1972	2219	28	77	0	43	34	0	0
1973	2706	32	83	20	41	15	0	7
1974	3245	35	91	69	13	4	2	3
1975	4673	52	89	70	17	2	0	0
1976	8311	76	109	81	24	3	0	1
1977	7647	94	81	71	9	0	1	0
1978	9827	94	104	100	0	0	4	0
1979	13463	97	138	134	0	0	4	0
1980	13214	125	105	102	0	0	3	0
1981	10439	91	114	106	0	0	6	2
1982	13466	111	121	121	0	0	0	0
1983	19949	160	124	114	0	0	10	0
1984	15821	97	162	154	0	0	7	1
1985	11280	101	112	111	0	0	0	1

NOTES:
(1) Total data days = 153,869.
(2) Total instrument deployments = 2223.
(3) Current Meter Types: AAND - Aanderaa, BRCN - Braincon, HW - Hydrostatenwerke, VACM - Vector Averaging Current Meter, and OTH - Other.

described an in situ current meter system consisting of recording meters and moored support buoys that could be left unattended at a deep sea location for extended times. They reviewed the fate of 106 such stations set out by the Woods Hole Oceanographic Institution; relatively few good records had been obtained, but the difficulties appeared remediable.

In 1964, BIO was requested to assist the Royal Canadian Air Force to obtain current data in deep water adjacent to the Scotian Shelf. Farquarson (1964) described planning for the first BIO deep moorings including a visit to WHOI to study their techniques. He discovered that the usable data obtained by Richardson and his colleagues in their earlier work amounted to 2% of the possible maximum, but concluded that the shallow water techniques used by BIO should be tested in deep water.

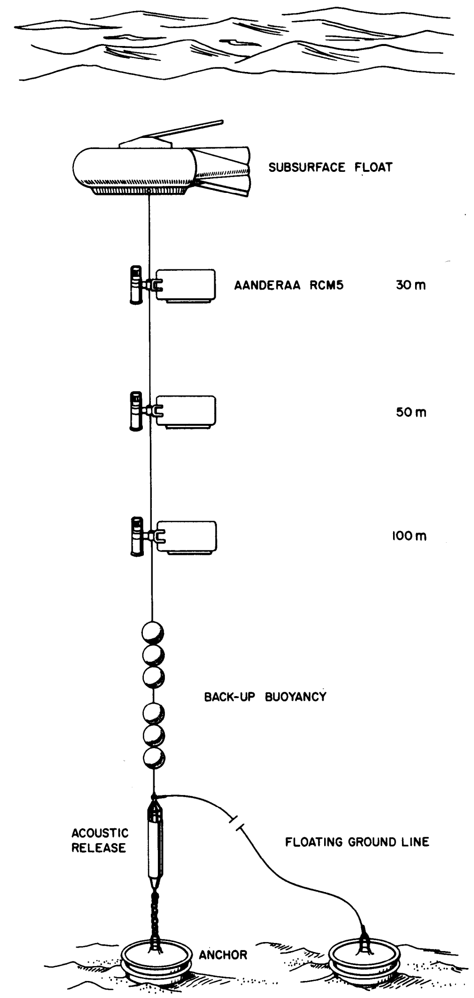
Farquarson (1965) described the deployment of 4 moorings in a line from the Scotian Self break to the edge of the Gulf Stream. The work was difficult and expensive in both materials and instruments: for instance a 6-km long ground line of buoyant synthetic rope was used to drag up the mooring on recovery [in place of the acoustic release used today]. Very few results were obtained from this program in which neither the current meters nor the mooring technology worked satisfactorily, and no further deep deployments were attempted for several years.

However, by 1969 the deployment of electromechanical meters that recorded data on photographic film was relatively routine in shelf depths and good results were obained as demonstrated against known tidal currents (Forrester, 1969). A BIO working group was set up to design a deep water mooring for use during the Hudson 70 expedition. 1970 was a highlight year for the current measuring program; in January, four deep water moorings were deployed in Drake passage in 3500-m depths for 11 days and 10 continuous records were obtained (Mann, 1971). This was followed in May by the deployment of a deep mooring under the Gulf Stream with the subsurface float at a depth of 3500 m; satellite navigation was used for the first time in the mooring program to reposition the ship to recover this mooring. During the Operation Oil emergency in Chedabuto Bay, 18 current meters were deployed in shallow water moorings (Neu, 1970) and good records were obtained despite the short time available to mobilize for the experiment. Also in 1970, two BIO scientists participated in the SCOR intercomparison of current meters (UNESCO, 1974) and, based on this experience, we selected the Bergen or Aanderaa current meter as the best prospect for our program.

The basic design for a BIO current meter mooring was determined during the next four years - the subsurface float, back-up buoyancy, anchor and parachute, acoustic release, and recording meter were selected and instruments of the same basic type are in use to-day; Figure 1 is a sketch of a typical BIO shallow current meter mooring. Of the 214 Aanderaa current meters purchased since 1970, 114 remain and we still have the first one purchased (only the end cap and serial number are unchanged).

By 1970 we could deploy moorings for up to 30 days; it took one week to process the record from each instrument and there was usually a delay of 12 to 18 months after the return of an expedition before the records were translated, digitized, and available for analyis. Further tests and trials by Keenan (1979) and Hartling (1978) have also disclosed previously unexpected errors in the performance and calibration of the instruments, and we have continued to investigate sources of error and to develop calibration techniques (Petrie, 1977; Smith *et al.*, 1978, 1984; Tang and Hartling, 1979; Keenan, 1981; Boyce, 1982). In 1986, record translation was accomplished in about 15 minutes and data were then immediately available for performance control before the next deployment of the same instrument. Within 6 months, all data are available for scientific analysis, and recording current meters routinely achieve a 90% data return except in some areas of active fishing.

This relatively mature technology has been gradually developed over the past 16 years by a process of performance review and calibration, engineering innovation, and software development. The most obvious obstacles overcome were the mechanical design of a reliable deep-water mooring (Fowler and Reiniger, 1981; Fowler ***et al.,*** 1985), and the development of guard buoys that could be handled by an oceanographic ship and served to warn off fishing vessels (Foote, 1985). However all the instruments and components used in the program have gone through a slow but continual process of evolution as design flaws were detected [such as crevice corrosion on acoustic release hooks] or more modern and reliable replacements for some parts became available [such as lithium cell batteries].



A typical BIO shallow water current meter mooring.

Table 2 summarizes mooring performance statistics since 1979 (Hartling, 1980-1987). Between 1970 and 1981, the

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Table 2. Mooring statistics.

Year (fiscal: April to end March)	78/79	79/80	80/81	81/82	82/83	83/84	84/85	85/86	86/87
Overall yearly loss rate (%)	—	21	9	16	6	1	6	8	1
Replacement value of losses during the year ($000)	304	390	221	480	155	19	208	198	21.3
Replacement value of equipment used ($000)	-	1857	1455	3000	2583	2414	3749	2564	2375
No. of recording instruments recovered	-	-	-	-	123	141	164	129	126
No. of moorings recovered after one year or more	-	-	-	0	10	12	14	14	14

number of moorings laid per year doubled and the operational period for a mooring increased to more than 6 times its 1970 level. There was an overall equipment loss rate of 13% [about the same rate encountered by Dobson, 10 years earlier]; however during the late seventies losses greatly increased and an additional engineer was assigned to assist the mooring development group. We have now reduced losses to less than 5% between 1983 through 1986 and in 1984 the three engineers who had lead the development group since 1969 received a Government of Canada Merit Award in recognition of their innovative work in mooring design. [The recipients - George Fowler, Robert Reiniger, and Albert Hartling - stressed the contribution of many coworkers, including ship's personnel, which their own reward highlighted.]

To collect the 11,000 days of records obtained in 1985 with 1963 technology would have required impossible resources even disregarding our lack of a deep-water mooring technology at that time. More than six times the amount of ship time used to-day would have been required - a minimum of an extra 50 ship days on station. Processing the data would have required years. The success at BIO and at other oceanographic institutes in the past 25 years in improving mooring technology is clear; the quiet but costly battle to achieve better long-term measurements continues as Institute staff along with engineers from the local private sector continue to adapt new technology for ocean applications. New challenges involve the design of measuring systems for use in the ice infested waters of an East Coast winter and in heavily fished areas where we have yet to obtain good data. The 50 year review of BIO's work will undoubtedly describe similar successes and the technology of 1987 will no doubt seem limited rather than extraordinary then.

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New thrusts in hydrographic technology

Adam J. Kerr

Adam Kerr.

Seafloor surveying

THE echo sounder was first introducted around 1930, yet, BIO hydrographers until quite recently continued to use the hand leadline for certain detailed surveys. Only in 1986 was a method finally introduced to speed up and improve the detailed surveying off wharves significantly. This has been brought about by the development and acquisition of the acoustic sweep system and its integration aboard the 35 m long catamaran F.C.G. *Smith.*

Although electronic positioning and echo sounding were regularly used on coastal and offshore surveys, the introduction of new technology into the very large-scale wharf survey was slow to materialize. Wharves were painstakingly measured off and a team in a dory with a hand leadline was carefully conned along range lines by keeping two poles in line or by a horizontally held sextant. The distance off the wharf was measured by a stretch-line, a length of marked rope or thin wire that was paid out as the dory moved away from the wharf; a sounding was plumbed as each mark passed over the wharf edge. This method was time consuming and, in poor weather, was probably inaccurate.

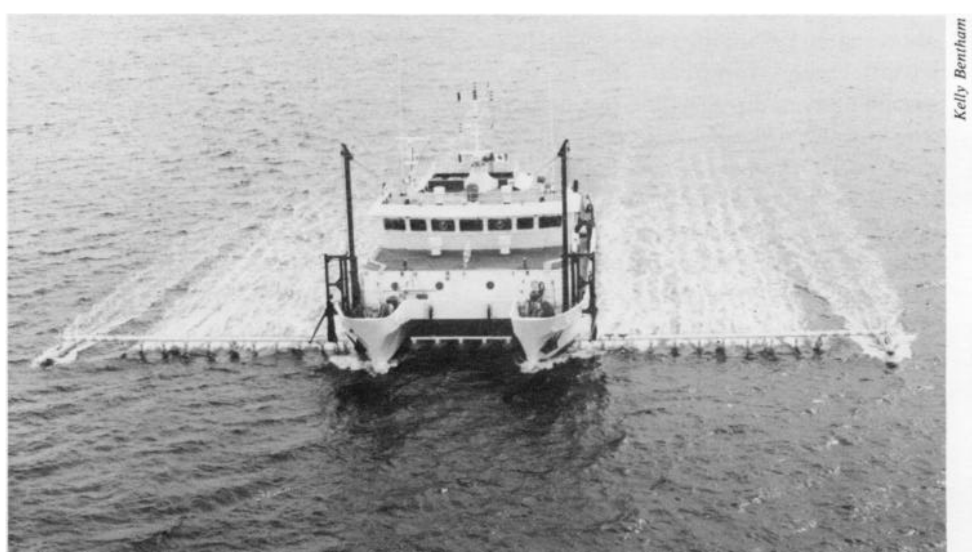
A step forward was taken when the subtense method was introduced in place of the stretch line. A specially painted board was lowered over the wharf edge and, by means of a sextant, the distance off the wharf was calculated from the subtended angle between marks on the board. Associated with this changing technology was the replacement of the leadline by an echo sounder and of the dory by a small outboard-motor-powered skiff. Nevertheless, all these methods did not provide total bottom coverage in these critical areas.

The acoustic beam sweep was introduced in this country in response to the TERMPOL code that was prepared by the departments of Transport and Environment to govern the conditions under which oil tanker berthing facilities could be operated, especially in the Arctic. It is a requirement that the approaches to such berths be completely swept to ensure that no obstructions are present.

Acoustic-beam sweeping technology, although new to Canada, had been introduced much earlier in Germany, where Krupp Atlas designed systems for use in rivers such as the Elbe and Weser, and also in Finland for use in lakes. Engineers with the Canadian Hydrographic Service initially developed the acoustic sweeping system to be portable for use in the Arctic and in 1984 demonstrated this possibility using electronics from Danish Navitronics and a specially made mechanical boom system.

The possibility of acquiring a small ship for deploying the sweep on a more permanent basis was suggested at this time and the Dartmouth firm of naval architects, Evans, Yeatman and Endal, proposed a catamaran design to meet the requirements. This led to the design and construction of F.C.G. *Smith,* which was commissioned on April 25, 1986. Equipped with a 29-transducer array that gives a swath coverage of *38* m, the vessel's sweep system can make in excess of 2 million depth measurements per hour. **A** state-of-the-art computer system and drafting plotter are carried on board to process and check the survey data prior to leaving the area.

On a trip to Scandinavia in the mid-sixties, Canadian hydrographers became convinced that the parallel sounding technique offered great possibilities for increased sounding productivity. Normally, a hydrographic survey is carried out by using a ship to run parallel sounding profiles in deeper offshore waters and by using launches, deployed from the ship, to independently sound the shallower water. The Swedish Hydrographic Office introduced the



F.C.G. Smith, *a hydrographic "sweep" vessel.*

concept of a parent ship with several smaller sounding boats in formation on each side of it. This system collected data in the form of a rake; small crews of one or two could be used on the side boats; and the positioning systems could be simplified.

At BIO, the concept was attempted on surveys of the Grand Banks using CSS *Baffin* as a master vessel and 9.45 m wooden launches as side boats. It soon became apparent that neither men nor machines were up to the sea conditions typical of the Atlantic coast of Canada. The Baltic was a far cry from the Grand Banks! A solution to the problem was proposed by the Metrology Group of AOL (DFO at BIO): use remote-controlled vehicles. Thus, in 1969 the Metrology Group acquired a small (4.25 m) fibreglass hull and equipped it with an engine, a towed transducer, and a radio control system.

Trials in the Bedford Basin proved successful and interesting! (The vehicle rammed a destroyer on one occasion and ended up 5 m above the shoreline on another due to extraneous signals on the radio control.) At sea, the vehicle maneuvered and collected data as planned except that in moderate seas it spent much time airborne and consequently lost power and steering.

Enthusiasm waned for a number of years following these experiments, but in 1980 discussions with International Submarine Engineering Research Ltd. of British Columbia led to the idea that a submerged remote-controlled body might do better. This was the genesis of DOLPHIN, a 7 m long torpedo-shaped vehicle that could be propelled through the water at 15 knots by a diesel engine.

Improvements in computers and radio systems have permitted a reliable and functional vehicle to be developed for parallel sounding. Trials to date have shown that the vehicle itself and its associated positioning and sounding systems are highly satisfactory. A specific problem is over the side handling system needed to allow the DOLPHIN to be launched and recovered in moderate seas (states 6-7). A system for this purpose has been developed, and may undergo refinement in the future.

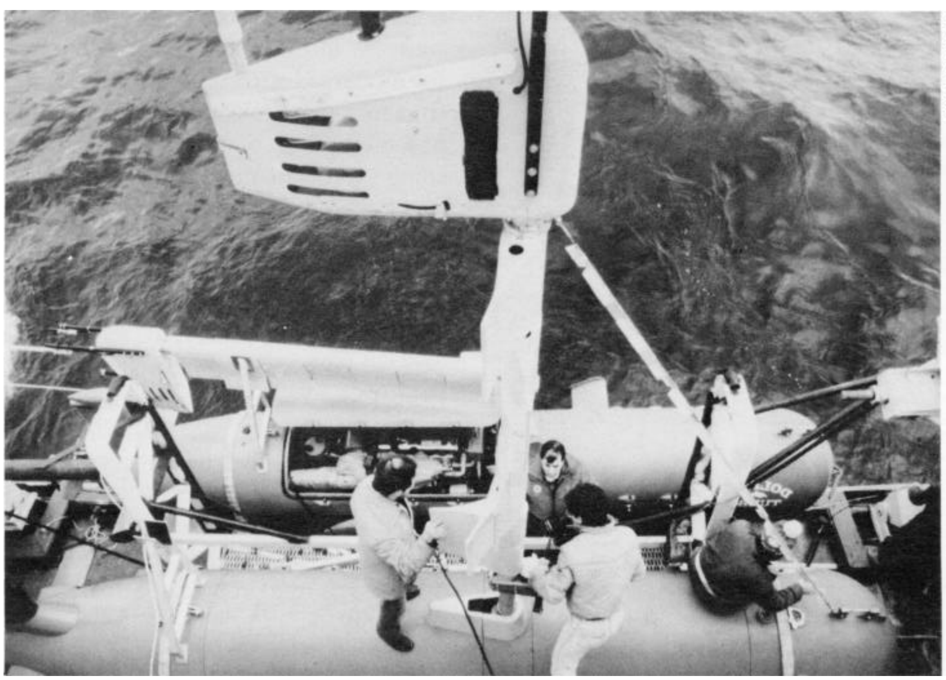
Electronic processing and presentation

The introduction of electronic data processing aboard survey and research ships took place during the sixties. Digital Equipment's PDP-8 computers were used as early as 1967 on the CSS *Hudson,* but 6 years before that a large flat-bed plotting unit with hard-wired controls was placed aboard ***CSS Baffin.*** This plotter was designed and built by Canadian Aviation Electronics (CAE) of Montreal and was a world first for a national hydrographic office. Unfortunately, the designers had not predicted the difficulties of working in the shipboard environment where motion and vibration are constant. Consequently the system never operated satisfactorily aboard ship and was later moved ashore where it was productively used for several years.

The possibility of achieving much faster incoming data rates from faster survey vehicles and the ability to operate under all weather conditions thanks to electronic positioning systems encouraged hydrographers to continue to investigate the use of the computer and other electronic data systems in the field. In 1968, the Hydrographic Automated Acquisition and Processing System (HAAPS), a hard-wired data logging unit that recorded survey data on punched paper tape, was designed and built at BIO. This development set the scene for a long line of advances in the data logging systems used aboard the Institute's ships and survey launches. Not all these developments took place at BIO; the various regions (Central, Pacific, etc.) of the Canadian Hydrographic Service also played major roles. In most cases, the prototypes developed by Canadian government personnel were taken up by private industry and manufactured. Today, the use of automated equipment by survey parties in the field is taken for granted.

Electronic data processing's impact on hydrographic work is most evident in the actual chart production processes. When the Institute was established in 1962, only hydrographic field survey activities were located there. Chart compilation and drafting remained a headquarters activity. In 1979 it was decided that the separation of the two functions was not efficient and most of chart production was moved from Ottawa to the regions.

Although computers had been introduced into chartmaking as early as 1965, it is only very recently that all new charts have been routinely digitized and


Kelly Bentham

Pre-dive checks aboard CSS Baffin before deploying two new turbo DOLPHINs.

drawn automatically. Even today, there are interruptions in the flow of digital data from the field to the chart, which will only be overcome when a complete digital data base is developed. At present this development work is a high priority in the Hydrographic Service. As the hydrographers have been in the field work, Canadian marine cartographers have been in the vanguard of introducing new technology for chart production. GOMADS (Graphical Online Manipulation and Display System) was developed internally by engineers and computer programmers. It is an interactive cartographic system that allows cartographers to digitize and edit data in preparation for drafting on precise automatic plotting units. GOMADS has been adopted by Universal Systems Ltd., which has produced the more sophisticated cartographic systems known as CARIS (Computer Assisted Resource Information System) I and II. These systems are not only in use in all regions of the Canadian Hydrographic Service but have been sold internationally and are used throughout Canada for all forms of mapping and more recently as geographical information systems. A CARIS system provides the basis for the Electronic Chart Test Bed discussed later. Marine cartographers, who in 1962 had not long given up the copperplate engraving tools in favour of plastic scribers, now find themselves in a new world where they must become familiar with digitizing tables and video display terminals.

In 1963, hydrographers in the Canadian Hydrographic Service were experimenting with the integration of radar displays with the paper chart. The concept of providing the navigator with a combined tactical display was a goal to simplify the decision-making process on a ship's bridge. Photographic images of the radar scope were observed aboard two of the BIO survey ships. The integration of these photographs on actual charts was never undertaken in Canada, although it was done elsewhere. The large number of variables in terms of target reflectance in response to target height and aspect, and the radar itself make the task difficult.

In 1984, the idea of an electronic chart was developed with the central objective of integrating radar and chart imagery. The information can now be presented on a video display instead of a paper chart and all the information can be handled in digital form. At BIO, the CHS Navigation Group has taken an active interest in the development of the electronic chart. It has been decided that certain aspects must be examined before the manufacture of electronic chart units proceeds too far. Particular matters to study include: the data base, updating the charts at sea, the format of the display, and the dynamics of the display in terms of presenting depths adjusted for tidal height instead of permanently reduced to the low-water datum as they are on paper charts.

Today, most BIO technical development is carried out under commercial contract. In the case of the electronic chart, Universal Systems Ltd. of Fredericton, has been hired to develop an electronic chart test bed on which the various concepts can be modelled. A particular requirement of the electronic chart is integration of the ship's radar imagery and an element of the process is therefore to convert the analogue-scanned radar data into digital form and then convert the polar co-ordinates to rectilinear ones. This work has been carried out under contract with a group at McGill University. The ship, using an electronic chart, must be precisely positioned so that the radar and chart imagery can be correlated. The satellite Global Positioning System (GPS) has been found most suitable for this, due to its high accuracy and independence from shore-based transmitters. Progress to date with the electronic chart test bed has demonstrated its feasibility, and Canada is at present a world leader in this technology.

Kelly Bentham

Preparing to hoist a survey launch onto CSS Baffin.

Survey launches

A word or two should be said about the hydrographic platforms. There is a very strong association between hydrographers and the ships and launches they use, nowhere more apparent than in the developing design of the latter. For many years hydrographers felt that seaworthiness and seakindliness were the sole requirements for their launches. While these parameters remain of prime importance it has now become recognized that the rate of data collection is directly related to operational speed when measuring depth profiles. Consequently in recent years there has been a determined drive to introduce launches that are at the same time seaworthy, seakindly, and speedy. This has not been easy.

The changing technology of positioning has also required changes in launch design. Horizontal sextant angle observation required the observers to be able to stand up and view the surrounding landmarks and then crouch into a sheltered place to plot their measurements. In rough weather the launch, both inside and out, streamed with water, a most unsuitable environment for modern electronic equipment. Even so, a reluctance to completely rely on the new methods in place of the old caused some inertia in moving to completely weatherproof launches. When BIO was established, survey launches were rugged wooden vessels, based on Cornish fishing vessels, capable of a maximum speed of 8 knots. Today, the most recent survey launches are constructed of fibreglass, kevlar, or aluminum and operate at speeds of 15 to 20 knots. Coxswains and hydrographers work in a 'shirt-sleeve environment'. Although increased speed must inevitably result in a rough ride in higher sea states, the new vessels remain both seaworthy and seakindly.

Progress ahead

Like much else in this world, the growth of hydrographic technology has been exponential rather than linear. Historically, hydrographers can look back to the development of the chronometer in the middle of the eighteenth century, the introduction of the echo sounder in the twenties, and the introduction of electronic positioning systems, such as Loran and Decca, in the fifties. It has been since computers really came on the scene in the early sixties that hydrographic technology has leapt forward. Computers have application in everything from sonar systems to vessel designs. Without them it would be impossible to process the mass of data that can be collected by modern acoustic swath systems or to model the infinite parameters that control a survey launch design.

The growth of technology is increasing. At this moment, hydrographers are introducing LARSEN, a scanning laser that will measure depths from a low flying aircraft. Foremost in the priorities is the development of a data management system that will take care of the huge quantities of data that can now be collected and to provide the information through systems such as the electronic chart that satisfy the needs of everyone who does business on the sea, be they fishermen, oil companies, or the transporters of cargoes or warships.

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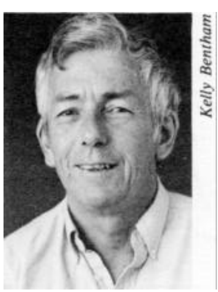
Twenty-five years of seafloor spreading

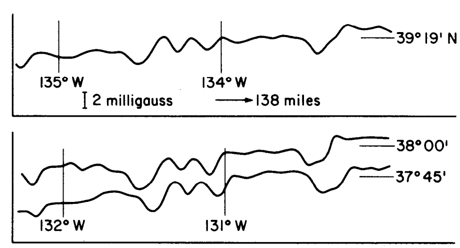
Michael J. Keen



Mike Keen.

CREATION of ocean floor at mid-ocean ridges and its destruction at trenches were proposed by Hess in 1962, the same year that BIO was founded (Hess, 1962; see Bullard, 1975). The following year the linear magnetic anomalies observed across ocean basins were explained as arising from the remnant magnetization of newly created sea floor solidifying in the earth’s reversing magnetic field (Vine and Matthews, 1963). The offsets of these anomalies at fracture zones such as the Mendocino Escarpment in the Pacific (Fig. 1) were explained in terms of transform faults by Tuzo Wilson in 1965 (Wilson, 1965a), and the sense of motion along these faults that he predicted, a sense contrary to the conventional wisdom (Fig. 2), was confirmed in a rather rigorous test using earthquake focal mechanisms by Sykes (1967). Plate tectonics, the hypothesis that the outer parts of the whole earth behave as rigid plates rotating on a sphere, was formulated by McKenzie and Parker (1967) and Morgan (1968), and was in a sense an offshoot of Bullard, Everett and Smith’s reconstruction of the continents by computer (Bullard *et al.*, 1965).

BIO was founded when the earth sciences were clearly in a state of revolution (Fig. 3). Geologists and geophysicists at the Institute and in institutions such as Dalhousie University tested and refined the new paradigm, investigating its depths, and applying it in their studies of the continental margin off eastern and Arctic Canada and the contiguous ocean basins. These investigations had surprising impacts on the



I. One of the early marine geophysical problems solved by the concepts of seafloor spreading and transform faults. The figure shows profiles of the earth’s magnetic field on both sides of the Pioneer Ridge Fault in the Pacific Ocean, the ship’s track parallel to the line of the fault. The match between the profiles when displaced 138 nautical miles is clear. The original caption read; “. . . showing left lateral slip of I38 nautical miles”. We now realize that the slip is in fact due to initial offset of the mid-ocean ridge at a transform fault. See Fig. 2. The original figure comes from Vacquier (1959, Fig. I).

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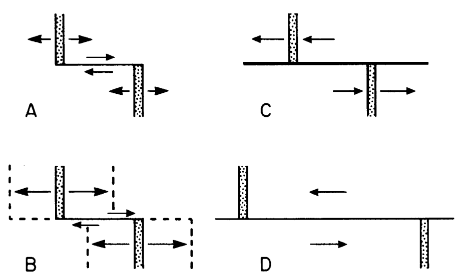
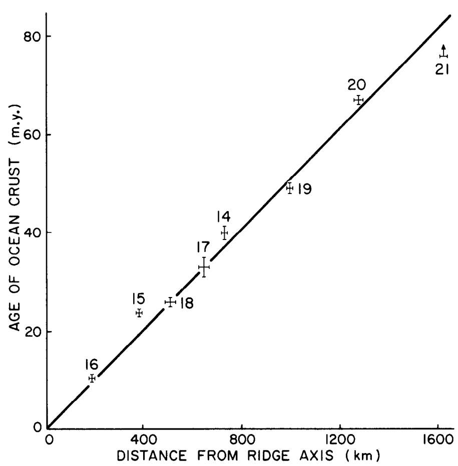


2. Tuzo Wilson's concept of transform faults explained the offset seen in Fig. 1. New ocean floor is created at mid-ocean ridges, and successively magnetized in opposite directions as the earth's field reverses from time to time. This creates the anomalies. Offsets of mid-ocean ridges are traced by the anomalies. The original caption read: "(a) Dextral ridge-ridge type transform fault connecting two expanding ridges. (b) Fault shown in I (a) after a period of movement. Note that motion has not changed the apparent offset. (c) Sinistral transcurrent fault offsetting a ridge, with offset in the same sense, but motion in the opposite sense to the transform fault in l(a). (d) Fault shown in I(c) after a period of motion. Note that the offset has increased. Open-headed arrows indicate components of shearing motion. Solid-headed arrows indicate ocean floor spreading from the ridge axis. " (a) and (b) explain the situation of Fig. 1. From Wilson (1965b, Fig. I).

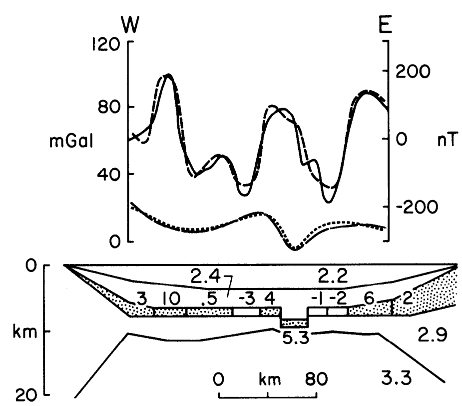
development of marine geology and geophysics in Canada which in turn influenced studies of geology on land.

Loncarevic led a number of expeditions to the Mid-Atlantic Ridge to test the new paradigm of plate tectonics and seafloor spreading, and attracted the interest of a variety of people in the rocks of the ocean basins (see e.g., Aumento et al., 1975; Keen, 1983). This led to creative work with the Deep Sea Drilling Project, as on its Leg 37 on mid-Atlantic ocean crust, and to land-based drilling programs in a variety of environments, in the Azores, Iceland, and Cyprus, on crust with oceanic affinities. Loncarevic and his colleagues developed new ways of surveying and sampling. They used radar transponders on moored buoys to provide precise positioning prior to satellite navigation and the Global Positioning System; navigation is described in the article in this Review by Grant and McKeown. They developed the BIO rock core drill and this was subsequently used to map the continental shelf off eastern Canada. The drill was used in 1986 to obtain extraordinary cores of metal sulphides from mineralized mounds on the active Juan de Fuca Ridge off British Columbia (Ryall, in press). Irving showed how reactive seawater is to the chemical and remnant magnetic properties of volcanic rocks newly formed at mid-ocean ridges, and Aumento recognized that seawater-rock interactions were mutually important to seawater and rock chemistry (see Aumento *et al.,* 1975). Chemical oceanographers had underestimated the influence of the ocean crust in their studies of ocean chemistry; geologists recognized that ocean chemistry is controlled by the complete recycling of the world's ocean water through the fractured ocean crust once every ten million years or so. Hall at Dalhousie proceeded from the work with Loncarevic on the Mid-Atlantic Ridge to drill the old ocean crust on the island of Cyprus; this program elucidated some of the processes controlling the formation of metal sulphides in volcanic rocks, and so was of great importance to economic geologists in Canada (Hall *et al.,* in press). Work begun as a focussed investigation of a relatively small area of the Mid-Atlantic Ridge had much wider impact.



3. The dramatic confirmation of seafloor spreading. Leg 3 of the Deep Sea Drilling Project drilled in the South Atlantic through sediments into the ocean crust beneath. If sediments are deposited on ocean crust immediately after the formation of the crust, then the age of the sediments, determined from their fossils, will give the age of the crust. The figure shows that the crust is systematically older away from the axis of the Mid-Atlantic Ridge. The original caption read: "Plot of age of sediment immediately above basement as a function of nearest distance to Ridge axis. "From Maxwell et al. *(1970, p. 463, Fig. 8).*

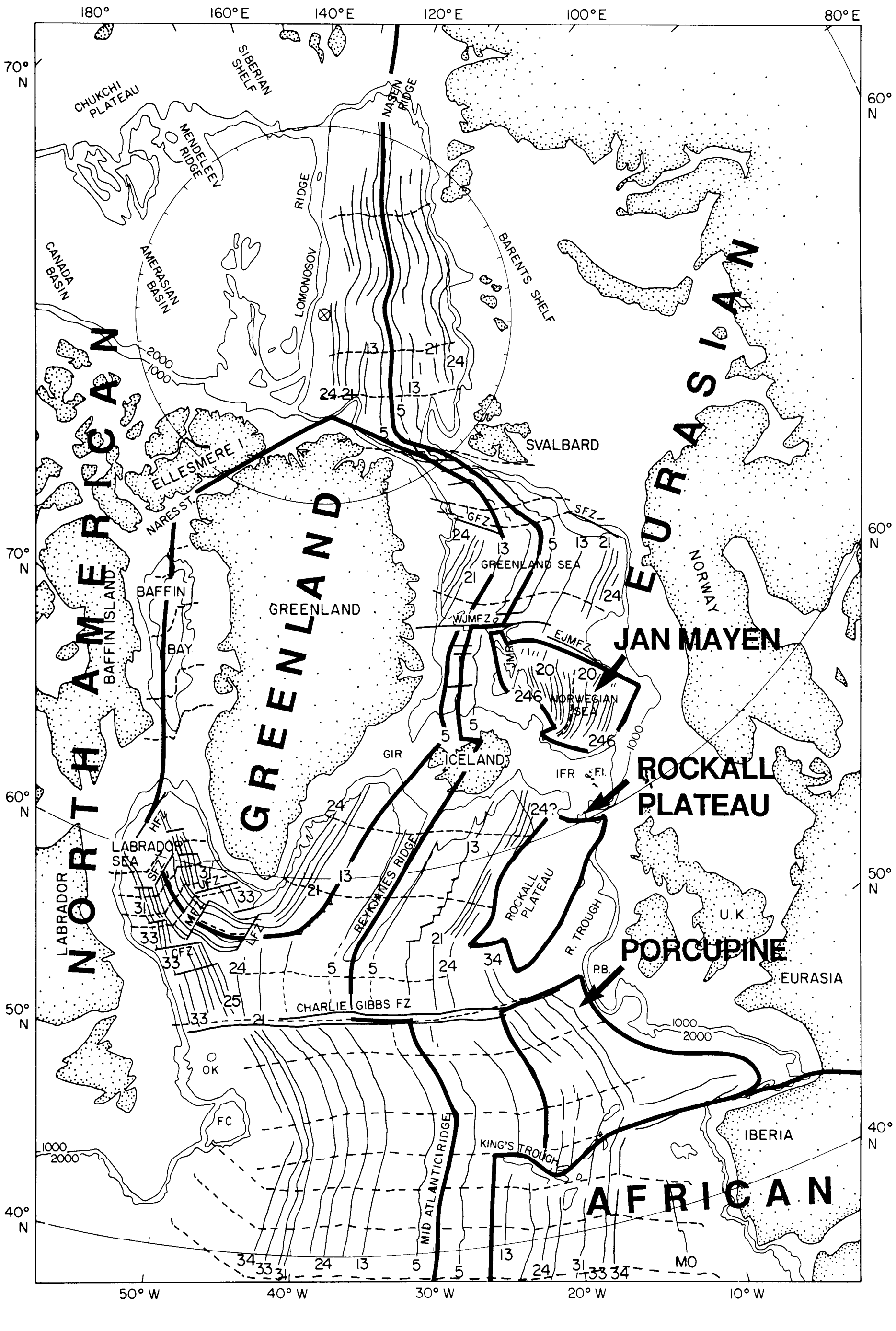
The opportunity was taken on the expedition HUDSON 70 to investigate the new ideas of plate tectonics in a variety of geological situations, and these were particularly informative in Baffin Bay (Fig. 4). The vessel CSS *Hudson* had set out to circumnavigate North and South America, and this led to important observations off the west coast, in the Beaufort Sea, and in Baffin Bay. Off British Columbia, the oceanic mantle was shown to be seismically anisotropic, with the maximum value of the compressional wave velocity in the direction of seafloor spreading (Keen and Barrett, 1971). The passage through Baffin Bay was particularly significant because in 1970 the Bay was practically unexplored geologically, and *Hudson* was the first vessel to investigate it with a more-or-less full panoply of geophysical equipment. Seismic reflection observations from CSS *Dawson* earlier in 1970 had shown that the sediment off Lancaster Sound was very thick, in



4. Model of the crust in Baffin Bay, based on gravity and magnetic data. The observed magnetic anomaly is shown as a solid line; the calculated anomaly is dashed. The observed gravity anomaly is shown as a dotted line; the calculated anomaly is an uneven dashed line. The large numbers are densities in g/cm³ The density of the magnetic source layer is 2.8 g/cm³. The smaller numbers are the magnetic intensities in A/m. From Jackson et al. *(1979, Fig. 9).*

agreement with the hypothesis of Fortier and Morley (1956) that the Arctic Island Channels represented Tertiary river channels that had been glacially over-deepened (Pelletier, 1966). The work from *Dawson* had also shown that the basalts off Disko Island, western Greenland, extended far offshore (Keen et *al.*, 1972). Work from *Hudson* showed that Baffin Bay is underlain by crust with an oceanic seismic structure, (Keen *et al.*, 1971). This led to plate-tectonic reconstructions of the Bay over the last 60 million years, with Greenland and Canada as adjacent plates. Central to the reconstructions in their simplest form was displacement along Nares Strait, one of Wegener's major faults in his original conception of continental drift. Geological evidence on land is inconclusive regarding the proposal for displacement, and the matter is still controversial (Dawes and Kerr, 1982).

Plate-tectonic reconstructions of the evolution of Baffin Bay are plagued by a lack of knowledge of the magnetic anomalies in the central part of the Bay. This is due to relatively poor navigation in early surveys, high magnetic diurnal variations, and the probable obliquity of spreading which will smear the magnetic signals. All reconstructions therefore depend heavily upon those for the surrounding oceanic regions: the Labrador Sea; Norwegian Sea; North Atlantic Ocean; and Arctic Ocean. The spreading histories of these regions, except for large parts of the Arctic Ocean, are now relatively well constrained by abundant magnetic anomaly data and the recent confirmation of the deductions from magnetic anomalies by drilling of the sediments and ocean crust in the Labrador Sea and the Atlantic Ocean (Laughton, 1972; Srivastava and Tapscott, 1986). The Atlantic Ocean off Nova Scotia opened about 160 million years ago; off the southeast margin of the Grand Banks, about 110 million years ago; off the Orphan Basin about 80 million years ago; and spreading started in the Labrador Sea about 70 million years ago (Fig. 5). This complicated history of opening is reflected in the oceanographic and tectonic events recorded in the rocks of the sedimentary basins of the margins and the oceans



5. Magnetic lineations and fracture zones in the North Atlantic Ocean, Labrador Sea, Norwegian-Greenland Sea, and Eurasian Basin. Also shown are 1000 m and 2000 m isobaths and flow lines (dotted lines). (Transverse mercator projection.) The bold lines outline the plates which were active during various stages of the evolution **of** *the entire region. Modified by S. Srivastava from Srivastava and Tapscott (1986, Fig. 1).*

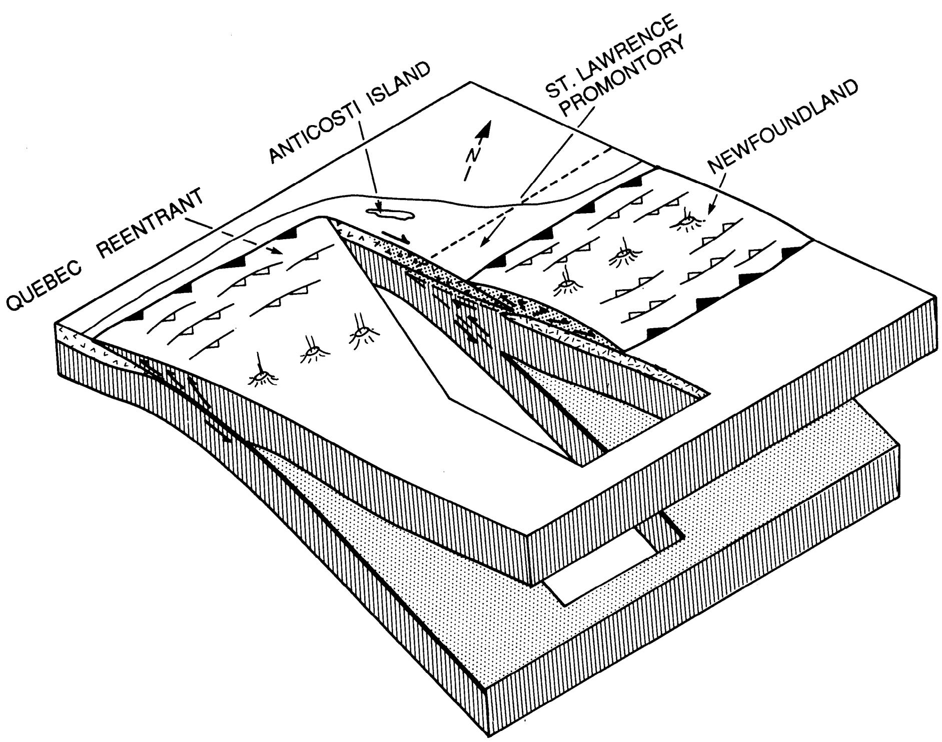
themselves.

This history cannot yet be understood as well as we would like for a variety of reasons, which include: the difficulty of tracing seismic reflectors across the continental slopes; problems of time scales; the gaps and ambiguities of the rock record; lack of suitable cores from exploratory wells; and structural complexities of the rocks of the sedimentary basins - for example, disruption of other sediments by salt unit flow. Nevertheless, a number of specific problems have been solved. For example, Gradstein and Srivastava (1980) showed that the Labrador Current is a relatively "recent" event of the last 10 million years in their study of the Labrador Sea and Baffin Bay using deep sea drilling and geophysical data.

Another example of this sort of problem is that of precisely dating the onset of seafloor spreading off Nova Scotia and the Grand Banks, because we will comprehend the evolution of the economically important sedimentary basins of those regions better if we can tie the record of the rocks in those basins to the spreading history. We cannot date the onset of seafloor spreading off Nova Scotia from magnetic anomalies because the ocean floor adjacent to the margin was created in one of the magnetic "Quiet Zones" of a time when reversals were rare, and so the magnetic time scale cannot be accurately applied. One approach to this problem is to date the onset of seafloor spreading by extrapolation from the relatively few ages obtained for ocean crust in deep sea drilling (e.g., see Sheridan, Gradstein *et al.*, 1983). Another approach is to argue that it is reasonable to relate the onset of seafloor spreading to the change, observed in the wells off Nova Scotia, from evaporites and elastic rocks typical of a "rift" environment to marine carbonates typical of a more-or-less open ocean (Jansa and Wade, 1975). This change, called the "breakup" unconformity, is recognized from many passive margins of the present ocean basins, and is beginning to be recognized from the record of former passive margins (H. Williams and C.E. Keen, personal communication, 1987). These different approaches may not always be consistent for a variety of reasons - the association of marine conditions with the onset of seafloor spreading will not always be appropriate, and the time scales used to date the different phenomena may be in conflict.

The time scales determined for the stratigraphic sections in the exploration wells are established on the basis of non-recurring events in the record of fossil fauna and flora, using groups such as foraminifera, ostracods, calpionellids and dinoflagellates. These time scales have to be tied to the magnetic time scale either directly by association with the fossil record in the ocean basins and the magnetic anomaly record, or indirectly through the world's type sections for the fauna and flora of interest and their links to the magnetic record through the "absolute" time scale. The absolute time scale is dependent on radiometric ages, which are still relatively rare. The recent time scale of the Geological Society of America (Kent and Gradstein, 1985) shows where its authors had no choice but to follow the practice of earlier workers on time scales by dividing a time interval arbitrarily into a number of equal increments. Uncertainties clearly arise.

The ideas of plate tectonics and seafloor spreading have been applied successfully to mountain ranges such as the Appalachians and the Cordillera of North America. Wilson (1966) showed that the Atlantic had opened and closed and opened again - the "Wilson" Cycle, discussed in Keen's article on sedimentary basins elsewhere in this Review. Plate tectonics has been adopted as a working model to explain the interactions between the geoloiical provinces of the world's Precambrian Shields (Gibb *et al.*, 1983; Hoffman, in press). In collisional regimes such as the Alps, Canadian Cordillera, Himalayas, and Appalachians, the plate tectonic paradigm must be modified because the plate boundaries are no longer rigid. Consequently, particular attention has been paid in the past 15 years or so to the mechanics of plate collision. If you slip a knife into flaky pastry, the individual flakes ride over and under the two surfaces of the knife blade, and in a similar way individual units of one plate may be transported over and under one another on collision, at all scales (Oxburgh, 1972; see also Price, 1986). Attention has also been paid to the effects of collision when the leading edges of the plates are irregular, with collision occurring at different times along the colliding margins. Both of these problems are central to current work at BIO because we have begun to investigate the collisional history of the Canadian Appalachians through seismic imaging with multi-channel seismic



6. Perspective sketch of proposed lithospheric plate geometry folowing Acadian orogeny. The cutaway, which is along the dextral wrench fault zone (stippled) between the Gaspe re-entrant and Newfoundland, reveals the collision in Newfoundland between the Grenville craton and the central lower-crustal block. The subducted North American plate is a continuous slab. From Stockmal et al. *(1987).*

reflection observations penetrating some 60 km into the earth (see e.g., Stockmal *et al.*, in press (Fig. 6)).

The discovery of plate tectonics and seafloor spreading changed the way earth scientists and indeed the general public viewed the world. In this respect, the new paradigm was to geology as Darwin's theory was to biology. Can we guess at comparable advances in the next decade? The new paradigm as it stands says little about driving forces. A geologist can use the principles to solve a particular geological problem with no concern for "what drives the plates?" Consequently the new advances are likely to be the solution to this last problem, perhaps confirming that plate motion is due to convection in the whole or in only the upper mantle. Investigations are well under way, and involve the technique of seismic tomography, in the same way that modern oceanographers use acoustic tomography in their studies of the oceans. Our own work already reflects the question. The initiation of rifting at an embryonic passive margin could be driven by active convection beneath the lithosphere at the site of rifting, or by stretching of the lithosphere by forces at sites quite remote from the rift zone (Keen, 1985). The new revolution will integrate a different set of phenomena from the set integrated by plate tectonics and seafloor spreading: it will no doubt relate to the igneous rocks and the earth's geochemical history, and so perhaps to the evolution of the earth's atmosphere and oceans, as well as to the evolution of its rocks.

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Marine oil contamination: From global pollutant to benthic food source

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Kelly Bentham

Eric Levy.

The early seventies: The era of major spills and environmental hysteria

ON a stormy night in February, 1970, the Liberian tanker Arrow ran aground in Chedabucto Bay, spilling most of its cargo of Bunker C fuel oil and eventually fouling much of the previously unspoiled Atlantic coastline of Nova Scotia. As a result, the fledgling Bedford Institute of Oceanography was suddenly plunged into its first major environmental crisis. With vivid memories of the *Torrey Canyon* incident in the English Channel, when primitive clean-up measures resulted in more environmental damage than the spill itself; the *Florida* spill on Cape Cod, which demonstrated the devastating and continuing impact on marine life of oil in the wrong place at the wrong time; and the Santa Barbara blowout and the extensive coverage on television of the suffering and loss of wildlife; much of the research at the Institute was placed in abeyance as scientists were commandeered to provide support to the Task Force set up to deal with the emergency. While marine biologists were enlisted to assess the impact of the spill on the living environment, physical oceanographers tried to predict its movement on and beneath the sea surface, geologists examined the disruption of beach processes, and a newly formed group of chemists undertook to quantify the amount of oil that was entering the water column. The need for data on the last of these, in particular, became urgent when droplets/particles of oil were observed throughout the water column in a stream 5 to 15 miles in width and extending southwestwards over the Scotian Shelf at least as far as Halifax and when oil was found in the intestines of copepods, presumably having been taken up during feeding. Thus, the spill clearly had serious implications for the fishery of the Scotian Shelf, because of its potential impact on marine life and the possibility for customer rejection of Canadian fish.

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The first step in dealing with this problem was to determine how much oil was actually entering the water column. Accordingly, several surveys were conducted to measure the concentration of oil in the waters of Chedabucto Bay and over the Scotian Shelf. To provide an estimate of the pre-spill background level, an exploratory survey of the waters of the Gulf of St. Lawrence, an area of similar oceanographic character but which was not affected by the spill, was also carried out. This work demonstrated that the concentration of oil in the water column over the Scotian Shelf had essentially returned to the pre-spill level within a year following the incident and suggested that the main source of dissolved/dispersed petroleum residues in the Gulf was the water that flows into the Gulf from the North Atlantic seaward of Cabot Strait and not, as had been presupposed, the water which

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enters from the St. Lawrence Estuary (Levy, 1972). Fortuitously, data were collected almost exactly at the site where the barge *Irving Whale* sank a few months later. For the first time anywhere, baseline data were available against which the impact of a marine accident could be assessed and it was evident, in this case, that the incident would have no serious environmental impact, a prediction which proved to be valid. Because there were few deterrents at that time to discharging oily wastes at sea, the stranding of oil on the shores of Atlantic Canada was common, and the Institute was frequently called upon to identify suspected sources. In particular, the appearance of oil on the beaches of Prince Edward Island inevitably resulted in an outcry that the *Irving Whale* was leaking and a major industry was facing ruin. Although this seemed to be an annual occurrence for several years, in every instance it was shown by analytical procedures developed at the Institute that the oil was from a source other than the sunken barge.

While the Institute was dealing with local problems, Heyerdahl (1971) reported having encountered high levels of pollution in the Atlantic Ocean during his crossing on *Ra II.*

> *On a daily survey we observe the shocking pollution of the ocean. Blobs of solidified oil - studded with hitch-hiking barnacles - turn up frequently, together with plas-*

tic bottles and other human refuse.
At times the water lies hidden
beneath soapy foam and oily
liquids shining in all colors.

Indeed, oil pollution was reported to have been so severe that there were only three days during the entire voyage when "black lumps of floating asphalt" were not observed. These highly publicized observations came just when it was realized that the populations of several species of birds were being drastically reduced by pesticides and when ever-present clouds of smog over many highly populated industrial regions provided a visible reminder of man's potential for environmental impact, and served to fuel the environmental movement of the early seventies. It was not long before hysteria that "the oceans are dying" supplanted the earlier concept of an "infinite ocean" with an unlimited capacity to assimilate the wastes of a rapidly growing world population and, at the same time, to provide food for the undernourished peoples of the world.

The age of reason: Environmental hysteria yields to scientific investigation

With the environmental "gloom and doom" of the early seventies thrust upon the Institute, several programs were initiated to address the question of pollution of the oceans by oil. Among the first of these was a chemical oceanographic investigation of the incidence and distribution of particulate oil residues (tarballs) floating on the North Atlantic, and for several years "oil tows" were a daily routine for all BIO research vessels. By 1974, sufficient data had been accumulated to demonstrate that the tar in the western North Atlantic was predominantly associated with the Sargasso Sea/Gulf Stream system and that regions to the north were essentially free from this form of oil contamination (Levy and Walton, 1976). Concurrently, regular cruises were carried out between 1971-1975 to examine the seasonal and spatial variations in the concentration of oil contamination in the North Atlantic between Halifax and Bermuda (Gordon *et al.,* 1974). Studies of the effects of oil on marine photosynthesis in natural phytoplankton assemblages and unialgal cultures indicated that photosynthetic productivity was significantly enhanced at very low oil concentrations but was impaired and eventually ceased at higher concentrations. Studies were also carried out of the concentrations of hydrocarbons in the waters over the continental shelf of Atlantic Canada and in the surficial sediments of the Scotian Shelf (Keizer *et al.,* 1978a). At the same time, a program to monitor the distribution of dissolved/dispersed petroleum residues in the Gulf of St. Lawrence was begun. Repeated surveys between 1970 and 1979 not only confirmed that the primary source of these substances in the Gulf is, indeed, the inflowing Atlantic water but also demonstrated that a definite decrease in their background level occurred during the early seventies and, by 1975, a steady state had been reached at approximately the same level as exists in the "pristine" waters of northern Canada (Levy, 1985). This decrease seemed to be a response to measures taken during the late sixties and early seventies to prohibit the direct discharge of oil into the Gulf and to control discharges on the high seas, and it clearly illustrated that the key to controlling an environmental problem of national concern may well lie outside a nation's immediate jurisdiction.

Meanwhile, as a consequence of the growing concern about the deterioration of the environment, the Stockholm Conference on the Human Environment in 1972 recommended that a program should be set up to monitor environmental pollution on a global scale and that the first step should be a pilot project to establish the framework for the large undertaking. Petroleum-derived oils were eventually selected as the pollutant of global concern that best suited the goals of such a project and, because of our experience in studying oil contamination in the Canadian context, BIO was requested to contribute the design and management of the project. This involvement grew over the next several years, and BIO eventually played a prominent role throughout the operational phase, the interpretation of the results, and the publication of the findings (Levy, 1984). Between 1975 and 1978, data were obtained from almost 100,000 visual observations of floating slicks, more than 5000 collections of tar balls, 3000 samples of water from a depth of 1 m, and 3500 collections of tar stranded on beaches. Despite the problems inherent in such a multinational study, the results demonstrated that surface slicks and floating tar were most prevalent near the major tanker routes, while broad expanses of the world ocean were relatively free from such contamination. Thus, the data from this project, as well as our own, refuted Heyerdahl's proclamations about the degree of oil pollution of the North Atlantic . . . . evidently *Ra II* remained in an abnormally polluted parcel of water as both were carried across the North Atlantic by the Canary Current/North Equatorial Current system. Indeed, the papyrus from which it was constructed might even have served as an effective scavenger for gathering floating tarballs! The project also indicated that dissolved/dispersed petroleum residues at concentrations in the microgram-per-litre range were present in surface waters almost everywhere, even in the most remote areas of the ocean. This widespread occurrence implies a diffuse source for this form of oil contamination and, therefore, that long-range atmospheric transport and deposition processes are involved.

Ecological and biological studies of oil pollution at BIO also began with the Arrow spill, when investigations at the spill site showed extensive mortality of intertidal biota, and have since evolved into investigations of the response of individual marine organisms, populations, and ecosystems to exposure to oil at both lethal and sublethal concentrations and of the rates at which recovery takes place. With oil from the Arrow still visible on the shores of Chedabucto Bay four years following the spill, a program was undertaken to determine its long-term persistence and impact on the marine environment. Following a survey of the amounts of oil remaining in the inter- and subtidal sediments (Keizer *et al.,* 1978 b), studies of the movement and chemical and microbial alterations of the oil residues in the intertidal zone indicated that beach-bound oil tends to remain as long-term reservoirs from which contaminants can be returned to

Roger Belanger

Doug Loring and Martin Thomas observe an oiled bird on the shores of Chedabucto Bay, after the Arrow *oil spill.*

the overlying waters. Deposit-feeding polychaetes from oiled sediments seem to play a significant role in the natural degradation of the oil (Gordon et ***al.***, 1978). The tissues of soft-shelled clams from these sediments invariably showed similar hydrocarbon patterns, and populations showed disruptions of growth and abnormalities in their young to adult ratios (Gilfillan and Vandermeulen, 1978). Bivalves do not possess the inducible mixed function oxidase (MFO) system and, therefore, can only slowly rid themselves of oil contamination (Vandermeulen and Penrose, 1978).

Concurrently with this biological work, studies of the incidence and distribution of petroleum residues in Canadian waters continued in an attempt to assemble a mosaic of the background levels of dissolved/dispersed petroleum residues in the waters throughout the Atlantic and Arctic regions of Eastern Canada. These data would serve as the baseline for evaluating the impact of future accidental spills and of offshore exploration activities; they are now available for the entire east coast of Canada including Baffin Bay, Hudson Strait, Foxe Basin and Labrador shelf areas, the Grand Banks, and the Scotian Shelf (Levy, 1986). Studies of the background levels of petroleum residues in the Arctic took an interesting turn when an oil slick discovered off Baffin Island in 1976 was shown to be partially weathered crude oil. Under the circumstances, natural seepage of oil from the seabed seemed to be the only reasonable source for the oil. Subsequent measurements of the distribution of volatile hydrocarbons and petroleum residues in the water column and in the surficial bottom sediments provided further evidence that the source of the oil was, indeed, natural seepage and indicated the site from which it was escaping from the sea floor (MacLean *et al.*, 1981). Complementary geological and geophysical studies indicated that the oil was migrating from the underlying sedimentary rock along the contact with the Precambrian basement. Direct visual examination of the seabed using the research submersible, *Pisces IV*, located what were thought to be pockmarks (sedimentary features formed by gas seepage). Methane, other low molecular weight hydrocarbons, and hydrogen sulfide were collected as they escaped from the sea floor (Grant ***et al.***, 1986). Experiments were also carried out to determine the time required for the oil to ascend to the sea surface and thereby provide an estimate of the degree of weathering that might occur in the water column. Most importantly, a sample of liquid oil was recovered from a specimen of rock collected from the seafloor, and its analysis resolved any remaining doubt about the origin of surface slick. In addition, growths of "white slime" present on the seafloor around the seeps were shown to be *Beggiatoa* (the organism responsible for chemosynthesis at hydrothermal vents in the deep ocean and giving rise there to extraordinarily prolific communities of benthic organisms that are totally independent of photosynthetic primary production) and other bacteria capable of degrading hydrocarbons. Since all the components for chemosynthesis are present at Scott Inlet, it has been postulated that chemosynthetic productivity may account for a significant portion of the total annual productivity in that area. Noting the striking correspondence between areas of known oil and gas seepage and commercial fishing grounds, it seems that the flow of energy from natural seepage may actually represent an important positive contribution to fisheries.

Starting with the request to assist with the Arrow crisis, BIO has had a long history of providing scientific support to

Heinz Wiele

Following the Kurdistan *accident, a scientist works his way to the edge of an ice floe in Chedabucto Bay to collect a water and oil sample.*

Home

the Department of Transport in dealing with oil spills, the major effort being our response to the *Kurdistan* spill when most of the coastline of Nova Scotia and portions' of the south coast of Newfoundland were polluted with oil. In addition to modelling the movement of the oil, a two-year program was carried out to identify the origin and to monitor the distribution and movement of oil on the Scotian Shelf and to identify the source of oil stranded on the coast. These data were an important component of the litigation to recover several millions of dollars in clean-up costs from the owners of the tanker. There were many occasions when seabirds were contaminated with oil, and the miniscule amount required to bring about the bird's demise under the high-stress conditions of winter on the North Atlantic provided a stark indication of the disastrous impact that a spill could have on colonial seabirds if a spill should occur during exploration, production, or transport of oil and gas in the arctic. Because of its experience in dealing with major oil spills, BIO was invited to assist in the scientific aspects of the *Amoco Cadiz* spill in France in 1978. As a consequence, several studies of the physical interaction of oil with sandy beaches and the effects of clean-up procedures have been carried out.

The discovery of gas and condensate on the Scotian Shelf and of crude oil on the Grand Banks presented a new dimension to the threat to the Atlantic coastal environment from oil. Although previous experience indicated that even the volatile low-molecular weight components of crude oil may persist much longer than predicted from thermodynamic models, a study of the chemical changes in condensate stranded on a low-energy sandy beach on the eastern shore of Nova Scotia confirmed that the normally volatile/soluble components of the condensate can linger with little chemical change for many months, even years (Strain, 1986). Subsequent work has shown that the controlling factor is the rate of degradation by micro-organisms, the sequence of events being an initial toxic response in which micro-organisms are destroyed by the condensate, followed by an increase in the numbers of bacteria that utilize the carbon released by the die-off of susceptible organisms, and eventually an increase in the numbers of oil-degrading bacteria. The rate of degradation then becomes limited by the supply inorganic nutrients but, accordingly, the overall rate of degradation can be considerably enhanced at this stage through periodic replenishment of the nutrients.

The bioavailability of oil-derived hydrocarbons has been studied using the English sole, *Parophrys vetulis,* and the brook trout, *Salvelinus fontinalis.* In the latter, MFO induction was greater with Bunker C than with diesel oil and occurred after a threshold concentration of hydrocarbons in the tissue was exceeded. Studies of hydrocarbon-induced stress in fish are presently underway with larval and juvenile Atlantic salmon that are under simultaneous stresses from rapid growth and passage from fresh to salt water. Other studies of sublethal effects have included alterations in the grazing patterns of copepods on exposure to naphthalene and crude oil and changes in respiration and the stability of the haemocyanin-oxygen binding capacity in the crab *Cancer irroratus* on exposure to Kuwait crude oil. A lack of mutagenetic activity of crude and refined oils on the unicellular algae *Chlamydomonas reinhardtii* and the toxic and mutagenic responses of oils and their water-soluble fractions have been compared (Vandermeulen *et al.,* 1985).

Future challenge: Can hydrocarbons have a beneficial effect on marine ecosystems?

Although the adverse impact of oil on marine life has been amply demonstrated by laboratory experiments, the extrapolation of such observations to the 'real world' has been tenuous, and attempts in the past to measure the effects of oil at sublethal concentrations on the living resources of the marine environment have been inconclusive, at best. While this is an extremely difficult task because of the variability normal in these resources, it is no longer acceptable to assume that these effects do not exist merely because they cannot be observed by the methods presently available or to evade the issue by assuming that the impact of oil would be insignificant in comparison with the natural fluctuations undergone by populations of marine organisms. The impact of oil on marine organisms must be considered in terms of the additional incremental stress superimposed upon the stresses to which the individuals are already subjected. This concept must then be extended to the population level and considered in terms of the cumulative effect of the additional stress on an already stressed system with a limited capacity to tolerate stress. On the other hand, there is growing evidence that where an ecosystem has had ample opportunity to adapt, such as in areas of natural seepage, hydrocarbons may represent an important factor in the overall benthic productivity and in the production of commercial shellfish and other species. While this effect of hydrocarbons on marine environments is still in the realm of speculation, it nevertheless offers a challenging area for research.

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Energy dissipation and advances in the study of microstructure in the ocean

Neil S. Oakey

Neil Oakey.

ENERGY dissipation is the expression used to describe the conversion of kinetic energy into heat. Because energy is conserved, it is interesting for a moment to examine where it ultimately originated. The sun is the major source of energy, driving our weather systems and generating the winds that create waves and currents and drive the ocean. A part of the balance for this continual input of energy from the sun is provided by viscous friction, which dissipates energy. Another source of energy is evident in the large tides created by the gravitational attraction of the moon on the waters of our oceans. As these tides move across our continental shelves, a great deal of energy is dissipated at the bottom by viscous friction. Energy is thus transferred from the orbital velocity of the moon to the tides whence it is dissipated. The moon should therefore slowly get closer to the earth!

From the oceanographer's perspective, energy dissipation is a measurable quantity of turbulent mixing processes. If one can measure all of the energy being dissipated into heat at a certain place and time and if one assumes that it is equal to the energy being provided to the turbulent field by external forcing (as in the two examples mentioned above) then the rate at which energy is being dissipated may be used to infer some mixing parameters.

These parameters may help us to estimate, for instance, the rate at which nutrients are mixed vertically in the water column as a result of turbulence generated by the tides. They may help us to understand the homogenization of water from two different sources with very different temperatures, salinities, and nutrient concentrations. In the discussion that follows, the terms dissipation and turbulence will be used to some extent interchangeably as turbulence provides the framework in which dissipation can occur through viscous friction. Where there is a mean temperature gradient, turbulence causes small scale spatial fluctuations in temperature. Temperature microstructure is the term we use to describe this and, equivalently, velocity microstructure is used to describe the velocity fluctuations that we measure to estimate energy dissipation.

The "microstructure practitioner" is trying to measure hydrophysical fields to the smallest scales at which they vary and interpret these measurements in terms of physical processes. For the ocean this implies measuring temperature fluctuations of a few microdegrees over distances of a few millimetres and velocity fluctuations of the order of 0.1 mm/s over distances of less than 1 cm. These requirements have been met only by newly developed small and fast sensors and quiet vehicles that sample rapidly.

In this look at the evolution of our knowledge of small scale processes over the past 25 years, it is worthwhile to examine the status in 1962 by reviewing some of the most prominent journals at that time.

By the early sixties, a great deal of elegant theoretical work had been done by scientists in many countries in an effort to understand turbulence. Many of these studies were aimed at the understanding of phenomena in the atmosphere and in the ocean. In 1962, the *Journal of Geophysical Research* devoted a whole issue to summarizing the International Symposium on Fundamental Problems In Turbulence and Their Relation to Geophysics. The range of topics covered can be seen by some of the titles:

- "Some features of atmospheric turbulence", by A.M. Obukhov,
- "Structure of turbulence in stratified media", by R. Bolgiano, Jr.,
- "Some mathematical models generalizing the model of homogeneous

and isotropic turbulence", by A.M. Yaglom, and
- "Determination of the rate of dissipation of turbulent energy near the sea surface in the presence of waves", by R.W. Stewart and H.L. Grant.
In *Deep-Sea Research,* only one paper on ocean mixing by Eric Eriksson was found and it presented essentially a transport model with little or no discussion of the mechanisms of mixing. The *Journal of Fluid Mechanics* in 1962 contained several papers on the subject, including two on turbulent mixing and dissipation in a tidal channel on the west coast of Canada by R.W. Stewart, H.L. Grant, and A. Molliet. By 1962, much of the basic theoretical work on turbulence was in place as a starting point for later studies in the deeper ocean. There were sensors and instruments being developed and used for near surface studies of turbulent energy dissipation.

The late sixties and early seventies were the start of a very intensive period of measurement of microstructure and turbulence spurred on by the advent of new instruments and sensors. C.S. Cox and his students developed the first of a number of free-fall vehicles to measure temperature fluctuations of a few microdegrees to depths of 2 km and showed a wealth of a microstructure, that was believed to be caused by turbulent mixing. The vertical flux of heat and nutrients was estimated using very simplified equations of turbulence and the measured values of the intensity of the temperature fluctuations, which were parameterized using a Cox Number. The "wiggly line" gatherers, as those preoccupied with microstructure studies were often called, used the Cox Number approach to compare their results to large scale estimates from mean temperature profiles and geochemical sampling.

It was at this time that a program of microstructure studies was started at the Bedford Institute of Oceanography with the development by N.S. Oakey and J.A. Elliott of a profiler deployed on a heavy steel CTD cable. It measured temperature fluctuations using thin-film platinum thermometers and was used during the Denmark Strait Overflow experiment in 1973 and to make measurements in the mixed layer during the Global Atmospheric Research Project in the equatorial Atlantic (GATE experiment) in 1974.

A new and simple turbulence sensor for ocean velocity microstructure measurements was developed in the early seventies by T. Osborn and T. Siddon at the University of British Columbia. This type of sensor, a Shear Probe, became an integral part of most of the next generation of profilers developed at various laboratories. At BIO, a version of this sensor was designed and incorporated on one of the first tethered-free-fall vehicles, OCTUPROBE, developed during 1974 and 1975. There have been several similar vehicles built subsequently at various laboratories, but a brief description of OCTUPROBE summarizes most of the important features of all of them.

OCTUPROBE is a 2-m long by 0.15-m diameter vertically profiling *free-fall* vehicle, which sinks very "quietly" to a depth of 100 to 150m. It trails a loose *tether* line which is used to recover the instrument. With this *tethered-free-fall* vehicle one has the advantages of a low vibration free-fall vehicle with the further feature that one can quickly recover it to obtain many profiles closely spaced in time. Since all turbulent mixing processes occur intermittently, this feature allows many determinations and so helps us to calculate better average values. OCTUPROBE recorded its data internally; thus it was limited to about 25 to 30 minutes of profiling. Newer instruments use the tether line as a data link so they may be cycled continually over hours.

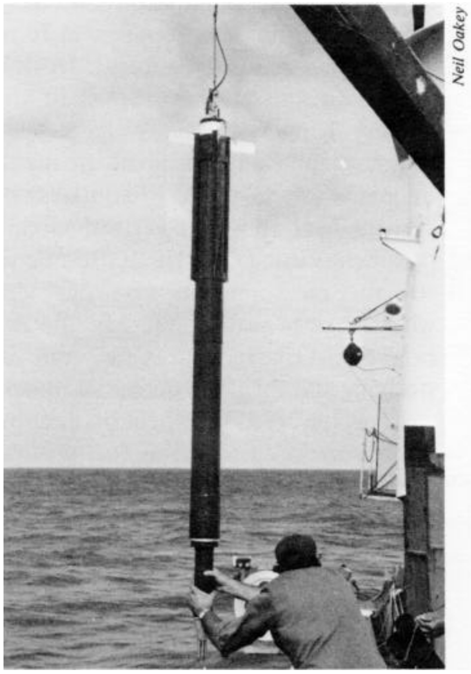
Using these new instruments and sensors, scientists made many interesting discoveries in the surface layer of the ocean. Oakey and Elliott in 1976 obtained turbulence profiles in the mixed layer on the Scotian Shelf over a period of 10 days and widely varying wind conditions. They found that the energy dissipation in the mixed layer was directly proportional to (and 1-2% of) the energy in the wind field. Most of the energy that entered the ocean from the wind field appeared to be dissipated, and little was used to deepen the mixed layer.

Many experiments have been done in various oceanic regimes to relate the physical processes at small scales to the large-scale features more conventionally studied. During the international Joint Air Sea Interaction experiment, JASIN, in the Rockall area northwest of the United Kingdom, many large-scale oceanographic and meteorologic measurements were made. Estimates of vertical heat flux and vertical mixing parameters using OCTUPROBE microstructure measurements were consistent with the large-scale studies. In another example, Osborn and Crawford, in studying the Pacific Equatorial undercurrent, observed turbulent dissipation levels associated with this feature that were large enough to balance the accelerating force of the pressure gradient driving the undercurrent. This is indeed an interesting speculation: an oceanic flow several thousand kilometres long that might be controlled by processes operating at scales of 1 cm!

In some early work, Batchelor (1959) implied that if one could measure completely the fluctuations in the temperature field one could infer the energy dissipation from the smallest scales of fluctuation observed. Techniques using these theoretical arguments were exploited 20 years later by Caldwell and Dillon at Oregon State University in studies of mixing processes in lakes. In 1982, Oakey showed that, at least in restricted circumstances, the results obtained by using temperature fluctuations were equivalent to those obtained from turbulent velocity studies.

The necessity of making large numbers of measurements to understand an intermittent process spawned the current generation of microstructure profilers, developed as new microcomputer technology became a cost effective option for on-line data logging and analysis. The most recent profilers are typified by the Advanced Microstructure Profiler (AMP) of Gregg at the University of Washington and by EPSONDE at the Bedford Institute of Oceanography. These instruments were developed in parallel and have many similarities: EPSONDE will be described.

EPSONDE is physically similar to OCTUPROBE and is deployed in a tethered-free-fall method. However, the tether line is a four-conductor kevlar cable used to send data to an onboard computer at a speed of 2000 data samples per second. This has expanded our capability to “see” in real time what we are measuring by performing on-line data processing using computers. It has allowed us to operate for long periods of time without instrument recovery and also to measure deeper in the ocean. This generation of instruments also contains many more sensors such as a CTD and we are exploring new ones such as light sensors and fluorometers for specific biological studies.



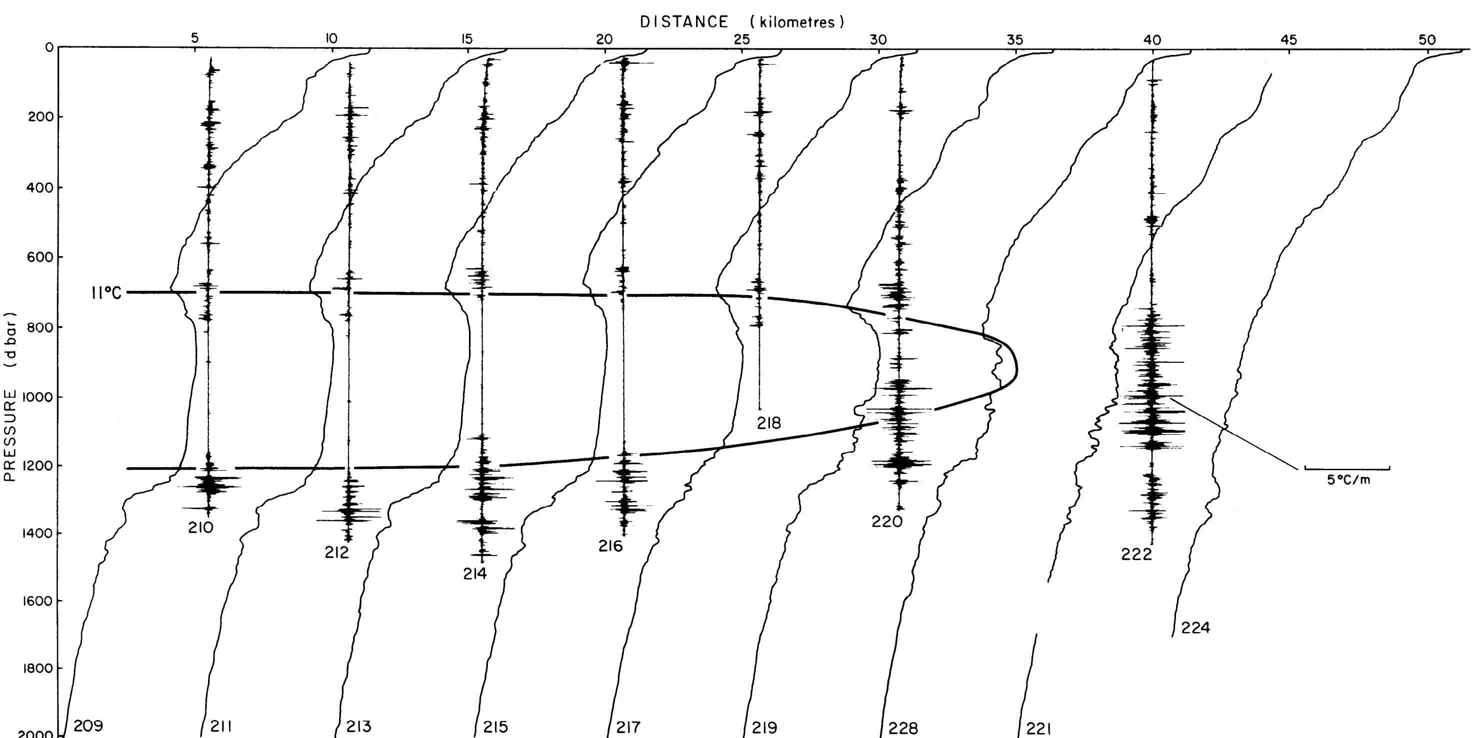
1. EPSONDE being deployed from the CSS Hudson during the MEDDY study, June 1985.

The two studies described below are good examples of the capability of the current technology.

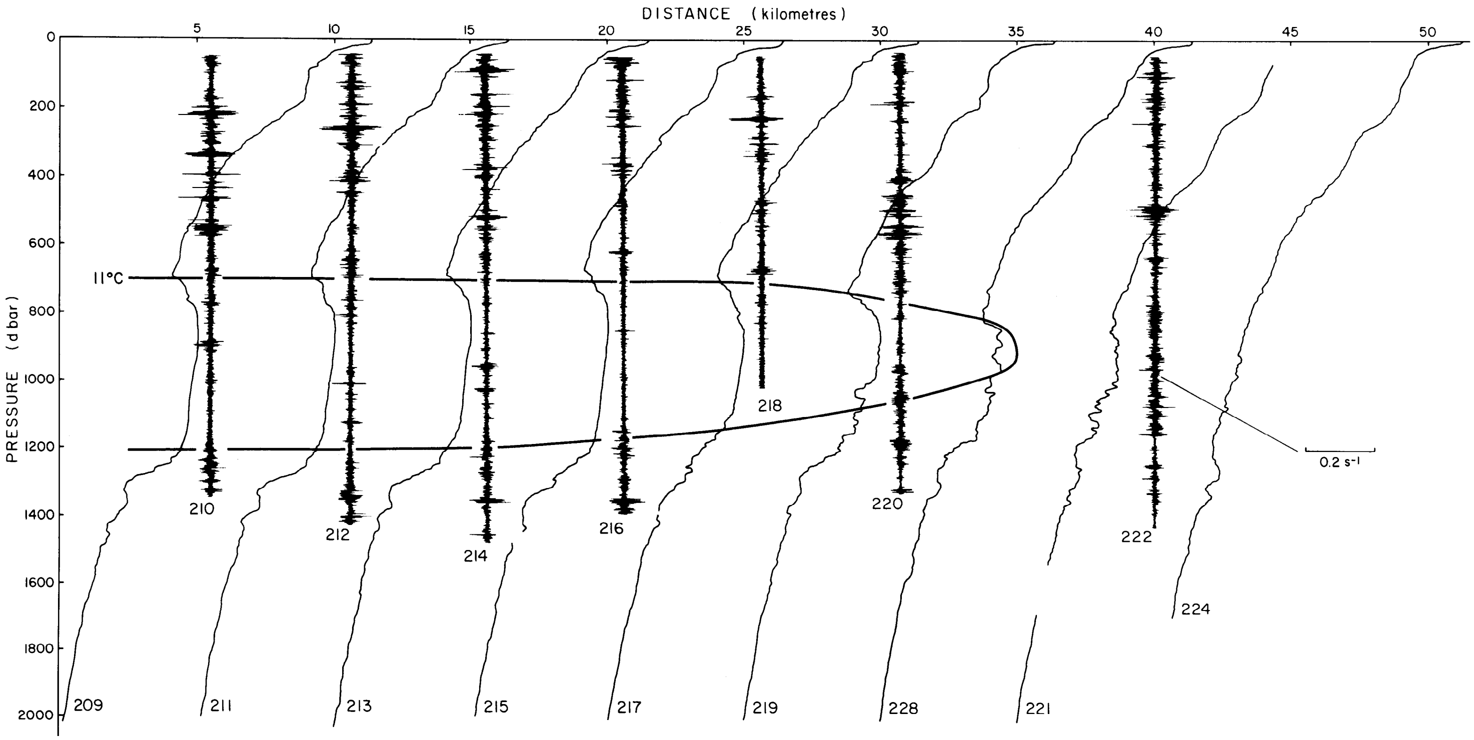
A reinvestigation of the turbulent mixing associated with the Pacific Equatorial undercurrent was done in the fall of 1984 during the Tropic Heat experiment by a number of investigators including a group led by Gregg of the University of Washington and using AMP. During a three week period, we obtained over 1700 profiles to 250 m in and near the undercurrent (over 1.5 billion words of data). These data showed dissipation levels lower than observed previously and a strong diurnal variation in the intensity of the turbulence. Turbulence was observed in relation to the strong velocity shear zones of the undercurrent, as expected.

In another experiment, Oakey used EPSONDE to study a Mediterranean Salt Lens (MEDDY) in the Canary Basin to find the rate at which energy is dissipated by turbulent processes. For the first time, a tethered-free-fall profiler was used to depths of greater 1000 m. In Fig. 1, EPSONDE is shown being deployed from the CSS *Hudson* during the experiment. From the large scale surveys over a period of 2 years, we know the rate at which this MEDDY is losing energy. The turbulent velocity and temperature fluctuations associated with this MEDDY are shown in Fig. 2 in a section from near the Centre of the lens to the edge. The intensity of the mixing is strongest near the periphery. It appears that energy dissipation at centimetre scales is an important contributor to the energy loss of this 100-km diameter feature.

We have not only tried to understand



*2.(a) Temperature microstructure section measured in a MEDDY using EPSONDE. The smooth profiles are temperature, the “wiggly” profiles are temperature microstructure, and the heavy line is a contour at 11°C indicating the edge **of** the MEDDY.*



2.(b) A velocity microstructure section in a MEDDY using EPSONDE. In this case the "wiggly" line is velocity microstructure and is used to calculate energy dissipation.

the role of microstructure in the physical mixing processes of the ocean but also some of the implications to biological productivity. In a study in the Bedford Basin, Nova Scotia, we simultaneously measured biological productivity and dissipation during the spring bloom. A strong inverse correlation between potential productivity and dissipation was observed. It was speculated that the larger the turbulence levels or dissipation, the less algal cells were able to photoadapt as they were moved up and down the water column by the turbulence.

In a study in the Canary Basin in June 1985, dissipation measurements obtained with EPSONDE were used to estimate the vertical eddy diffusivity and the corresponding vertical nitrate flux. At the same time, nitrogen flux was being estimated by measuring the biological uptake of nitrogen. Carbon dioxide from the atmosphere is incorporated with nitrogen in the ocean by photosynthetic production. It may thus be limited by the nitrate flux. The physical and biological estimates of production measured in this experiment were essentially in agreement and indicated that this oceanic region (representative of 75% of the world's oceans in this respect) may be much less capable of using carbon dioxide from the atmosphere than currently thought. This may have implications on the capability of the ocean to act as a sink for global carbon dioxide emissions.

In conclusion, the past 25 years have been important ones in the development of our understanding of small scale mixing processes in the ocean. I have referred to some and not necessarily the most important research in this area. We have developed new instruments and sensors and used new technology to study these intermittent processes. We have designed and executed experiments that are slowly giving us a clearer picture of turbulent mixing in the context of the larger scales of the ocean.

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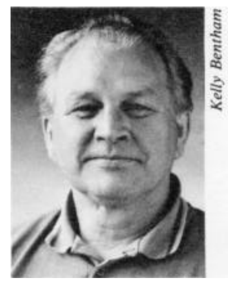
Shelf edge processes

Peter C. Smith and Helmut Sandstrom

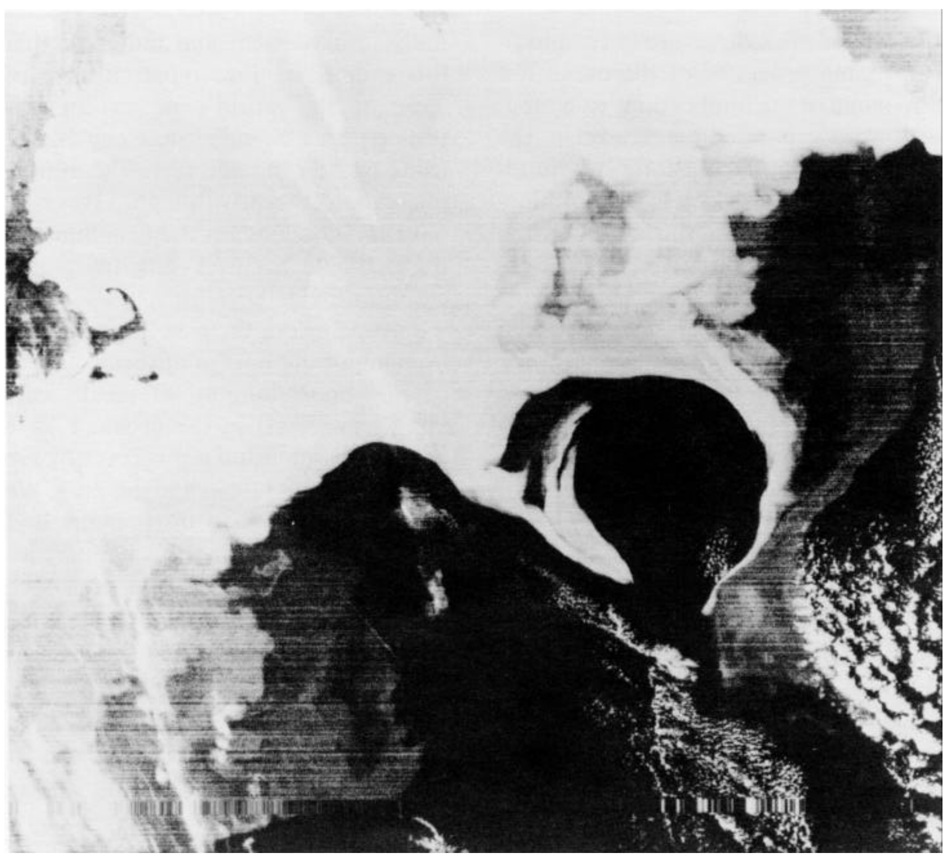
Peter Smith.



***Hal** Sandström.*

ABRUPT depth changes that characterize the edges of continental shelves lead to interesting and important physical processes in the ocean. The associated steep bottom slopes are responsible for guiding low-frequency currents along isobaths; for refracting, reflecting, and scattering various wave motions; and for promoting the upwelling of deep ocean waters to the shelf. On the western sides of major ocean basins, strong boundary currents, such as the Gulf Stream or Kuroshio, radiate low-frequency energy that impinges on but rarely crosses the continental margin because of vorticity constraints associated with the large change in depth.

Other important energy sources for shelf edge phenomena include the barotropic (surface) tide and surface wind stress. In addition, the reduced thermal capacity of shallow shelf seas relative to the deep ocean and the input of freshwater runoff to the shelf may lead to sharp contrasts between coastal and oceanic water masses at the shelf edge. These strong gradients, combined with energetic physical processes, generally lead to enhanced mixing and biological productivity. Off the southeastern coast of the United States, for instance, the upwelling of deep water at the shelf break caused by wind and eddy activity along the inshore edge of the Gulf Stream is considered to be the major source of nutrients to the shelf ecosystem (Atkinson *et al.*, 1982). Similarly, Fournier *et al.* (1977) suggest that shelf-break processes are responsible for the observed maxima of biological rates and standing stocks at the edge of the Scotian Shelf. Even in the absence of forcing by energetic offshore currents, as on the Northwest European Shelf, eddy activity associated with the shelf-break front may promote high rates of



1. Satellite infrared image showing interaction between warm core Gulf Stream ring (dark) and colder surface shelf water (light).

cross-shelf mixing (Pingree, 1979) while vertical mixing by internal waves injects nutrients into the euphotic zone.

In the following sections, attention will be focussed on studies of three different varieties of shelf edge processes: (a) the interaction of offshore currents and eddies with the topography of the continental margin; (b) wind-driven upwelling at the shelf break; and (c) the generation of internal tides and nonlinear waves by the M_2 surface tide.

Each section will give a brief account of the historical development of understanding of the particular phenomenon. For a shelf edge process, as in many areas of oceanographic research, advancement does not occur steadily but in spurts. The combination of many factors, such as technological change and new ideas, creates conditions for rapid progress followed by slower-paced periods of "firming up" of ideas. The past two decades have seen renewed worldwide interest and intensive research into shelf edge processes, and BIO has made significant contributions to the understanding of them.

Eddy interactions with the continental margin

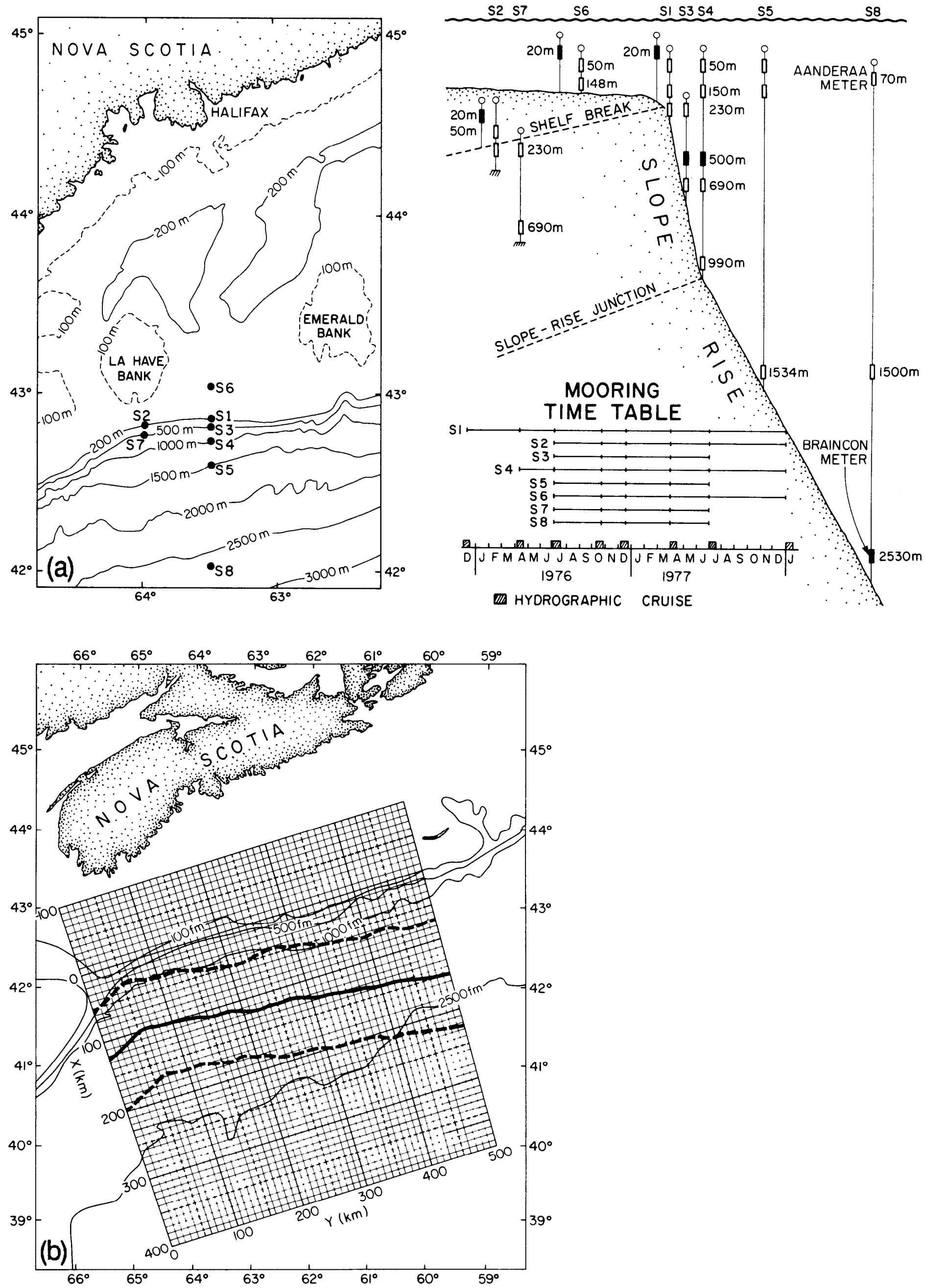
There are many possible energy sources for low-frequency eddy motions near the edge of the continental shelf. Petrie (1983) credits the interaction of transient wind-driven flows with shallow banks for anomalous currents on the outer Scotian Shelf, whereas Pingree (1979) attributes baroclinic eddies bordering the Celtic Sea to hydrodynamic instability of a shelf break front. However, on the western sides of ocean basins, a more likely source is strong western boundary currents. When this current flows along the shelf edge, as the Gulf Stream does in the U.S. South Atlantic Bight (SAB), the forcing is direct in terms of "frontal eddies", which form on the inshore edge of the current and extend into shallow water. On the other hand, when the current lies farther offshore, like the Gulf Stream north of Cape Hatteras, the forcing is indirect via large-scale meanders and "pinched-off" Warm-Core Rings (WCR, See Fig. 1). These features, which contain vast stores of potential energy in their mass fields, are capable of radiating low-frequency waves, known as topographic Rossby Waves, up the continental rise and slope to the shelf edge. The development of ideas about these two different modes of shelf edge forcing by offshore currents will now be traced.

The earliest accounts of eddy currents in the SAB come from ship's logs in the late 1500's (Brooks and Bane, 1981). However, the first quantitative measurements of the velocity and temperature structures in the surface layers of the Gulf Stream were made by Webster (1961), who characterized the meanders off Onslow Bay as skewed, wavelike oscillations with periods of 4 to 7 days. Webster's observations, which were made with a bathythermograph (for temperature) and a set of towed electrodes known as a geomagnetic electrokinetograph or GEK (for current), have been considerably augmented by modern measurement devices such as moored current meters, the CTD (conductivity, temperature, depth profiler), and radiation thermometers borne by satellite or aircraft. In synthesizing the results of extensive field programs off Florida and the Carolinas, Lee et *al.* (1981) and Bane *et al.* (1981) have described the circulation of "frontal eddies" that produce warm salty tongues of Gulf Stream water that "fold backwards" along the inshore edge of the stream to enclose a core of rich upwelled water. With cross-stream scales of 10 km, the eddies amplify as they propagate northward (at an average rate of 40 km/day) with maximum growth rates occurring just north of the "Charleston bump", a localized topographic irregularity that deflects the Gulf Stream seaward. Brooks and Bane (198 1) have demonstrated that the eddy fluctuations are not correlated with wind or coastal sea level, which suggests that their energy comes from hydrodynamic instability of the Gulf Stream front. The observed energy transformations and recent model results indicate that the primary source is the potential energy of the stream (i.e., baroclinic instability) and that the loss of the stabilizing effect of the steep shelf edge topography causes the enhanced growth rates north of the Charleston bump (e.g., Dewar and Bane, 1985).

After leaving the continental margin at Cape Hatteras, the dominant instability mode of the more "jet-like" Gulf Stream shifts to larger scale, lower-frequency meanders of the entire current. These meanders often amplify and "pinch-off" to form both cold- and warm-core (WCR) rings on the southern and northern sides of the Stream respectively (Figure 1). Warm-core rings were first observed by Jonathan Williams, the grandnephew of Benjamin Franklin, in 1790. In the thirties, Iselin (1936) made numerous hydrographic observations of isolated WCRs, but their formation from a growing meander was not observed until the fifties (Fuglister and Worthington, 1951). The influence of rings and meanders on the coastal waters of the Scotian Shelf was noted by McLellan *et al.* (1953), who pointed out that the position of the narrow boundary separating shelf and slope waters varied "unsystematically' by as much as 250 km in the region south of Halifax. More recently, BIO scientists have described how tongues of Scotian Shelf water may be drawn offshore by WCRs that approach the shelf, and have calculated that such large-scale exchanges, at the observed rate of six per year, have a significant impact on the heat, salt and nutrient budgets for the shelf waters (Smith, 1978). In fact, in the context of a simple box model, Houghton ***et al.*** (1978) have shown that measured low-frequency fluxes at the Scotian Shelf break are capable of supporting the observed alongshore gradients in temperature and salinity as well as the biological requirements for nitrogen, the single most important nutrient for supporting primary production on the Shelf (Fournier *et al.*, 1977).

In the deeper layers, the clockwise circulation of the WCR interacts with the shoaling topography of the continental rise to generate topographic Rossby waves (TRW), which radiate energy away from the ring. The properties of linear, inviscid TRW were originally explored theoretically by Rhines (1970) and confirmed by a series of long-term current meter measurements on the New England continental rise described by Thompson (1977). Theories have also been developed for the transmission and reflection of TRW energy on the steep continental rise and slope (e.g., Kroll and Niiler, 1976) and for scattering some of that energy into trapped baroclinic waves ("fringe modes") at a sharp change in topography such as the shelf break (Ou and Beardsley, 1980).

Although these simple models presume that the energy source for the TRW is the Gulf Stream, direct evidence for a generation mechanism was not obtained until 1976-77 during an experiment conducted by BIO scientists at the shelf break south of Halifax. Important elements of the Shelf Break Experiment were an array of 11 moorings at 8 sites (Fig. 2a) and a series of weekly sea-surface frontal analyses based on satellite infrared imagery, which were digitized on a 10 x 10 km grid oriented to the shelf break (Fig. 2b). During July/October, 1976, near bottom records of alongshore current (Fig. 3) revealed a burst of topographic wave energy in which the period gradually increased and the phase propagated offshore [consistent with onshore energy flux; Louis *et al.*, 1982]. Louis and Smith (1982) then formulated an initial value problem for an isolated circular vorticity disturbance on the Scotian Rise, which explained both the temporal variations in wave period (Fig. 4a) and amplitude (Fig. 4b). As a result, the generation time for this wave packet was identified as week 27, 1976, when the frontal analyses indicated that a WCR known as Eddy I was forming 200 km south of the array (Fig. 5), and the scale of the vorticity disturbance beneath the ring was estimated to be 70 km. Furthermore, analysis of the three-dimensional TRW energy flux over realistic topography indicated that the strength of low-frequency current oscillations at the shelf break was determined by competition between amplifying effects of shoaling and refraction versus decay due to radial spreading of the energy. However, for reasonable estimates of bottom frictional dissipation, the wave energy that reaches the shelf edge is expected to decay over alongshore scales of 100 km, so that the disturbances caused by WCR are localized to that extent (Smith, 1983).

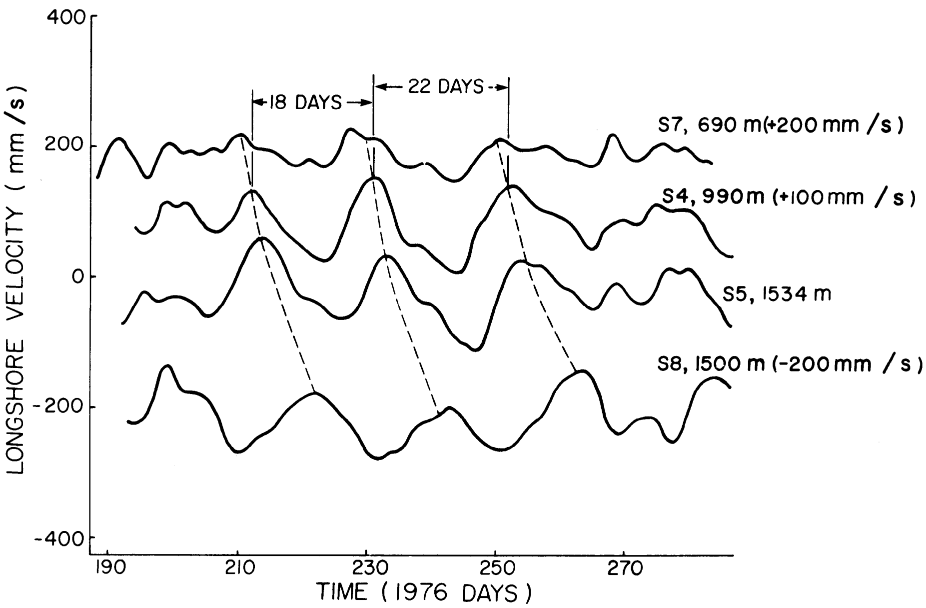


2. The monitoring networks for the BIO Shelf Break Experiment: December 1975 to January 1978. (a) Mooring array and time table. (b) 10 x 10 km grid used to digitize the position of the shelf/slope water boundary and Warm Core Rings. Mean position (solid) and standard deviation (dashed) of the shelf/slope water boundary are shown **for** *the period* **of** *the experiment.*

With regard to their influence on the shelf circulation, Garrett (1979) has shown that the strong TRW currents at the shelf break are capable of inducing upwelling via the bottom Ekman layer, a process which may contribute to the enhancement of cross-shelf fluxes at low frequencies. However, longshore wind is also effective at producing shelf-break upwelling at somewhat higher frequencies.

Wind-induced upwelling

On a broad continental shelf (i.e., much wider than the typical baroclinic adjustment scale of about 10 km), the response to longshore-wind forcing occurs both at the coast and in the vicinity of sharp changes in the bottom

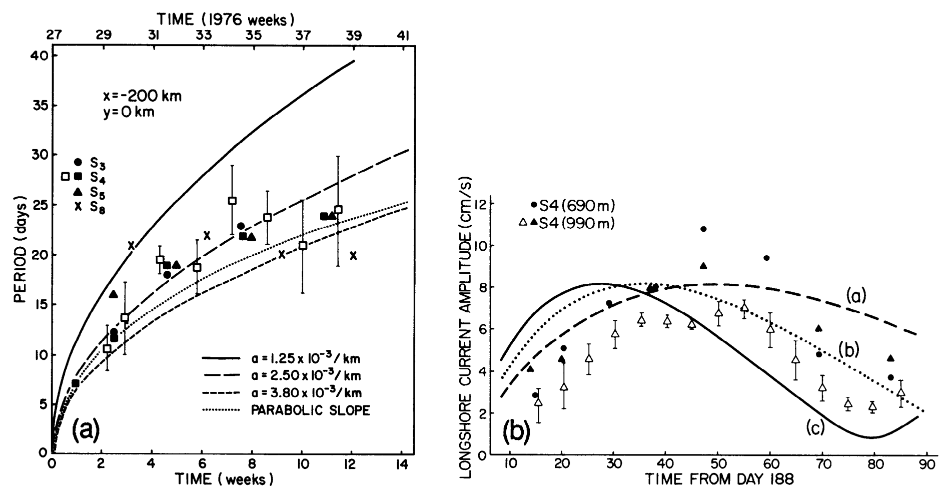


3. Filtered records of the longshore (eastward) current at deep instruments in the offshore region during July/October, 1976. Dashed lines indicate offshore phase propagation; period variations are shown for the S4 record.

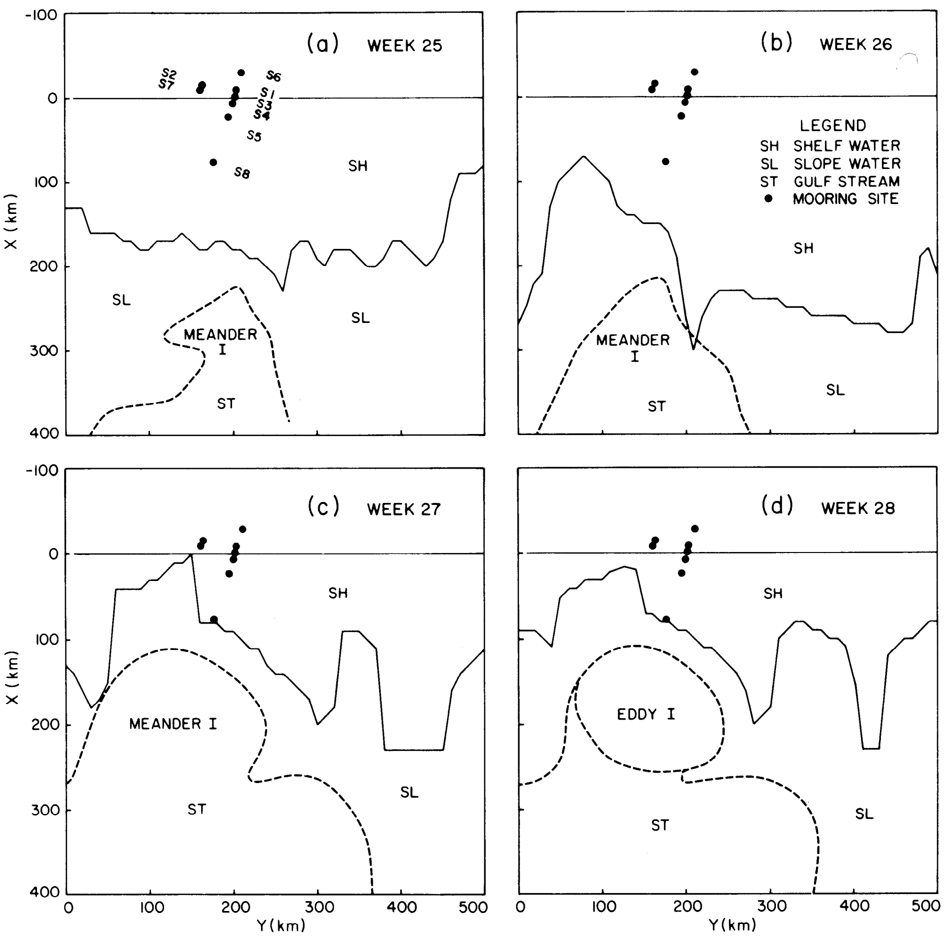
slope such as the shelf break. Since the early seventies, many theoretical and experimental investigations have been focussed on the coastal upwelling phenomenon, most notably on the narrow shelves of the west coasts of North and South America where the shelf-edge and coastal responses are merged. However, theoretical and particularly observational studies of wind-induced shelf-break upwelling are sorely lacking (Huthnance, 1981).

Using a simple two-dimensional "step-shelf" model, Huthnance (198 1) demonstrated that shelf-break upwelling is caused by a divergence of the offshore flow in the surface layer, which is proportional to the large depth change between the shelf and ocean as well as the strength of the forcing. With a similar two-layer model, Csanady (1973) showed that the character of a wind-induced longshore jet at the shelf break was controlled by the distribution of bottom slope and stratification. Janowitz and Pietrafesa (1980) have also formulated a model for transient upwelling, which includes both bottom friction and weak stratification. Their results suggest that sufficiently sharp changes in the bottom slope at the shelf break produce a persistent upward bulge in the isopycnals, which implies a vertical shear in the longshore current according to geostrophic dynamics. Furthermore the strength and timing of this model circulation are in reasonable agreement with measurements in the SAB, where wind-induced upwelling in summer is credited with supplying significant quantities of nutrients to the mid-shelf region (Atkinson *et al.*, 1982).

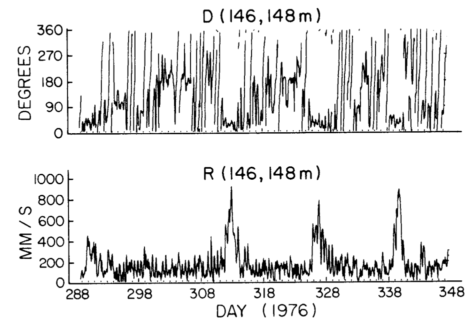
On the Scotian Shelf, early hydrographic observations (e.g., McLellan *et al.*, 1953; Hachey, 1953) indicated that the Scotian Gulf, which lies between Emerald and LaHave Banks south of Halifax, is a favoured location for wind-driven slope water intrusions. Petrie and Smith (1977) suggested that such events are capable of flushing the deep waters of Emerald Basin in the fall and winter. More recently, Petrie (1983) has found evidence in data from the BIO Shelf Break Experiment (Fig. 2) that moderate (10-20 m/s) longshore winds that persist for at least two days produce upwelling at the shelf break from depths of 400 m or more on the continental slope. Peak vertical velocities are of order 2 mm/s and the upwelling appears to be confined to within 10 km of the slope. Furthermore, the vertical longshore current shear and horizontal density gradients at the shelf break were found to be in geostrophic balance. However, on the shelf, large anomalous bottom currents with maxima near 1 m/s (Fig. 6) were attributed to local topographic variations on the outer banks. Moreover, attempts to model the transient current fields with two-dimensional analytical and numerical models failed both quantitatively and qualitatively! Thus, the BIO shelf edge measurements reveal the distinctive character of this important process and



4.(a) The observed (symbols) and model (curves) wave period versus time for topographic wave oscillations 200 km north of the initial disturbance. Curves represent various definitions of model topography. (b) The observed (symbols) and model (curves) wave amplitude variations at the S4 mooring site. Best model fit is achieved **for** *an initial disturbance with a diameter of 70 km (dotted curve).*



5. *(a-d) Frontal analysis **of** sea surface temperature depicting shelf/slope water boundary (solid) and north wall of the Gulf Stream (dashed) on a rectangular grid with one axis roughly coincident with the shelf break (Fig. 2b). Panels (a) to (d) illustrate the formation and development of Eddy I during weeks 25 to 28 of 1976.*



6. *A time series **of** rate and direction from the shelf mooring, S6, at 148 m during October through December 1976.*

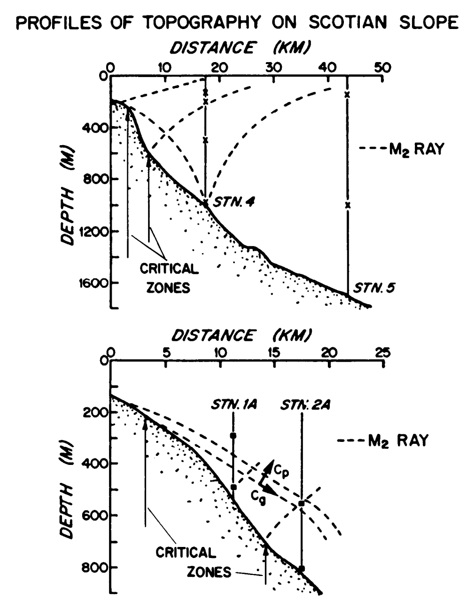
also serve to point the way toward future research into three-dimensional, wind-driven response over complex topography on the Scotian Shelf.

Internal tide and nonlinear waves

One question that arises with regard to the low-frequency shoreward fluxes of nutrients, which are concentrated from mid-depths to the bottom at the shelf break, is, How do they reach the euphotic zone at the surface? One likely mechanism is vertical mixing caused by internal waves.

The discovery of internal waves dates back to the early part of this century. The rapid development then, which included the development of many new instruments (e.g., the Ekman current meter) and techniques, was led by Scandinavian oceanographers stimulated by the need to know more about large fluctuations in the food supply for fish. Nansen (1902) was the first to observe internal waves in the ocean, but it took Ekman's (1904) model calculations to identify them. Many more observations of internal waves followed, and Fjeldstad (1933) extended the dynamical theory from the early layered models to a continuously stratified fluid.

By 1960, despite a large volume of literature on internal waves, little was known about their generation and distribution in the ocean. But then Rattray (1960) used a simple two-layer, step-shelf model to demonstrate coupling between the surface and internal tides. In 1962, Cox and Sandstrom (the latter on educational leave from the yet unopened BIO) calculated the rate of energy flow from surface to internal tides by scattering from bottom roughness in a continuously stratified ocean. This paper has since become a cornerstone in the study of deep ocean internal tides. The early sixties also saw the first applications of optical ray theory to oceanographic problems (e.g., Sandstrom, 1966). This technique has formed the basis for many important subsequent investigations of the interaction between surface and internal tides - for example by Baines (1974), and by Prinsenberg (now at BIO) and Rattray (1975). According to Baines' model, the most efficient conversion of energy occurs where the local topographic slope and the ray slope of the internal tide are



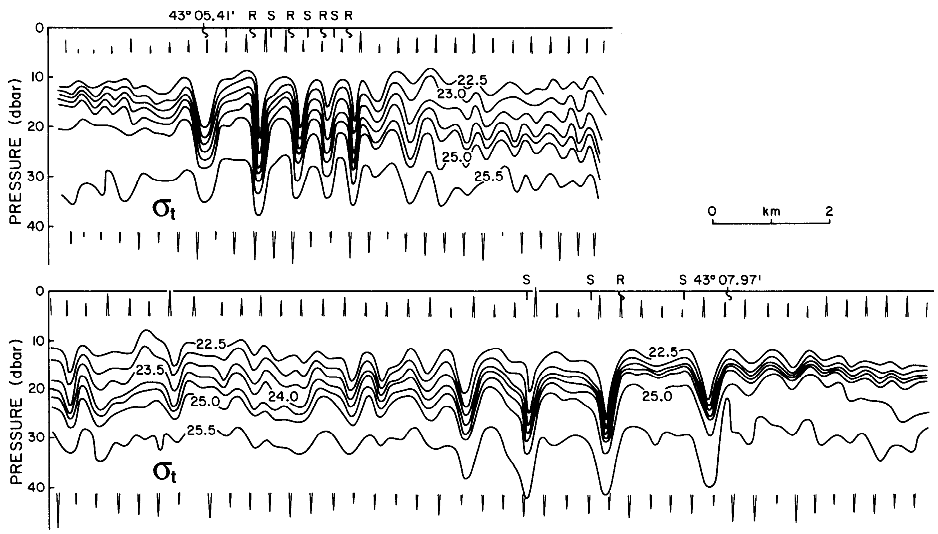
7. *Topographic profiles on the Scotian Slope with positions of current meter moorings. Dashed curves indicate critical rays for the M2 internal tide, which intercept the slope near 200 and 600 m (from Petrie, 1975).*

equal. This condition is generally met at the shelf edge.

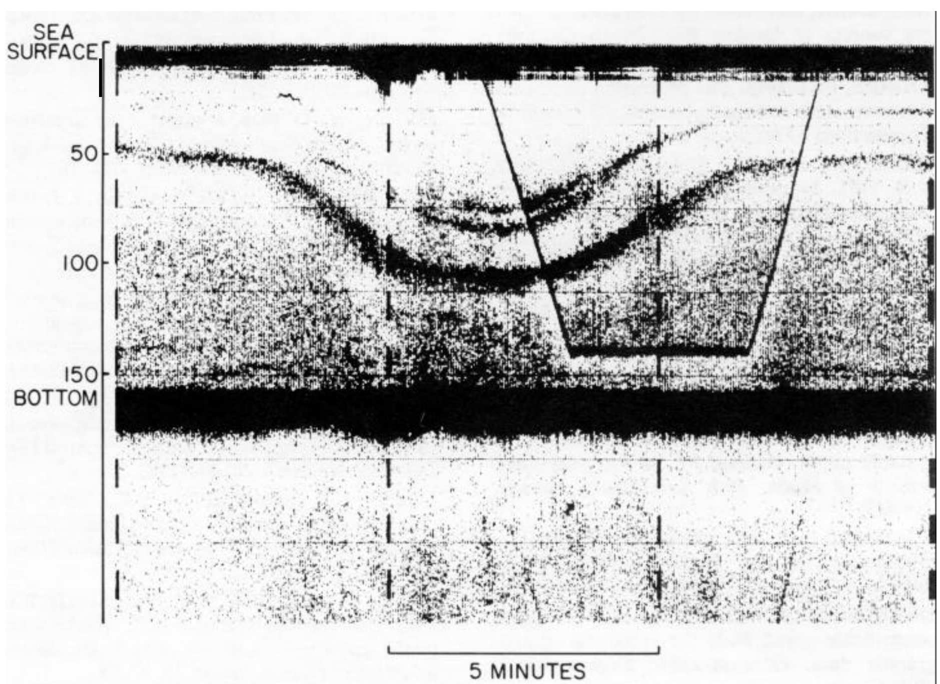
At BIO, internal-tide studies of the seventies were aided by both theoretical advances and new instrumentation of the sixties. Thus both Warner (1970) and Petrie (1975) analyzed moored current and temperature measurements on the Scotian Shelf and Slope. Petrie, in particular, demonstrated that the intersections of critical rays from generation sites at the shelf break with the moorings were consistent with the observed structure of the M_2 internal tide (Fig. 7). In addition, Sandstrom (1976) formulated a unified ray theory to explore the sensivity of the topographic generation problem to variations in stratification and bottom profile. Other BIO studies included Forrester's (1973) examination of hydrographic variability in the St. Lawrence estuary, which clarified the role of internal tides generated at the head of the Laurentian Channel.

In this decade, internal tide research has been spurred first by the realization that internal tides cause or enhance fine and microstructure events related to ocean mixing and second by the discovery of finite-amplitude, short internal waves (solitons, internal bores), which are somehow related to the internal tide. Groups of these short-period (e.g., 10 min) waves have been detected at certain phases of the M_2 tide in many locations, usually with temperature measurements [e.g., in the Strait of Gibraltar by Ziegenbein (1969), in Massachusetts Bay by Haury *et al.* (1979), in British Columbia fjords by Farmer and Smith (1980), and, more recently, on the shelves of northern Europe by Pingree and Mardell (1985), who emphasize their biological importance]. These studies have benefitted considerably from the development of remote sensing techniques to study the ocean from satellite-, aircraft-, and shipboard platforms.

In 1980, BIO scientists commenced a multi-year investigation of the relationships between tides, turbulence, and ocean mixing at the edge of the Scotian Shelf, in order to understand the reasons for high nutrient concentrations and biological productivity in the euphotic zone. Furthermore, observations have been made all along the Scotian Shelf and Grand Banks of Newfoundland to map the occurrence and nature of the large amplitude waves, and this information has been provided to offshore industry concerned with their potentially-harmful effects (e.g., current surges). In conjunction with the field program, theoretical studies of the connection between the internal tide and ocean mixing are continuing. Much of the recent progress in this work is due to BATFISH, a towed undulating body developed at BIO (Dessureault, 1976) for surveying hydrographic properties in the surface layer (Fig. 8). Acoustic sounding systems using single or multiple frequencies have also been used to provide high resolution images of short internal waves at the shelf break (Fig. 9), while rapid sampling turbulence probes (Oakey, 1983) serve to



8. The density field observed by BATFISH for two consecutive crossings of a short internal wave packet: top - ship and waves travelling in opposite directions; bottom - ship overtaking the waves. A banded pattern observed at the surface is marked as R = rough and S = smooth.



9. Internal solition on the shelf as seen by the 12-kHz sounder. The "bucket" is the trace of the CTD package during station 45. The "sech^2" overlay is computed with h/c = 190 s, amplitude = 53 m.

quantify ocean microstructure and dissipation rates.

Conclusion

In summation, progress in understanding three distinctive physical processes at the shelf break, to which BIO scientists have made distinct contributions, has been described. The low-frequency forcing of the shelf break circulation by strong western boundary currents and mesoscale eddies in the U.S. South Atlantic Bight, where the Gulf Stream itself meanders onto the shelf, has been contrasted to the situation on the Scotian Shelf, were intermediary Warm Core Rings radiate low-frequency topographic Rossby waves to the shelf break and promote mixing across the shelf/slope water boundary. Wind-induced upwelling at the edge of the Scotian Shelf has also been shown to result in exceptionally strong bottom currents as a result of the complex topography on the outer banks. And, finally, advances in our knowledge of the internal tide and large-amplitude internal waves at the shelf break promise to lead to a clearer understanding of oceanic mixing as it relates to biological productivity on the continental shelf.

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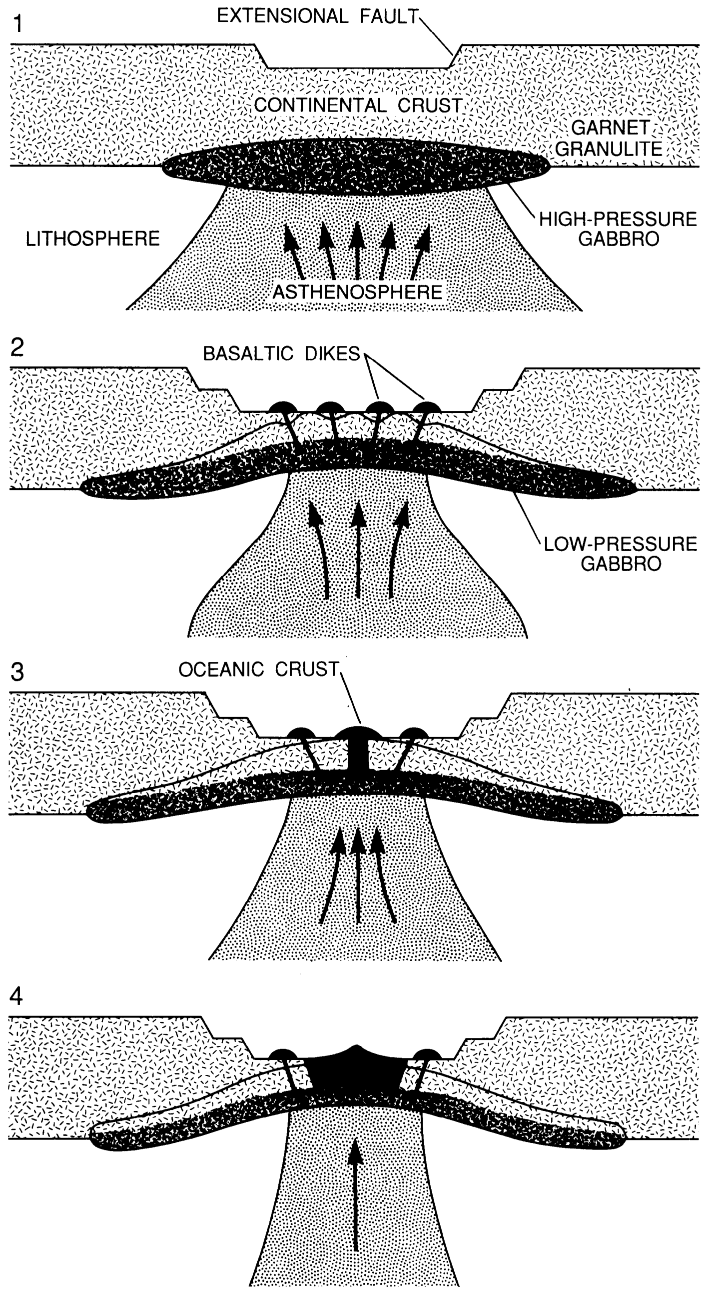
Sedimentary basins of the passive margin off Eastern Canada

Michael J. Keen

SEDIMENTARY basins, in places more than 20 km deep, lie beneath the continental margin of eastern North America from Florida to Baffin Bay. Similar basins are found off other comparable passive margins worldwide.

The basins can be understood in terms of the paradigm of seafloor spreading (see "Twenty-five years of seafloor spreading" in this Review). Rifts form in extending continental lithosphere, and the asthenosphere beneath wells up, replacing the lithosphere, and may reach the earth's surface as volcanic rocks. If extension is sufficiently great, the lithosphere breaks completely, and seafloor spreading starts; ocean lithosphere forms (Fig. 1). The new oceanic lithosphere and the adjacent continental lithosphere cool down and contract, forming basins which are sinks for continental debris and dead organic matter. Sediments formed therein load the lithosphere, amplifying the subsidence so that the basins are deeper than lithospheric cooling by itself would produce. Sedimentary basins like those off eastern North America are typical of the modern "passive" margins of the world (Fig. 2). These continental margins are a product of the creation of the new ocean basins during the last 200 million years, rather than the product of destruction of oceanic lithosphere, which will occur at the collision of two plates.

Remnants of sedimentary basins like these are found in older rocks, now incorporated in products of deformation on the continents; for example, evidence of the 500 million year old passive margin of the Precambrian Shield is found in western Newfoundland. This ancient margin was a participant in the "Wilson" cycle; an ocean has opened and closed, and the basins on the passive margins, which were the products of opening, have been deformed as a result of the closing and the collision (Wilson, 1966). The Wilson



1. Initial rifting and the start of an ocean basin - the analogue of the East African Rifts, the Red Sea, and the Gulf of Aden. Enrico Bonatti, following many others, has postulated that these regions are archetypes for continental rifting and the beginning of seafloor spreading. His original caption read, in part: "The first stage in the evolutionary sequence is typified by the East African rift valleys(r), where the continental crust is being underplated by gabbros. . . . In the northern Red Sea(2) the crust has already been stretched and thinned considerably. . . . Basaltic dykes have also been injected into fissures in the crust. In the southern Red Sea(3) the zone of melt injection has become concentrated at the rift axis; the African and Arabian continental blocks have split, and oceanic crust is forming in the crack. In the Gulf of Aden (4), the sea floor has been spreading for 10 million years. " Evidence of underplating comes not only from the East African rift valleys, but also from seismic experiments undertaken off eastern North America (LASE, 1986). (from "The Rifting Continents" by Enrico Bonatti. Copyright ©March 1987 Scientific American. *All rights reserved.)*

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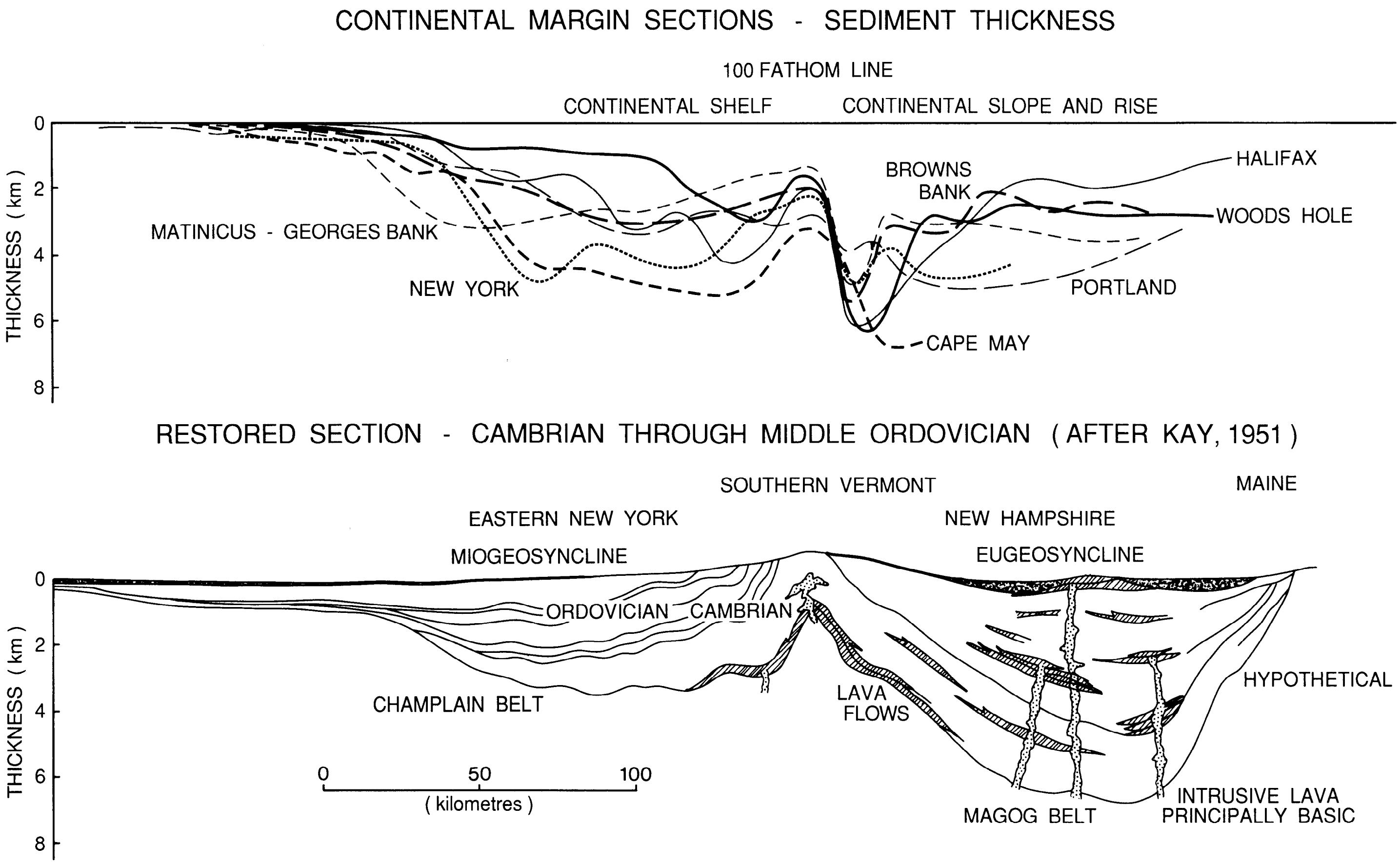


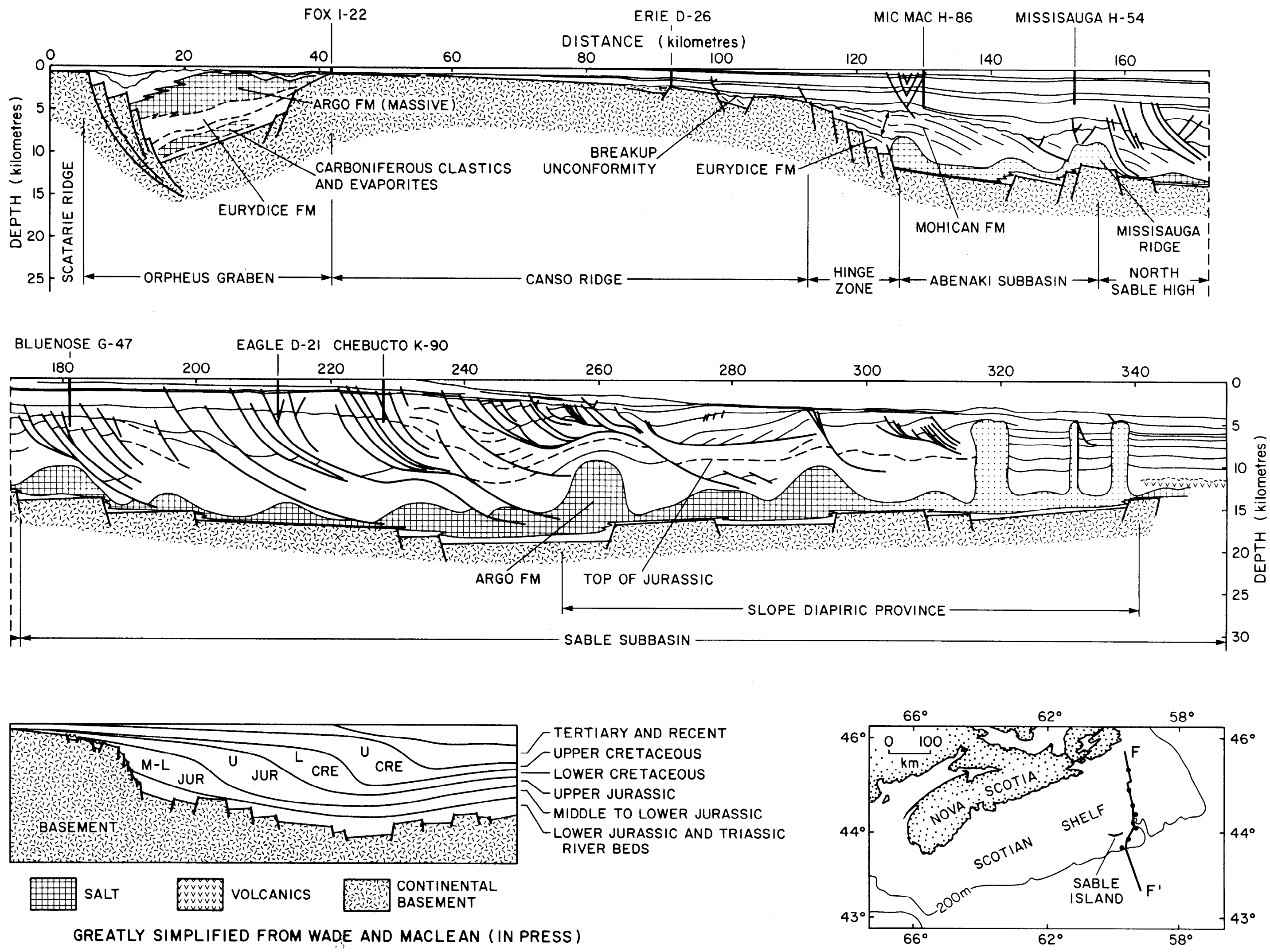
2. An early comparison between the sedimentary wedge of the continental margin off eastern North America (upper) and the Appalachians as it was then thought they would appear if "unfolded" (lower) (from Drake et al., 1959, *Fig. 30).*

cycle has often been called more graphically - and more musically perhaps - the "Harry Hibb's" cycle, after the well-known Newfoundland accordion player.

The lithospheric framework in which these basins developed has been delineated by a variety of geophysical techniques. An early good example is the discovery of the Orpheus Graben by Loncarevic and his colleagues in 1967 (Loncarevic and Ewing, 1967). They mapped a linear negative gravity anomaly of about 60 milligals which exploration later showed was associated with a Triassic sedimentary basin along the extension of the "Glooscap" Fault system of northern Nova Scotia (Fig. 3). Multichannel seismic studies have delineated basin-bounding faults of some of the extensional basins of the Grand Banks, and at least one of these faults penetrates to depths of many tens of kilometres (Fig. 7). It appears that the whole crust at least was involved in the extension that led to the formation of the basins (Keen et *al.,* 1987). Vulcanism associated with upwelling of the asthenosphere early in rifting and extension is seen in the 200 million year old basalts of the North Mountain of western Nova Scotia and the Avalon Peninsula of southern Newfoundland, and in younger volcanic rocks associated with later rifting in exploration wells (Jansa and Pe-Piper, 1985). Early extension and later subsidence is reflected in the descent of the sediments of the basins off Nova Scotia to depths approaching 15 km (Figs. 3 and 4) (Wade and MacLean, in press).

The sediments of the Mesozoic-Cenozoic basins off eastern Canada record the history of oceanographic, climatic, and lithospheric processes of the last 200 million years (Figs. 5 and 6). As such, they are a mine of scientific information. Moreover, because the basins contain substantial resources of oil and natural gas, they are potentially economically important. The Hibernia field in the Jeanne d'Arc Basin off Newfoundland is classed as one of the world's "giant" fields, containing reserves of more than 500 million barrels of oil.

Twenty-five years ago these basins were barely known. The offshore basins were discovered by the Lamont-Doherty Geological Observatory as a result of seismic refraction experiments in the fifties. Maurice Ewing and his colleagues at Lamont made systematic seismic refraction observations along a large part of the margin of eastern North America, and discovered a thick wedge of sediments. Using dredged samples and seismic refraction velocities as their guide, they suggested that these sediments were a submerged part of the "coastal plain" sediments of the eastern and southeastern United States



3. A cross-section of a mature rifted continental margin. The cross-section runs from north to south from off Cape Breton Island to the continental rise south of Sable Island. It shows the aborted rift of the Orpheus Graven (top left), and the Abenaki (top right) and Sable (middle) subbasins of the Scotian Basin. The figure shows: the great thickness of sediment accumulated in the past 200 million years; the salt near the base of the basin, which has risen to form diapirs, dramatically on the middle right as the "diapir province;" and the faulting that accompanied subsidence and deformation caused by salt. Faulting in the crust beneath the sediments is shown only schematically. From Wade and Maclean (In press, Fig. 5.19).

(Drake *et al.*, 1959; see also Keen, 1983). Mobil Oil Canada Ltd. applied for exploration permits in 1959 for Sable Island and parts of the shelf around the island. The company undertook aeromagnetic surveys in 1959 and seismic reflection surveys in 1960. The Geological Survey of Canada started aeromagnetic surveys offshore in 1958, and sea magnetic surveys with the Canadian Hydrographic Service in 1959. Consequently, when BIO was formed in 1962 little was known by anyone about the massive sedimentary basins offshore. The Institute began its geological investigations by dredging rocks from canyons on the continental slopes and by geological mapping on the shelves (e.g., King and MacLean, 1974). Our early geophysical studies focussed on measurements of the gravity and magnetic fields, and, with other institutions, on shallow and deep seismic refraction experiments (e.g., Keen, 1983). The advances since 1962 in our understanding of the internal structures of the sedimentary basins themselves has depended substantially on the massive expenditures by the petroleum industry for acquisition of seismic reflection data of increasingly higher quality, and for offshore wells.

The geographical extent of the "modern" basins - the Mesozoic and Cenozoic basins of the last 200 million years - off eastern Canada are now well defined by geological and geophysical surveys. The inner, feather edges of the basins lie, for the most part, only a few tens of kilometres offshore, and this inner boundary can be traced in the south to the coastal plain sedi-

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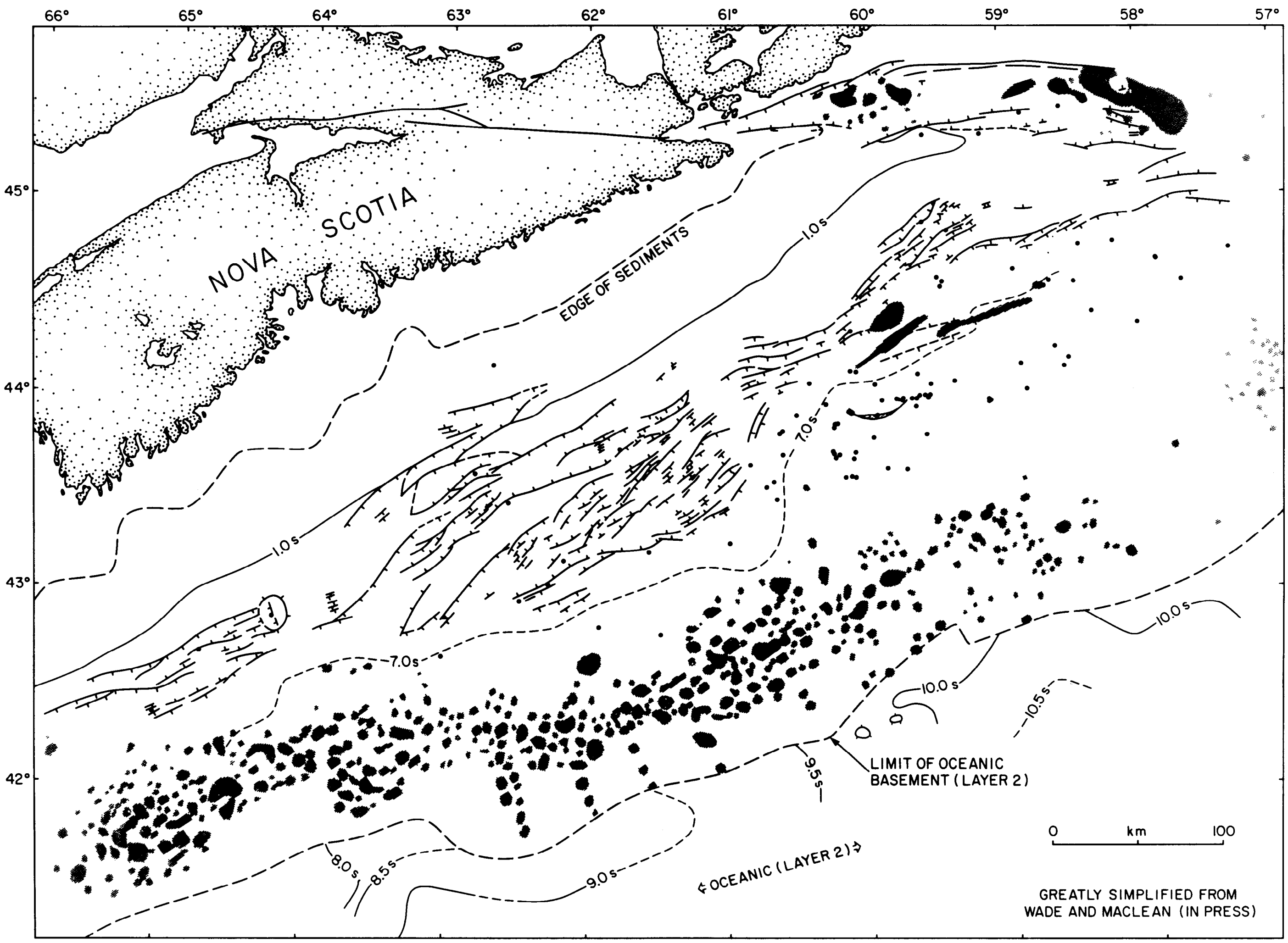
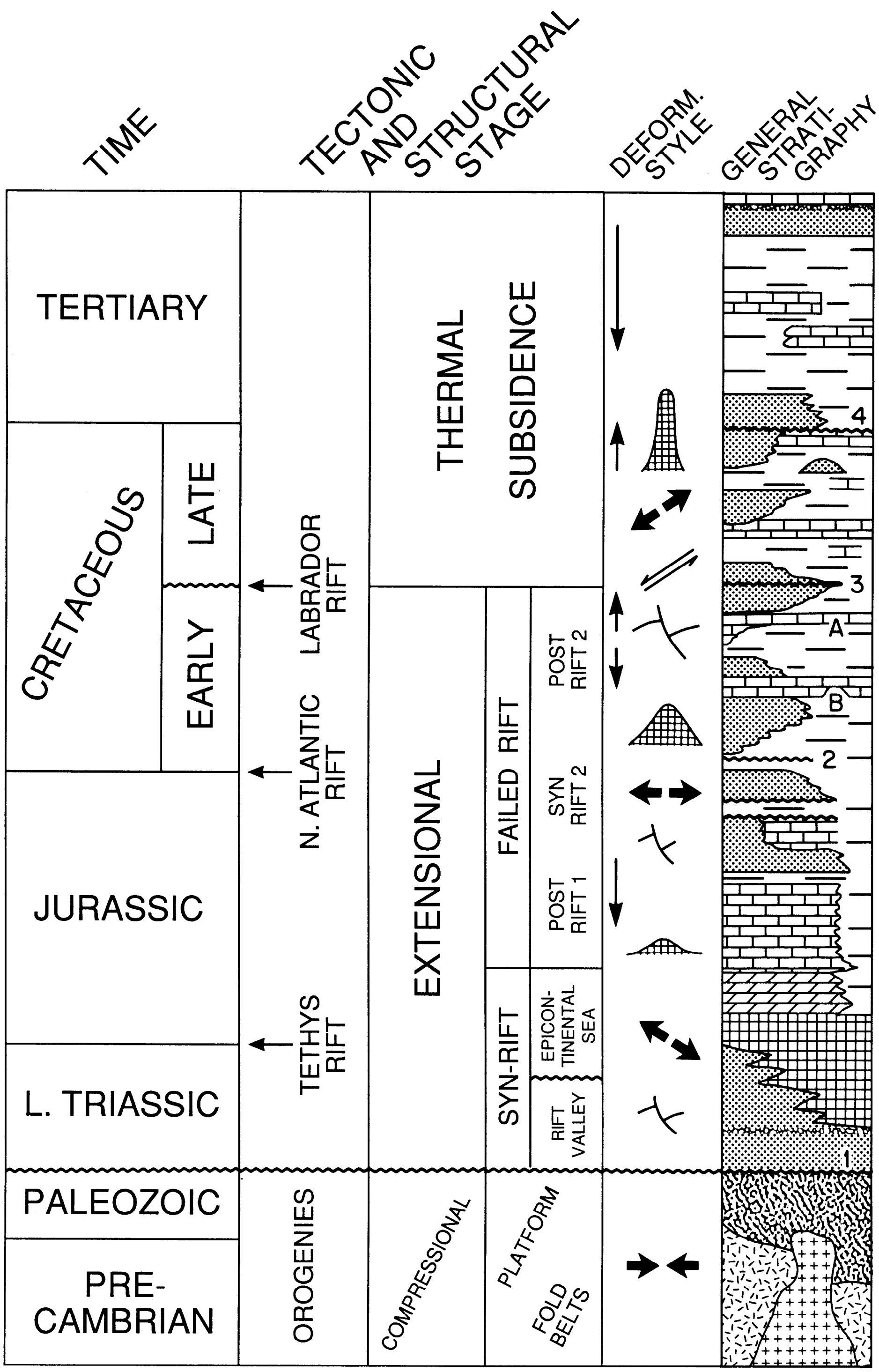


4. The complexity of the structure of the uppermost crust beneath the sediments of the western part of the Scotian Basin, and the intense field of diapirs beneath the rise off Nova Scotia. The Scotian Basin subsided at a "hinge zone" shown here by the crowding of the dashed contours between about 4 and about 8 s. The contours are of two-way seismic reflection time to the base of the sedimentary sequences. They are absent beneath the diapir field, where the base cannot be seen. Diapirs are shown as cross-hatched. The dash-dot line indicates the northern (landward) limit of oceanic crust as it can be seen on industry reflection seismic records. From Wade and MacLean (In press, Fig. 5.17).

ments of the same age on land in the United States. In some areas the feather edge lies further offshore, and this provides important windows into the Paleozoic rocks beneath (Bell and Howie, 1987). The outer limit of the sedimentary basins is less well defined, because the sediments of the basins merge distally with those of the ocean basins deposited upon oceanic crust (Figs. 3 and 8).

The ease of surveying the shelf improved with technology. Early surveys in the southern parts of the Canadian margin could use the radio-navigational aid DECCA, but early surveys in the north depended upon astronomical observations and radar fixes on land for positioning. Later surveys had integrated navigational systems involving radio-aids such as LORAN-C, satellite navigation, and in some cases early versions of the Global Positioning System. Comparable advances came in high resolution seismic systems and side-scan sonar systems (Hutchins et al., 1976). The BIO rock core drill was used as the equivalent of a geologist's hammer on land, sampling after high resolution seismic studies had identified bedrock within reach.

The Geological Survey of Canada at BIO initiated studies of the geological development of the sedimentary basins in 1971, using data from industry supplemented with our own. These showed that the sediments were deposited along the length of the margin in a series of discrete basins and subbasins, separated one from the other by faults and arches. The basins south and north of the Grand Banks are bounded on their landward side by hinge-zones, from which the sediments are faulted down towards the ocean basin into deep troughs (Figs. 3 and 4). The basins of the Grand Banks are exceptional because they are in a, sense "failed rifts", that is rift basins



5. *The evolution of the Jeanne d'Arc basin, one of the sedimentary basins of the Grand Banks, through a complicated history of extension and subsidence (from Enachescu, 1987, Fig. 7).*

which did not develop into ocean basins (Figs. 5, 6, and 7).

The basins developed more-or-less sequentially as rifting and seafloor spreading migrated from south to north, and so, for example, the oldest sediments in the basins off Nova Scotia may be as old as Triassic, perhaps 210 million years old, but the oldest basin sediments off Labrador are Early Cretaceous, about 130 million years old. These ages reflect the initiation of rifting, and the earliest sediments of the rifts are the products of erosion of the continent and deposition in a continental, not a marine environment, or an environment where access to the sea was very restricted so that salts were precipitated. These depositional sequences of the rift phase are followed by marine sediments, reflecting the onset of seafloor spreading, in places with a distinct break between the non-marine rocks and the marine rocks above: the "break-up" unconformity. The sediments of the basins of the Grand Banks are more complicated than are those elsewhere because the region suffered the effects of the rifting south and north of the Grand Banks prior to seafloor spreading (Figs. 5, 6, and 7).

The sediments of the basins between the northern Grand Banks and Georges Bank are intensely disrupted by salt structures, and these make obvious first targets for hydrocarbon exploration; oil and gas may be trapped in reservoirs above or at the sides of structures domed by the vertical movement of salt, and some of these potential traps lie at relatively shallow depths below the seafloor (Fig. 4). Deeper structures were well-defined only as technology advanced. For example, early work by a variety of investigators suggested that a "ridge" formed by "basement" rocks or evaporites lay beneath the slope off Nova Scotia (Emery *et al.*, 1970), but later work leading to more dense data showed that this "ridge" is in fact an incredible set of salt diapirs that have risen from depth (Fig. 4). The features of many individual hydrocarbon prospects were known by the late sixties, and the general configuration of the Scotian Basin by the mid-seventies (Jansa and Wade, 1975).

Many conceptual advances have aided the interpretation of the rocks of the sedimentary basins off eastern Canada. Plate tectonics and seafloor spreading give a framework for the gross interpretation of the sedimentary rocks encountered. Worldwide changes in sea level may account for many of the unconformities between different sequences of rocks identified from seismic records. These changes in sea level may be related to re-arrangement of continental plates and to changes in rates of seafloor spreading, because these changes would

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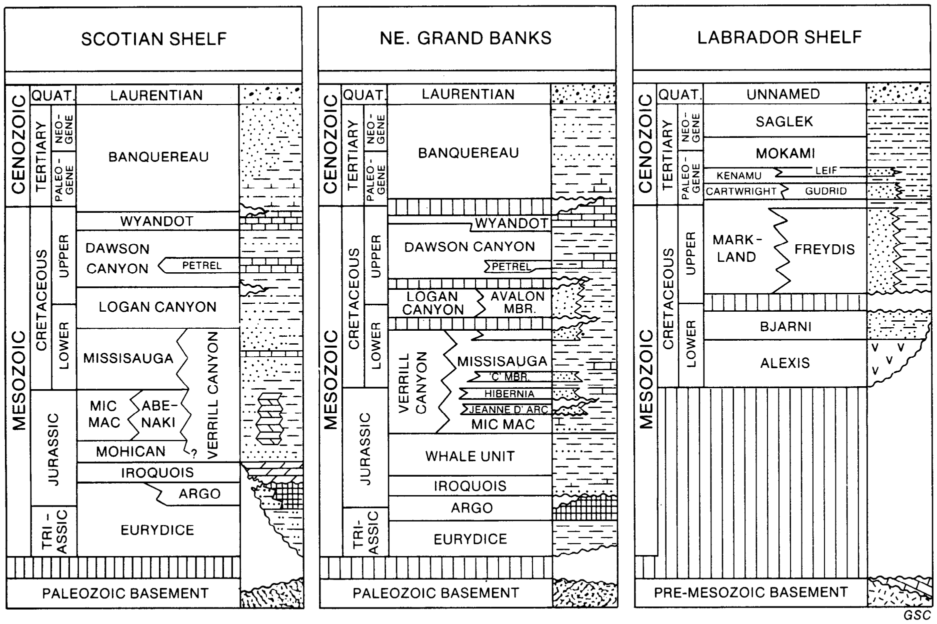
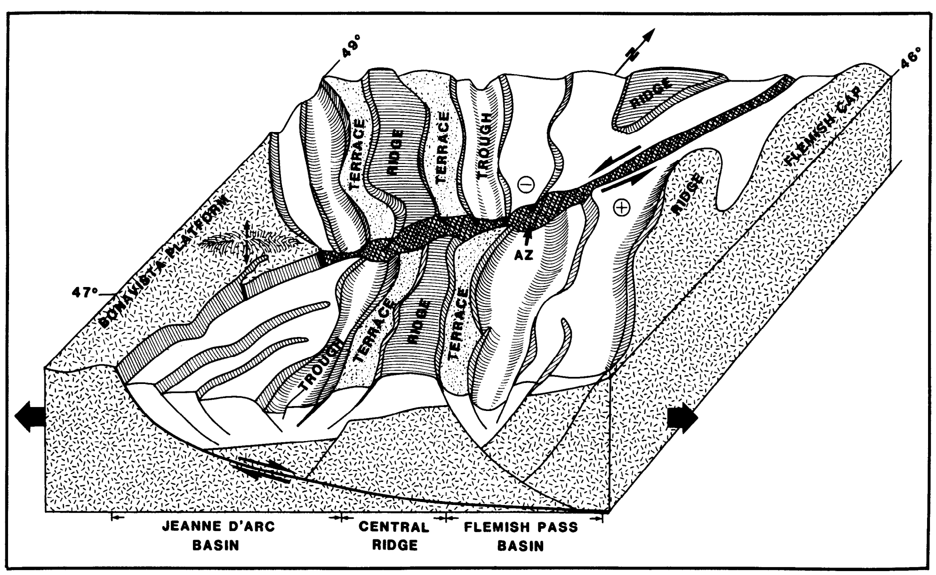


6. Generalized stratigraphic columns for the three principal areas of hydrocarbon exploration off eastern Canada. On the Scotian Shelf, Grand Banks, and east of Newfoundland, the Mesozoic-Cenozoic sediments onlap the Paleozoic and Precambrian rocks of the Appalachian orogen; to the north, in the Labrador Sea and Baffin Bay, they onlap Paleozoic sedimentary strata and crystalline rocks of the Precambrian Shield. The stratigraphic range of the Mesozoic sediments on the Scotian Shelf and Grand Banks contrasts with that of the Labrador-Southeast Baffin Shelf, because of differences in the seafloor spreading histories in three regions. (From Grant et al., 1986, *Fig. 3).*

alter the rates of production of new oceanic crust at mid ocean ridges, and so alter sea level. Drift of plates across climatic zones will alter the types of fauna and flora that will flourish and the types of sediments that will form. For example, extensive carbonate banks developed in areas off eastern Canada only in the Jurassic; they could only form in warm waters, appropriate to the latitudes of the time (Jansa, 1981).

Interpretation of the ages and depositional environments of sedimentary sequences and the solution of many practical problems in oil and gas exploration depend on paleontological correlation. Our ability to do this has increased dramatically through our advances in statistical techniques for analyzing well data and for correlating from well to well. The need for these advances is clear if we appreciate that the number of species recognized from one group alone, the dinoflagellates, has increased from a few hundred to some three thousand in the last 30 years, and these have to be correlated in about 150 wells (Gradstein *et al.,* 1985).

Sedimentary basins will contain significant oil and gas deposits if geological conditions were suitable for their generation and entrapment. Source rocks, containing sufficient organic matter of the appropriate type, have to have been deposited and heated to therma1 maturity to produce oil and gas. The oil and gas formed has to have accumulated in reservoirs, porous and permeable rocks sealed to form traps that prevent fluids from escaping. The timing of formation and of migration into traps has to be right. If the organic matter matures and migration occurs before traps have been formed, the oil and gas will be lost. If the traps are eroded after receiving their oil and gas, the fluids may again be lost. If any one of the appropriate factors is missing, oil and gas will not be formed. The Jeanne d'Arc Basin of the Grand Banks serves as an example (Grant and McAlpine, 1987). Source beds were deposited during the Late Jurassic; these are highly oil-prone organic rich shales developed on account of the particular oceanographic conditions of the time. Reservoir beds (porous sandstones) were deposited in the Late Jurassic and Early Cretaceous, and these were formed into traps by deformation caused by movement of underlying Triassic-Early Jurassic salt. These traps were sealed by impermeable shales interfingering with the sandstone reservoir beds. The source beds were connected to the reservoirs by faults, many of which developed as a result of the formation of the basin, or



7. The continental margin northeast of Newfoundland. A block diagram showing the complicated structures that arise when a continental block is rifted (from Enaschescu, In press, Fig. 16).

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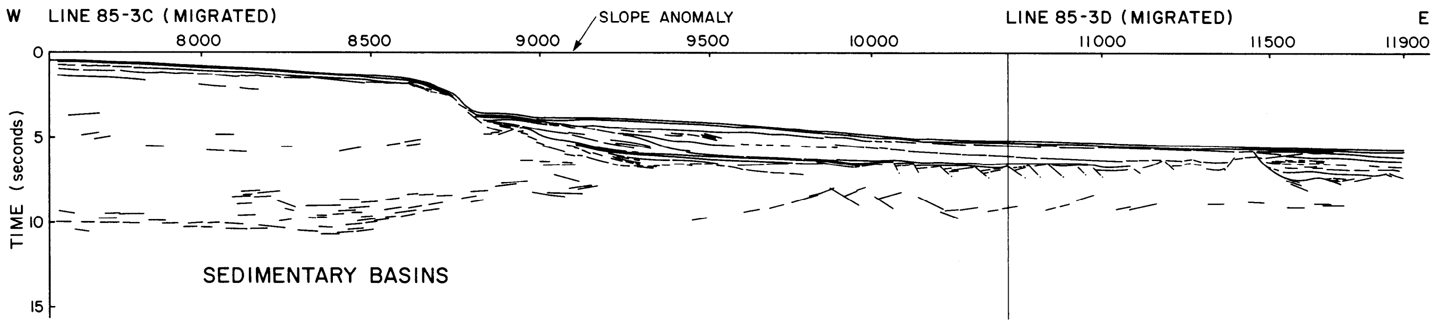
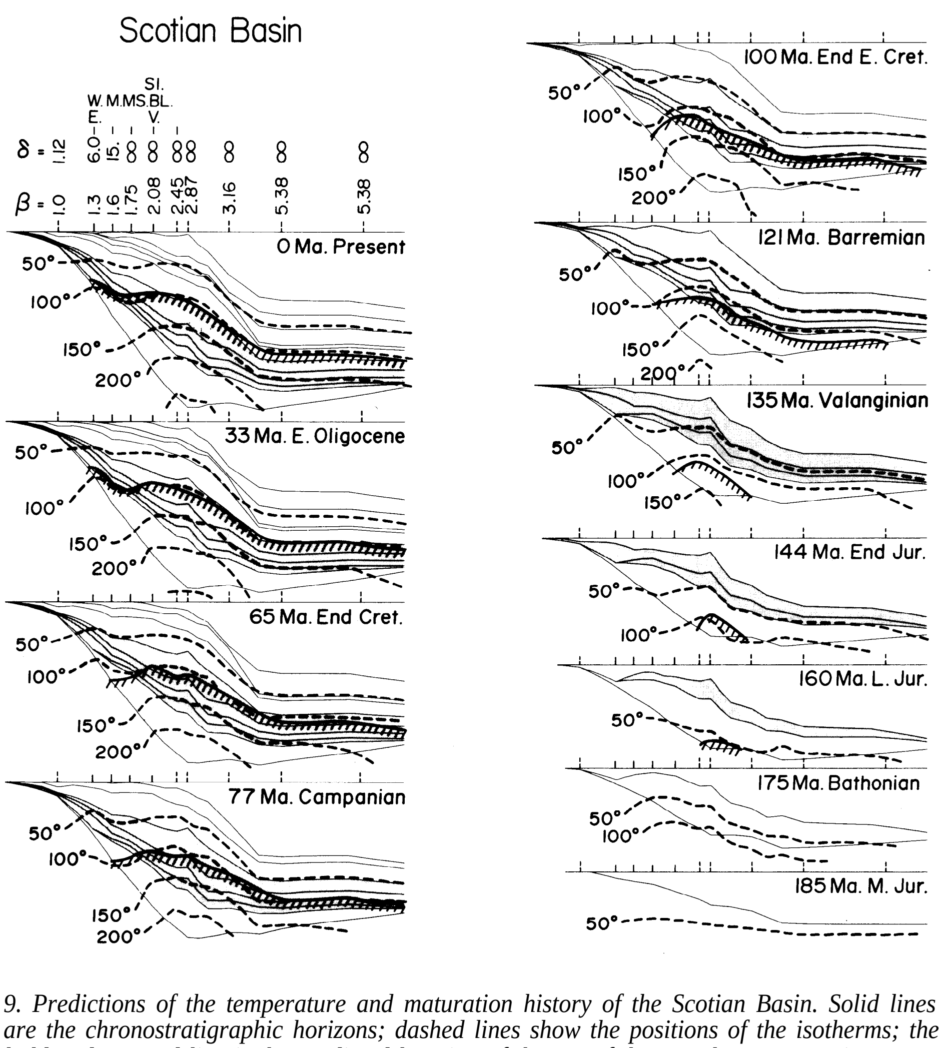


8. The transition from continent to ocean northeast of the Grand Banks. The figure shows a line drawing of a multi-channel seismic record obtained as a part of the Frontier Geoscience Program of EMR. The main features to note in this drawing are: the change in depth to the Mohorovicic discontinuity from continent to ocean (left to right) and the fractured nature of what may be the oceanic Moho (middle right). The reason for this fracturing is not yet known, but we speculate that it occurs where flow lines in the North Atlantic with different directions intersect (from De Voogd and Keen, In press, Fig. 5).



9. Predictions of the temperature and maturation history of the Scotian Basin. Solid lines are the chronostratigraphic horizons; dashed lines show the positions of the isotherms; the bold underscored line is the predicted location of the top of the petroleum generation zone. The shaded zone shows the Verrill Canyon formation and its time equivalent. This is one of several models which have been generated, using different distributions of values of stretching in the upper (beta) and lower (delta) crust. From Keen and Beaumont (1987, Fig. 6.13).

as a result of fracturing caused by increased pressures generated by fluids not able to escape. The source beds were not heated enough to produce oil until the Late Cretaceous and Early Tertiary, long after all the other factors were in place. This combination of fortunate circumstances has lead to the Jeanne d'Arc Basin being the site of all the major oil discoveries off Canada's eastern margin.

The formation of the sedimentary basins of the passive margin can be modelled in a relatively simple way. The extension is deduced from observations of crustal thickness, and the subsidence history is known from the records of the offshore wells combined with seismic reflection data. Using an approach suggested by McKenzie (1978), predictions of a variety of phenomena can be made and checked against the observations. These include the temperature history of the sediments of the basin (and thus the thermal maturity of the sediments with respect to hydrocarbons) and the change in gravity anomalies with time, in concert with the evolution of the basin. This approach has been remarkably successful in reproducing the main features of the development of the sedimentary basins, and we can for example, predict the time when sediments of a particular age will produce hydrocarbons (Fig. 9). This approach, rather simple conceptually although difficult in practice, does not of course tackle the principal problem of sedimentary basins or of plate

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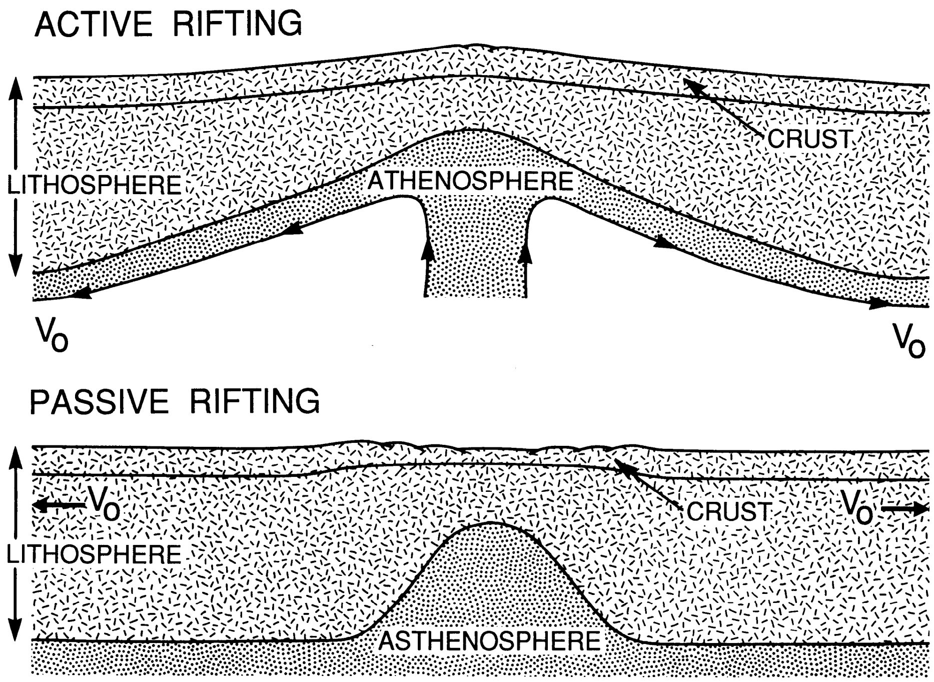

10. Sketch of rifting by active and passive driving forces, as predicted from numerical models (from Keen, 1985, Fig. 18).

tectonics: it says nothing of the processes at work, or of the forces acting on plates to produce rifting and spreading.

This problem of processes has to be approached by specifying the forces on a plate at the beginning. Two sorts of processes can be specified, one in which the lithosphere is pulled apart by forces distant from the site of rifting (passive rifting), and one in which the lithosphere is in a sense pushed apart by flow in the asthenosphere (Fig. 10). The geological consequences predicted by numerical experiments are not yet sufficiently clear on account of our ignorance of the properties of the lithosphere and asthenosphere to allow us to distinguish between these two classes of possibilities (Keen, 1985). Progress will undoubtedly come from investigations of this sort.

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Advances in marine trace metal geochemistry in the last 25 years

Philip A. Yeats and J. Michael Bewers

Phil Yeats.

OVER the past two decades, the marine geochemistry of trace metals has undergone something of a revolution. This revolution, which is largely a consequence of improved techniques for sampling and analysis, has profoundly improved our understanding of the sources, sinks, transport, and removal of trace elements in the ocean. Our aim here is to assess the nature of this revolution by contrasting our understanding of geochemical processes controlling the transport and behaviour of trace metals in the mid-sixties with that in the mid-eighties.

In the mid-sixties we knew little about how trace metals were introduced, transported, and removed within the ocean. There existed, on the basis of classical geochemical modelling, an appreciation of the aggregate oceanic throughput of elements and the manner in which seawater and marine sediments had acquired their major compositional features. This restricted understanding related to the adequacy of techniques for measuring the trace (part-per-million) compositions of rocks and sediments and the inadequacy of techniques for measuring lower concentrations in aqueous phases. Little reliable information was available regarding the occurrence of any trace constituents having concentrations of less than 1 µg/l since methods for determining their concentrations were severely limited. These were, in general, either laborious wet chemical techniques or neutron activation analysis. In a benchmark publication for this era, Schutz and Turekian (1965) attempted to understand the distribution of several trace elements, determined by activation analysis, in the world ocean in terms of sources and sinks and the intensity of biological primary productivity, but an examination today shows that the distributional data in this paper were seriously flawed as a result of contamination artifacts and limited analytical sensitivity. Most of the effort in trace element geochemistry at BIO from 1963 to 1970 went into refining instrumental activation analysis techniques for application to seawater. Although this effort was, to some extent, successful, the entire analytical base for marine trace element geochemistry research was revolutionized by the development of atomic absorption spectrophotometry.

The widespread application of atomic absorption spectrophotometry beginning in the late sixties, in combination with improved chemical preconcentration techniques, resulted in two major developments. The first of these was a rapid downward revision of estimates of the concentrations of trace metals in both seawater and freshwater. The second was the recognition of the severe biases introduced, at the new low levels being measured, by contamination artifacts at the sampling, sample storage, and preconcentration stages. This led to considerable effort being devoted to the identification and resolution of various contamination problems. By the mid- to late-seventies, major revisions to the estimates of the concentration of some metals in seawater were being made and some indications were emerging that there was a systematic pattern to the oceanic distributions of metals that was related to physical oceanographic conditions. For example, by 1976, Shutz and Turekian's (1965) estimate of the level of nickel in seawater of about 2 µg/l had fallen by a factor of ten to about 200 rig/l (Bewers *et al.*, 1976). Other techniques, such as anodic stripping voltametry, also began to play a role, especially in speciation studies and for determining the labile fractions of metals in solution. Thus, by the late seventies various sampling and analytical refinements had set the stage for the major revolution in the subject that really emerged in the early eighties. The consequences of these improvements in the quality of metal determinations are well reflected in the scientific literature and most specifically documented in the results of various international intercalibration exercises carried out since 1974.

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Largely as a result of the blossoming concerns about the state of the marine environment and a desire to better appreciate the extent of marine environmental contamination, the International Council for the Exploration of the Sea (ICES) and the Intergovernmental Oceanographic Commission (IOC) embarked on a systematic assessment and improvement of analytical techniques for the measurement of trace metal contaminants in seawater. Early intercalibration exercises conducted by ICES in the years 1974 to 1978 demonstrated that even the analysis of homogeneous artificially enhanced samples of seawater were far from acceptable in terms of accuracy and comparability. Major discrepancies existed among the results reported by different laboratories for determinations of several environmentally important trace metals (e.g., Hg and Cd) in real seawater samples. By 1980, this situation had improved dramatically (Bewers *et al.*, 1981), and

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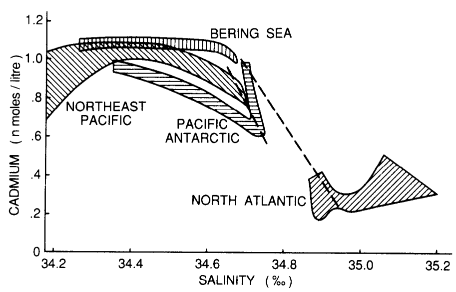
sufficient improvement in analytical reproducibility had been made to permit attention to be paid to the determination of the influences of sampling devices on sample integrity and the development of non-contaminating techniques for discriminating between the dissolved and suspended particulate fractions of metals in seawater (Bewers *et al.,* 1985). At various stages in this process of intercomparison, the relevance and importance of standards and reference materials for use in marine geochemistry became evident. Canada was the first country to establish (in 1976), principally at the behest of chemical oceanographers at BIO, a program dedicated to the production of such materials for application in marine environmental science and the improvement of associated marine analytical methodology. This program, established within the National Research Council of Canada (NRCC), has been a remarkably successful venture, partly due to the close and effective co-operation between analytical chemists in NRCC and marine chemists within BIO. It has resulted in the production of a number of novel and valuable marine reference materials for both research and regulatory application that have found acceptance worldwide (Berman *et al.,* 1985).

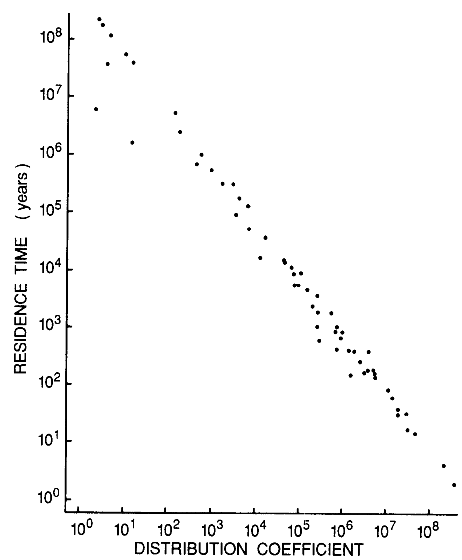
Investigations of the marine biogeochemistry of metals have generally been designed to gain an appreciation of the rates of introduction and removal of metals and the processes that control the internal oceanic transport and transformation of chemical species. To a large extent, these studies have focussed on the effects of biological activity, particle-water interactions, and chemical oxidation and reduction processes that sequester metals to particles or result in their redissolution and recycling within the ocean. Coastal geochemical studies have been directed primarily at understanding the processes that influence the transport of substances entering the sea through continental runoff. A knowledge of these processes and their magnitudes provides estimates of the extent of nearshore removal of runoff constituents and the net fluxes of substances into the deep ocean that are essential to an understanding of oceanic transport pathways and mass balances.

An early investigation using the more refined analytical techniques was a study of metal distributions on the Scotian Shelf and Slope that demonstrated statistically significant differences between coastal waters, Slope Water, and North Atlantic Central Water (Bewers *et al.,* 1976). This study also indicated the role of biological processes in depleting metal concentrations in surface waters compared to the underlying layers. The biological cycling of metals and the close similarity of the distributions of Cd, Ni, and Zn with those of the nutrients in the Pacific Ocean was clearly demonstrated shortly thereafter (See Bruland, 1983, for a review of this work). The hallmark of this work has been to produce "oceanographically consistent profiles", vertical profiles that can be explained in terms of known biogeochemical or oceanographic processes. Some attempts have also been made to interpret spatial variability in terms of geochemical and oceanographic processes including comparisons between oceans. The situation has now developed to the degree that metal distributions can be described by metal-salinity diagrams analogous to the temperature-salinity diagrams of classical descriptive physical oceanography (see Fig. 1). This figure also illustrates the extent of analytical improvements in that it reflects the consistency of data from a number of laboratories. Such collective use of data from different laboratories would not have been possible a few years ago.

Improvements in analytical techniques have facilitated advances in several other areas of geochemical research. The ongoing improvements in our knowledge of environmental concentrations and behaviour of a continually expanding suite of elements have resulted in a marked improvement in the consistency of empirical characterizations of metal reactivity in terms of particle-water interactions. This can be illustrated by the plot of marine residence time (a measure of reactivity in the ocean) versus the distribution coefficient between seawater and sediments using the most recent data (Fig. 2). This figure shows much better coherence of the data than have previous plots of this sort. This improved empiricism now permits more systematic examinations of metal distributions and partitioning in terms of basic chemical properties such as hydrolysis constants, `solubility products, and ionic potentials of elements. Another example is the role of metals in biological production studies. Early measurements of primary productivity invariably used metal concentrations far higher than those that we now know are typical of marine waters. The importance of metals either as micronutrients or toxins to phytoplankters is now being investigated at metal concentrations that more closely represent the metal levels in the marine environment. In addition, the improvements in ana-



1. Cadmium-Salinity diagram for waters of the Atlantic and Pacific oceans.

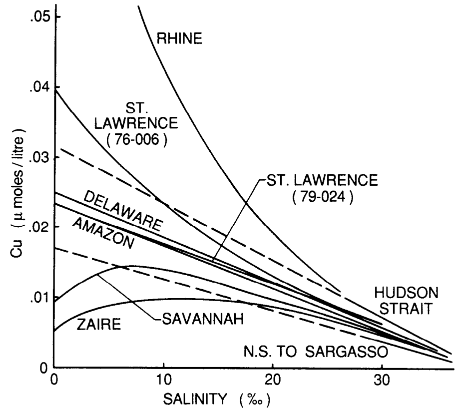


2. Oceanic residence times of elements based on inputs versus distribution coefficient between pelagic clays and seawater for 62 elements.

lytical methodology and geochemical understanding have led to more detailed investigations of the interactions between metals and biota including metal speciation and the formation of natural biometallic species.

Most of the early studies of metal geochemistry in coastal areas were undertaken to describe the spatial and depth distributions of dissolved trace metals in estuaries and coastal waters. Initial studies in estuaries resulted in some understanding of the metal concentrations and some rudimentary idea of the relationships with salinity that indicate the magnitude of removal or dissolution. Coastal zone studies were mainly directed towards establishing average concentrations in coastal waters (e.g., Preston et ***al.,*** 1972). Our contributions to this early work included studies of the St. Lawrence estuary, the Saguenay Fjord, the Gulf of St. Lawrence (Bewers and Yeats, 1979), and the Scotian Shelf (Bewers *et al.*, 1976). In addition to establishing the background levels of Mn, Fe, Co, Ni, Cu, Zn, and Cd in these waters and describing some of the fundamental variability, these initial studies provided some very interesting observations that stimulated subsequent detailed studies aimed at investigating some of the processes responsible for the observed behaviour.

Metal-salinity relationships have now been determined for a large number of estuaries, including two additional studies of the St. Lawrence estuary at different seasons. The results of many of these would seem at first to be rather contradictory, an individual metal having been reported to show conservative behaviour in one estuary, removal in another, and addition in a third. A closer examination of these results shows that these apparently contradictory observations can be rationalized. Copper, for example (Fig. 3), shows addition in the Zaire and Savannah estuaries (Moore and Burton, 1978; Windom *et al.*, 1983), conservative behaviour in the Amazon and Delaware estuaries (Boyle *et al.*, 1982; Sharp *et al.*, 1984), and estuarine removal in the Rhine (Duinker and Nolting, 1978). Our results for the St. Lawrence show estuarine removal for a voyage in May 1976, and conservative behaviour in August 1979. These differences in behaviour can be explained readily by differences in the river concentrations. For rivers with low copper concentrations, the copper distribution shows evidence of augmentation in the mixing zone. At intermediate river concentrations of about 25 nM (1.5 µg/l), conservative behaviour is evident and at higher concentrations the distribution shows evidence of copper removal during mixing. Despite these differences in river concentrations and estuarine behaviour, the copper concentrations for all these estuaries converge on a very narrow range at salinities of 30 parts per thousand or greater. For other metals, variability in estuarine behaviour is not necessarily as simply related to a single variable. Other factors including changes in redox conditions, changes in quantity and character of the suspended load, interactions with sediments, etc., can all have an effect on the metal behaviour.



3. Estuarine metal-salinity relationships for dissolved copper.

The estuarine behaviour of manganese is perhaps the most interesting because it can exhibit both addition and removal in the same estuarine transect as a result of dissolution and precipitation reactions. Our studies in the St. Lawrence estuary have shown this type of behaviour in the upper estuary and rather surprising dissolved and particulate manganese distributions in the deep waters of the lower St. Lawrence estuary (Yeats *et al.*, 1979). Dissolved Mn concentrations increase exponentially with depth reaching a maximum at the sediment/water interface. Particulate Mn concentrations are also higher in the deep water than at intermediate depth, but in this case the maximum concentrations are found some 50 m above the sediments. These distributions result from the release of dissolved manganese into the water column from the sediments followed by precipitation onto the suspended particulate matter in the deep waters of the lower estuary. Because these manganese oxide precipitates can sequester other trace metals, this process of dissolution and reprecipitation of manganese in the estuary can have an important effect on the behaviour of the more toxic trace metals.

Investigations of metal behaviour in coastal areas have not only improved our knowledge of natural distributions and variability but have provided greater insight into the processes that control them. Further, our increased knowledge of oceanic influxes and removal rates has improved our ability to estimate the impact of anthropogenic inputs and to make comparisons between natural and anthropogenic fluxes. Many of these advances have resulted from mass-balance calculations. The Gulf of St. Lawrence is an almost ideal semi-enclosed coastal/shelf system for which the influxes and effluxes of nutrients and metals can be experimentally quantified. Based upon assumptions that this system is typical of other coastal zone and shelf systems that are not amenable to similar flux measurements, the results of mass balances for the Gulf have been extended to the global ocean. Such extension provides estimates of the net influxes of runoff-derived metals into the deep ocean and the extent of shelf metal recycling, and enables construction of global oceanic mass balances (Bewers and Yeats, 1977; Yeats and Bewers, 1983). Understanding of the fluxes of metals through the Gulf of St. Lawrence and of variability in the Gulf has also been used to calculate the sensitivity of the Gulf to changes in trace metal emissions (Yeats *et al.*, 1978). It was concluded from this study that rather large changes in the inputs would be needed to see changes in the metal levels within the Gulf. More recently, we have used the mass-balance approach to make a comparison of the natural and anthropogenic components of the fluxes of cadmium in the marine environment to determine the extent to which anthropogenic activities have increased the global dissemination of this element and to examine the nature and time-scales of oceanic response to these increased cadmium fluxes.

During the last 15 years, we have learned that several metals (Cd, Zn, Ni) exhibit vertical distributions in the deep ocean similar to those of the more reactive nutrients, phosphate and nitrate, and that these distributions are the result of metal incorporation into, and release from, biological organisms during their growth and decay. Indeed, we now have some idea of the proportions of the dissolved metals incorporated and released from organisms in relation to nutrient uptake and regeneration. It has also been deduced that the major spatial features of the oceanic deep water distributions of the metals largely reflect deep water sources and physical oceanographic processes. This, in itself, allows far better resolution of anomalies in the distributions that reflect chemical reactivity. For example, some features of the distribution of manganese in the deep ocean are a consequence of the slow oxidation of Mn^{2+} in the dissolved phase to MnO_2 which is precipitated from solution and is sequestered by settling particles. These and related studies have improved our understanding of internal oceanic metal fluxes while studies of metal geochemistry in estuarine and coastal waters have greatly contributed to our knowledge of both gross and net influxes of continentally derived material into the ocean. Another major advance has been the recognition that tectonic processes near to spreading centres and other hydrothermal inputs are important sources of trace elements at the bottom boundary of the ocean.

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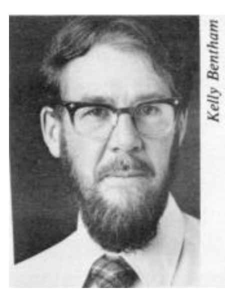
History of navigation research and development at BIO

Stephen T. Grant and David L. McKeown

Steve Grant.

WORLD War II marked the beginning of the modern era in navigation. Not only have there been remarkable improvements in existing instruments since then, but there also have been a number of totally new developments; the most significant of which are the use of radio waves, acoustic techniques,



Dave McKeown.

computers, and navigational satellites. Although the groundwork for most of these modern developments was done during and soon after the war, many really significant advances took place during the sixties and seventies, and the Bedford Institute of Oceanography was much involved in most of these developments.

Before reviewing BIO's role in modern navigation, it is important to understand the navigational needs of the scientists and surveyors carrying out oceanographic and geophysical research and hydrographic surveying in Canadian waters. The navigational requirements for marine science depend substantially on the parameter of interest. Marine phenomena can be mobile (both horizontally and vertically) or stationary and in both cases they can vary with time. Seabed features such as bathymetry, gravity, magnetics, and surficial and subsurficial geology for most practical purposes are considered to be stationary and time invariable in all but the geological time scales. Fish populations, the chemical composition of the water, tides, and such parameters as currents and eddies are generally both mobile and time variable.

Marine environmental parameters are not only difficult to measure, but the environment itself makes their measurement difficult. For example, it is relatively easy to determine the position of a stationary surface craft a few metres from shore; it is another story to determine the course, speed, rate of descent, and position of a remotely controlled subsurface vehicle relative to a bottom feature far from the nearest land.

Navigation is a limiting parameter for much marine scientific work. Navigation limits the work done and it also limits the horizons of conceivable projects. In many cases it is difficult to present absolute requirements for navigation because the nature of the work presently done might be radically modified if better navigation was available.

Early navigation at BIO

When BIO came into existence in 1962, navigation in the deep sea zone, over 1000 km from land, was based primarily on conventional astronomical techniques that had been in use for the past few centuries. The only exceptions were a low accuracy azimuthal radio navigation system called CONSOL and Loran-A skywave. Positional accuracies of 2 to 5 nautical miles were the best that could be achieved. Nearer land, radio positioning systems such as Hi-Fix, with a range of about 100 km, and Decca (both Navigational Decca and Decca Lambda), with a range of about 300 km, were capable of providing accuracies of tens to hundreds of metres under ideal conditions. But, these continuous wave systems were very susceptible to skywave interference, particularly at night and/or over long ranges; undetectable errors of a few kilometres were often present. Very near shore, in small bays and harbours, positions were determined accurately by horizontal sextant angle measurements or approximately by radar.

During the first few years, there was little change in the navigational situation at BIO, but there was considerable discussion with the growing awareness that inadequate navigation was placing severe limitations on the scientific programs. However, by 1965 Loncarevic (1969) had devised a method for accurately determining the relative position of the CSS *Hudson* over the Mid-Atlantic Ridge by using radar transponder buoys. Meanwhile Kuehnel and Loncarevic had started to investigate the use of Very Low Frequency/Omega signals for navigation in the deep ocean zone, Eaton (1966) was studying the use and accuracy of hyperbolic Hi-Fix, and Dalby (1968) was developing computer programs to calculate the ship's position automatically from Decca observations.

Elsewhere, especially in England and the United States, new radio positioning systems with a wide range of frequencies, accuracies, etc., were being developed. There were probably more than two dozen systems by the end of the sixties. However, the system that was to have the most significant impact on navigation at BIO was the Transit Satellite System or U.S. Navy Navigation Satellite System (NNSS).

The Transit Satellite System became operational for military users in January 1964 and was released for commercial use in July 1967. BIO took delivery of two receivers in early 1968 and by late 1969 they had been used extensively at sea and for land surveys. They were used for positioning on Mid-Atlantic Ridge cruises, for geodetic surveying in northern Canada and Greenland, for determining Decca Lambda lane counts, for accurately positioning moorings in Drake Passage on the HUDSON 70 Expedition and for numerous other projects (Wells and Ross, 1969; Ross ***et al.***, 1970; Brunavs and Wells, 1971). The main limitations on the use of Transit at sea were the need to know the ship's course and speed accurately during the approximately 20 minute satellite pass and the fact that it did not provide continuous positioning.

The seventies and eighties

Although from the preceding it is clear that a considerable amount of effort was being devoted to navigation studies at BIO, it was equally clear to the management of the day that this piecemeal approach could not take full advantage of all the new technological advances that were taking place. It therefore was decided that a specialist group was needed that could carry out mission-oriented research and development in all aspects of navigation. The Navigation Group came into being in late July 1970.

The study of radio-navigation systems and radio-propagation problems was an important aspect of the work of BIO researchers from the start. The navigation group continued this tradition with the study of Loran-C.

Loran-C is a hyperbolic radio navigation aid that operates at 100 kHz. It achieves long range (over 750 n.m.) and medium accuracy (0.2 microseconds or 30 m on the baseline) by making phase-comparison measurements on a pulsed groundwave signal. Loran-C was adopted by the U.S. Coast Guard as their standard coastal/confluence zone navaid in the late seventies.

Initially, the navigation group studied the system characteristics and a unique application called "rho-rho" Loran-C to determine their suitability for offshore multiparameter (hydrographic and geophysical) surveys. From 1972 onwards it was used exclusively for accurate positioning by BIO ships in the

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offshore zone where Loran-C coverage was available.

The navigation group was also closely involved with the Canadian Coast Guard in the early eighties in determining the locations of the transmitters for the new Canadian Loran-C chains on both coasts. The CHS is responsible for accurately portraying the Loran-C lattices on nautical charts. From the start the navigation group was responsible for calibrating the Loran-C lattices being published on CHS charts. The accuracy and thoroughness of the data collection and analysis procedures and the unique methods that were devised for warping the lattices to account for the peculiar overland propagation effects have enabled the CHS to extend the lattices right up to the shore with acceptable accuracy.

Throughout the years the navigation group has also studied Hi-Fix propagation over water and sea ice, Syledis propagation and performance, Mini-Ranger range holes, Polar-Fix accuracy, and many other aspects of these and other radio positioning systems.

In late 1975, the BIONAV (BIO Integrated Navigation System) project was started to combine the outputs


Kelly Bentham

Hydrographer Graham Rankine plots field calibration points for Loran-C chart latticing.

optimally from the numerous navigation devices on BIO ships. Eighty surveyors and scientists, consulted in setting BIONAV specifications, indicated that reliability, simplicity, and flexibility in input and output were generally more important user priorities than accuracy. Initially BIONAV combined the Transit Satellite system, rho-rho Loran-C, and ship's log and gyro. It used a unique method of combining the outputs from one system to check and/or supplement the inputs of the other systems. Not only did it do away with the need for continuous navigation watchkeepers and a number of error prone manual checking processes, it also achieved better accuracies than the individual components alone and provided a more reliable and consistent output, especially when the performance of the individual components degraded.

At BIONAV's peak, three systems were in operation on both coasts and over the years it has been interfaced to a wide variety of sensors and systems such as Decca Navigator, Mini-Ranger, Omega, propeller rpm and rudder angle, hyperbolic Loran-C, NAVSTAR/GPS, etc. A dozen or more copies of the software and documentation were supplied to Canadian companies and, presumably, parts of BIONAV are in use in the various commercial systems on the market to-day. One BIONAV system is still in operation at BIO and it will probably remain until GPS becomes fully operational.

NAVSTAR or the Global Positioning System (GPS) is a satellite based radio-navigation system being developed by the U.S. Department of Defence. When fully operational in the early to mid nineties it is expected to provide continuous positioning accurate to 25 m worldwide regardless of vehicle motion. GPS will have a profound effect on marine science and hydrographic surveying, thus, it is important at this early stage to keep abreast of the latest developments and to discover the strengths and weaknesses of the system before it becomes operational. To this end the navigation group has been involved in several tests and contracted studies. Items under investigation include the effectiveness of phase tracking, rough weather operation in ship and launch, multi-path effects (i.e., interference from signals reflected from the sea surface), use of low elevation satellites, differential ionospheric refraction, and the development of mathematical models to integrate differential code and phase measurements. To date it is clear that accuracies of 5 m are possible. It is also clear that there are still many problems to be solved before a system tailored to BIO's requirements can become fully operational.

The CHS began its involvement in collecting and processing digital hydrographic data in the late sixties. During the intervening years, the Service has been actively involved in the development, testing, and implementation of digital data acquisition systems for the recording and processing of hydrographic data and the processing of digital data in the chart production process. The value of the digital data itself for the maintenance of the charts and possibly its eventual use on the bridge was of course recognized. However, only with the recent advances in microprocessor technology, fast high-resolution graphics displays, and compact, high density, large capacity, digital storage devices has the concept of the Electronic Chart on the bridge of a ship been seriously considered. It is now receiving considerable attention around the world. Mariners introduced to it immediately recognize its usefulness in displaying combined position, chart features, and radar images.

In an effort to determine the demands on the Canadian Hydrographic Service that the eventual use of electronic charts will create, the navigation group has been developing a prototype system under contract. Not only have a number of technical problems been encountered, and in many cases overcome, but also a number of much broader issues have been identified such as the method and format of data transfer, both of the original chart and, perhaps even more important, chart corrections; the legal liability of the hydrographic offices around the world and the Electronic Chart manufacturers; the hydrographic database structure that will be necessary to support electronic charts in general;

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etc. Most important of all however is the necessity to demonstrate that electronic charts are a safe and reliable aid to the ship's watchkeeper.

Acoustic positioning

In oceanographic research, there is often a requirement to position sensing systems and sampling devices underwater. The positioning methods described earlier are of little use for this purpose as the electromagnetic and optical energy that they rely on only penetrates to very shallow depths. Instead, systems based on the propagation of acoustic energy in the frequency range of a few to hundreds of kilohertz are used.

There are three common acoustic positioning methods. While all rely upon measurement of the transit time of an acoustic signal between the unknown position and a reference array, they differ mainly in the dimensions of the array. Long Baseline Systems (LBS) utilize an array of seafloor acoustic sources hundreds to thousands of metres apart. Transducers for a Short Baseline System (SBS) are usually mounted only a few metres apart on a surface vessel. UltraShort Baseline System (USBS) transducer arrays have dimensions of a fraction of a metre and are also usually mounted on the vessel.

A quarter of a century ago, the operating principles of these three methods were already known. The Scripps Institution of Oceanography was using a home made LBS for positioning their deep ocean geophysical survey vehicle; Project Mohole had plans to use a combined long and short baseline system to dynamically position the drill ship. The Woods Hole Oceanographic Institution was using an SBS to position deep sea cameras during a search for a missing submarine and the US Navy was using an SBS at missile impact and torpedo test ranges. No one appeared to have a working USBS although development was underway.

Here at BIO, little happened in this field until about 1969 when a requirement developed for precise positioning of a deep sea hard rock drilling device. An early commercial LBS was purchased and interfaced to a minicomputer; survey procedures were evolved and positioning software developed. In 1970, the system was used to locate the site of six rock cores and a camera station on the Mid-Atlantic Ridge at 45° North. During that decade the system was used to position a free-fall current profiler and a seafloor vehicle designed to investigate a wrecked oil barge. Considerable effort was expended in evaluating the accuracy and improving the operational efficiency of survey methods.

In parallel with the LBS work, a short baseline system was designed, constructed, and tested. It was used for some years to position a shallow-water variant of the hard rock drill along the Labrador coast and in the Eastern Arctic. Because our LBS was cumbersome to install on the ship and to use at sea, several attempts were made to purchase a commercial ultra-short baseline system. Because of weaknesses in signal processing hardware during that decade, none of these systems passed our evaluation trials.

When one compares the present acoustic positioning systems with those of a quarter century ago, the contrast is truly dramatic. The most significant improvements occurred during the seventies. LBS and SBS time-measuring and logging systems changed from the manual scaling of graphic records and subsequent entry of data into off-line computers to fully automated simultaneous measurement and real-time display of positions of multiple acoustic sources. LBS repeatability improved from 20 m to 10 cm, and self-calibrating arrays now greatly reduce the time required for surveying the array. Perhaps even more dramatic has been the advent of the high performance USBS, a consequence of major improvements in signal processing technology over the last two decades. It now ideally complements long baseline systems. Little, if any, research is now being done on acoustic positioning methodology. Instead, research organizations are devising ever more complex and demanding experiments that utilize the technology. Meanwhile, manufacturers are concentrating on improving the performance and reliability of their equipment and reducing its size and cost.

Many commercial systems of all three types are now available and their use has become common not only by the research community but also by the commercial/industrial sector. Acoustic positioning systems are routinely being used for a wide variety of applications ranging from tracking movement of water masses in the open ocean to the precise placement of bridge piers in a shallow lake. However, the advent of high-quality worldwide surface-positioning systems has virtually eliminated the use of acoustic positioning for all but very specialized surface positioning requirements.

Acoustic positioning work at BIO has kept pace with these developments. Although the LBS hardware presently in use here does not contain the latest technology, it is adequate for the work required of it. For example, the transponders are not of the self-calibrating type. However, a way has been devised to use a pair of transponders on each mooring to perform the same function. A few years ago, the home-made SBS was replaced by an up to date commercial system that then underwent extensive field testing before going into service as a positioning system for geophysical towed sensor systems and seafloor samplers. A state-of-the-art USBS was also purchased recently and its performance parameters defined in an operational environment. Methods were devised to use it in a portable mounting over the vessel's side rather than in a permanent mounting within the vessel. It has recently been integrated with a specially modified acoustic source to create an effective current-meter mooring relocation system. At present, both the LBS and the USBS are being integrated into a positioning system being designed to track Lagrangian surface drifters.

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Tidal fronts and tidal mixing

David A. Greenberg and Peter C. Smith

Dave Greenberg.

IN the coastal communities around the Bay of Fundy and Gulf of Maine, the way of life is strongly influenced by the tides. The largest tides in the world not only restrict the sea transportation on which these communities rely, but also control much of the mean currents, play a large part in the fisheries productivity on which many of the residents depend, and can even have a significant influence on the local climate. The major Gulf of Maine fishing grounds for cod, haddock, herring, lobster, and scallops are all located in or near areas of intense tidal mixing. The mixing of the cool water keeps the air temperature lower in the spring and summer and promotes fog formation. In the winter, tidal mixing can prevent ice formation and the surface water then warms the coastal air. In the past 25 years, BIO has been part of a major effort in studying how the tides mix the oceans and why this mixing has such a strong influence on the very productive fishing areas.

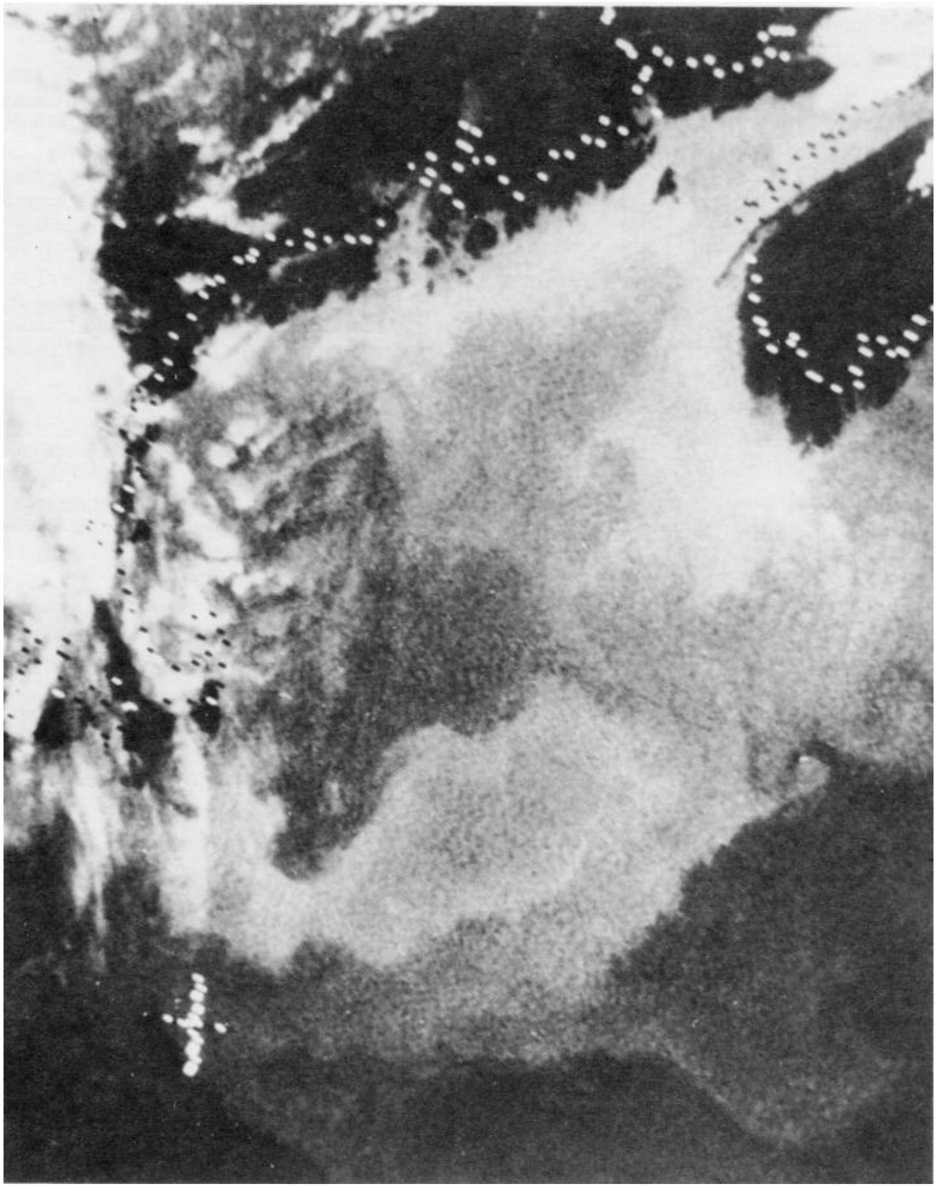
Early work

With the tools of modern technology, such as satellite infared imagery (Fig. l), we can make detailed observations giving us a good picture of the surface temperature over the Gulf of Maine, from which we can infer tidal mixing. The pioneering work of Huntsman (1924) and Bigelow (1927) was based on sparser data, yet the picture that emerged (Fig. 2a) has not greatly changed to this day. Huntman's observations in the Bay of Fundy were incorporated into Bigelow's treatise on the Gulf of Maine. In both cases, the well-mixed areas were delineated and the importance of the tide in mixing these areas was clearly identified. Hachey's (1952) detailed summary of observations in the Bay of Fundy reiterated the importance of tidal currents to the mixing in the Bay. On the European Continental Shelf, tidal mixing was also considered to be an important factor in determining water characteristics, for example, the low sea surface temperatures in the English Channel, which lead to fog formation in the area.

In the years since BIO was founded, there has been progress along two lines that has allowed scientists to advance from the qualitative, descriptive state of the art that existed previously. One of the developments has been the improvement in instrumentation that provided much more detailed observations. The other was the development of a theory that was capable of predicting the frontal boundary between the mixed and stratified regions from a knowledge of the strength of the tidal currents and the depth of the water. As a result of these two advances, the relationship between tidal mixing and the rich fishing grounds was becoming more evident.

Instrumentation

The observations of Huntsman, Bigelow, and Hachey were based mainly on bottle and thermometer data. These were used to calculate salinity and temperature profiles at stations typically separated by many kilometres and with vertical resolution of 5 m or more. When Simpson and Hunter (1974) first derived the formula that delineated the front separating mixed and stratified areas (see "Theory and modelling" below), they were able to confirm their



1. Satellite infrared image of the Bay of Fundy and Gulf of Maine showing surface temperature. Tidally well mixed areas in the upper Bay of Fundy, off Southwest Nova Scotia, and over Georges Bank are delineated by sharp contrasts in temperature from adjacent waters.

predictions with ART (Airborn Radiation Thermometer) data giving surface temperature values every 50 m and CTD (conductivity temperature depth recorder) data that could resolve vertical variations of a few centimetres. In later field studies (e.g., Denman and Herman, 1978), scientists were able to use a new device called BATFISH, a towed undulating body that carries a CTD for profiling the ocean's surface layers. BATFISH provides good resolution in both the vertical, down to depths of 400 m, and the horizontal; this allowed the structure of the front separating the mixed and unmixed areas to be well defined. In more recent studies (e.g., Simpson and Bowers, 1979) satellite infrared imagery has been used to give an instantaneous picture of the surface temperature, which often reflects variations in stratification due to tidal mixing (Fig. 1).

The Bedford Institute of Oceanography has been involved in CTD development from its earliest stages, in a collaboration with the National Research Council of Canada and Guildline Instruments Ltd. Subsequent development has included motion control systems and sensors (Dessureault, 1976). High-resolution measurements of dissolved oxygen, fluorescence (a measure of biomass), and optical and electrical sensors that count planktonic particles along with the physical variables are now helping to show how the primary productivity is related to tidal mixing (Herman and Denman, 1977).

Theory and modelling

A major step forward in tidal mixing theory was taken by Simpson and Hunter (1974). In earlier work, Simpson had attributed mixing in the Irish Sea to tidal currents, but the 1974 analysis showed that the boundary or front between the well-mixed and stratified areas occurred where the parameter h/U^3 (where h is depth and the U the tidal current amplitude) was a constant. This parameter is proportional to the ratio between the rate at which stratification is produced by buoyancy input and the rate at which it is destroyed by tidal mixing and dissipation. The front occurs where the two rates are equal. It was assumed that the buoyancy inputs - solar heating or fresh water runoff - are relatively uniform over the region, so that the horizontal variations in stratification are governed primarily by the ratio of depth to dissipation. Depth and current are a basic part of the formulation of barotropic numerical sea models. Garrett ***et al.*** (1978) (Fig. 2b) used the Bay of Fundy - Gulf of Maine model that was employed for tidal power studies (Greenberg, 1979) to examine variations in the mixing parameter over the region and found reasonably good correspondence between theory and observations. Other studies showed similar agreement in European waters and other Canadian seas (Pingree and Griffiths, 1980; Griffiths *et al.*, 1981).

As these studies proceeded, it became clear that areas of intense tidal mixing were often associated with the richest fishing grounds or spawning areas (e.g., Iles and Sinclair, 1982). The theoretical mechanism for this was pieced together with observations from several areas (Pingree *et al.*, 1978, Denman and Herman, 1979, Fournier *et al.*, 1984).

The nutrients essential for phytoplankton growth are carried upward from the bottom and mixed throughout the water column by the tides. In shallow areas, or in quieter areas near the mixing zone where these nutrients remain for a long enough time in the euphotic zone (water shallow enough for sunlight to penetrate), photosynthesis can take place and so phytoplankton can grow. This primary production is step one in the food chain. Around the Gulf of Maine, there exist strong and diverse concentrations of sea creatures rooted to specific tidal mixing zones. An example is found near Brier Island, which in the late summer is surrounded by zooplankton, krill (shrimp), birds, fish, seals, and whales. In more northern waters, Sutcliffe *et al.* (1983) described a progressive development of the food chain starting with its initiation in Hudson Strait by tidal mixing. They trace this succession, within a given water mass as it is advected by the mean currents, down to the large cod stocks found on the southern Labrador Shelf.

The mixing parameter has been examined from many viewpoints. Garrett *et al.* (1978) found that at the tidal front, only 0.26% of the energy dissipated by friction was expended in the mixing process. The efficiency of mixing was reduced in stratified water and thus the front did not strictly follow spring-neap tidal variations (Simpson and Bowers, 1979; Loder and Greenberg, 1986). The studies also showed that winds can play a major role in determining the extent of the mixing regions. In their update on Gulf of Maine mixing, Loder and Greenberg (1986) (Fig. 2c) tried to refine the descriptions of the processes that lead to tidal mixing. They found that existing data were not sufficient to choose between the h/U^3 mixing parameter and other criteria based on the near surface energy balance or the bottom Ekman layer thickness.

The future

Even with the recent increases in quantities and resolution of data, new theories are going to need more and better data to be fully tested. At the Bedford Institute of Oceanography, instrumentation and theory are being developed hand in hand. The spatial and temporal variability of the turbulence at tidal fronts and in tidally mixed areas is being examined using state of the art instrumentation that is able to resolve temperature and velocity changes at scales of millimetres. BIO's image processing facility will be able to synthesize data from the coming generation of satellite sensors that promise to give a detailed picture of biological activity over wide areas. Modelling sophistication is increasing with three dimensional mixing models now being developed. Thus, BIO's research into the phenomenon of tidal mixing will continue to make important contributions.

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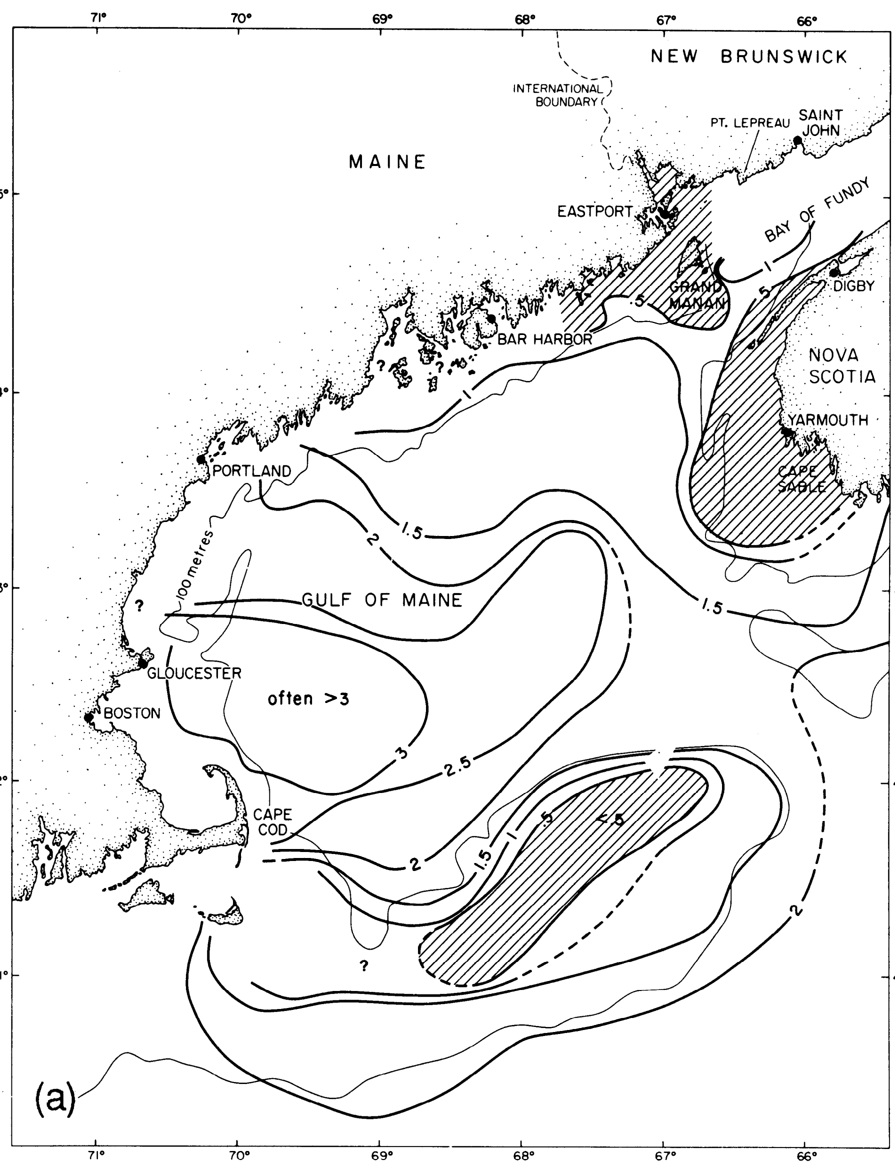

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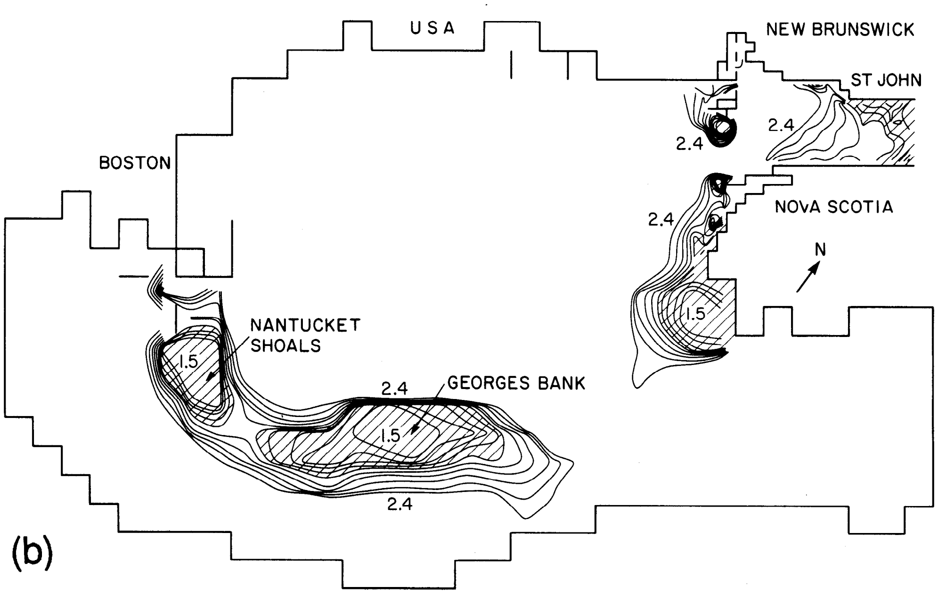
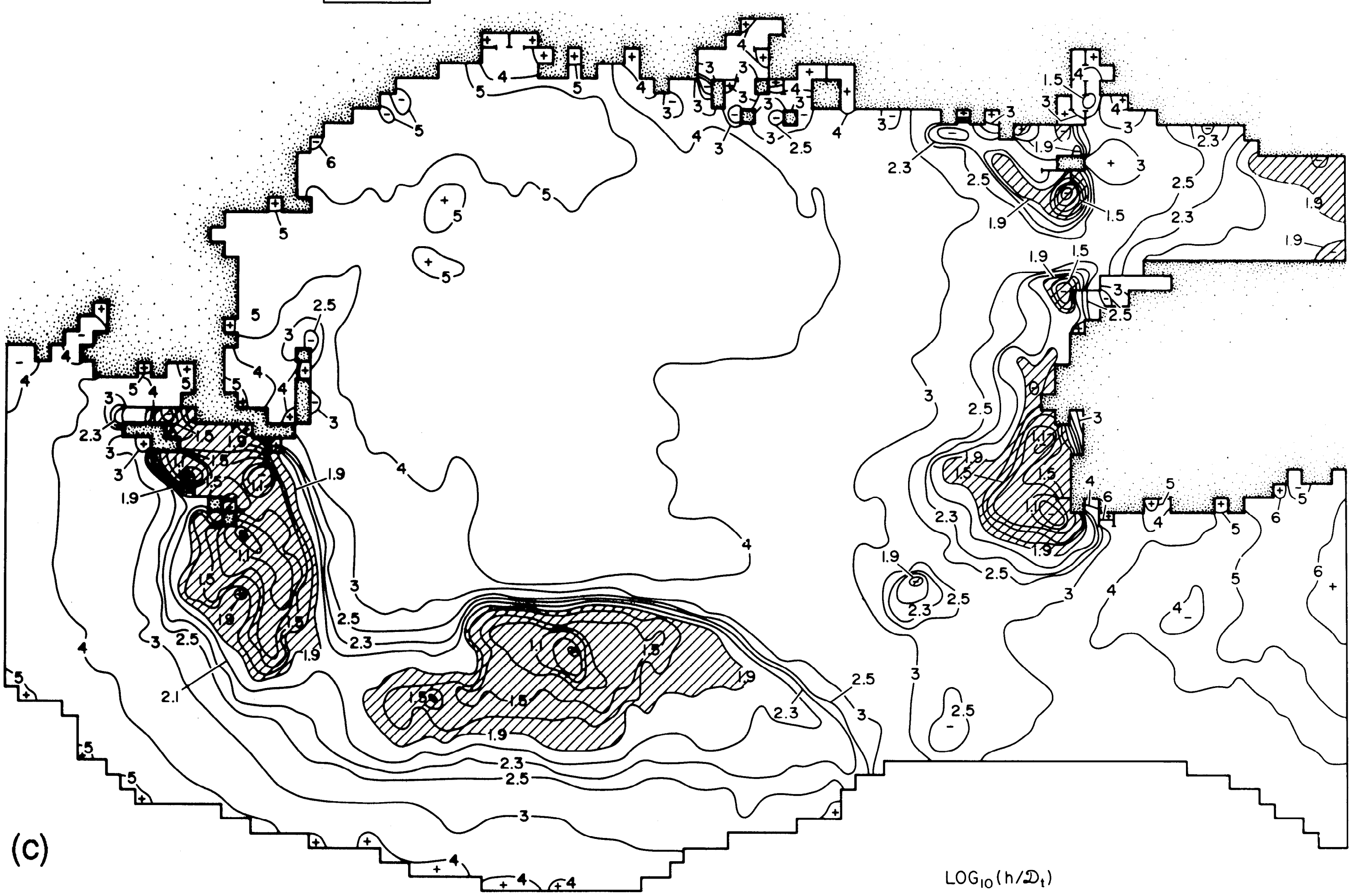




2. The development and refinement in identifying the tidally-mixed areas in the Gulf of Maine from (a) Bigelow (1927) where values of 0.5 kg/m^3 or less in the density contrast indicate mixed areas, (b) Garrett, Keeley and Greenberg (1978) and (c) Loder and Greenberg (1986) numerical model results where values of the mixing parameter of less than 1.9 indicate well-mixed areas.

Ocean climate

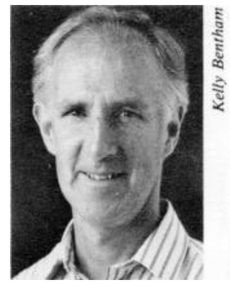
R. Allyn Clarke and Fred W. Dobson

Allyn Clarke.

DURING the sixties, a good-natured argument raged within the physical oceanographic community over whether the field should be renamed oceanology in order to symbolize a transition from the process of mapping the ocean to a search to understand the ocean. Now in the eighties, in spite of the fact that we have a far greater understanding of many of the processes that move and mix the waters of the ocean, it seems clear that we will remain oceanographers in name and to a large extent in function for a few more decades at least. Many of our current ideas about how the ocean moves in response to the atmosphere are based on interpretations of patterns seen in the rather sparse data sets available from the seagoing programs of oceanographic institutions.

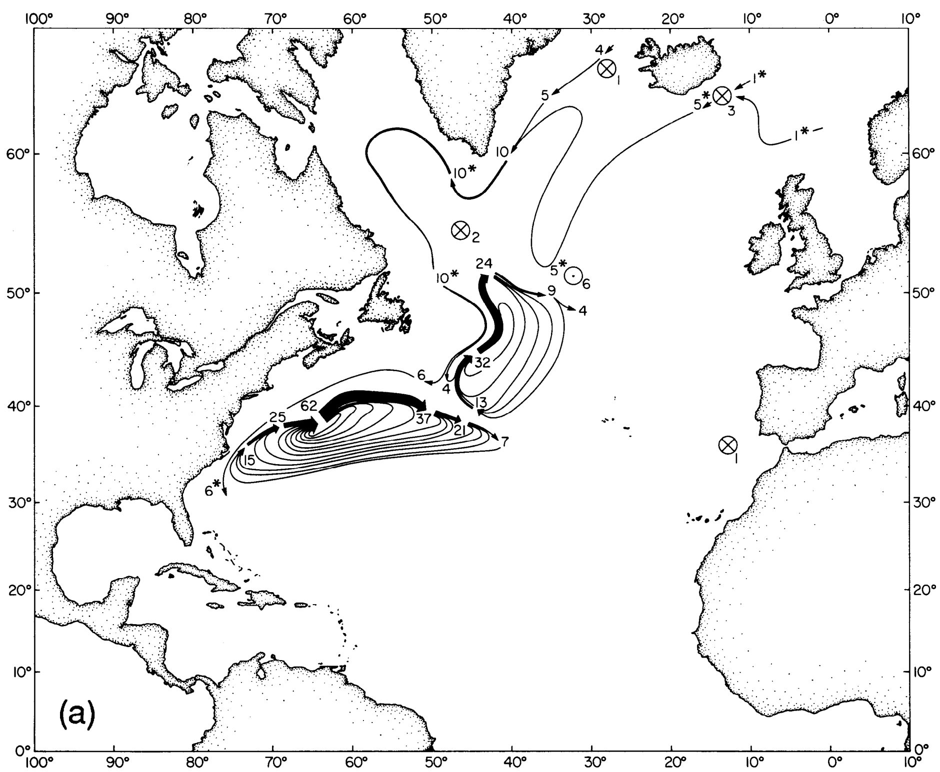
The year that BIO was opened, Worthington (1962) published a novel interpretation of the North Atlantic circulation. He argued that the Gulf Stream turned southwards southeast of the Grand Banks of Newfoundland and that the waters that flowed northeastward across the North Atlantic towards Europe were part of a second circulation gyre. Worthington had created his hypothesis in response to two observations. First, in the central Atlantic, as in the interior of the subtropical gyres of all the oceans, there is a layer at depths of hundreds of metres in which the oxygen content is a minimum. The oxygen content of the water in this oxygen minimum layer increases as one moves from the Sargasso Sea northward past the Tail of the Grand Banks of Newfoundland into the Newfoundland Basin and thence into the Labrador Basin. If the waters of the Gulf Stream flow directly around the southeast corner of the Grand Banks, he argued, then the oxygen content in the oxygen minimum layer should not change as the waters flow in a strong current such as the Gulf Stream.

Worthington then looked at the data collected along a section of hydrographic stations running from southwest to northeast across a topographic ridge, the Southeast Newfoundland Ridge, that extends southeasterly from the Tail of the Banks towards the Mid-Atlantic Ridge. He noted that there was a trough of cold, lower salinity water over the axis of the ridge separating Sargasso-Sea-type waters in the southwest from the cooler waters of the North Atlantic Current in the northeast.



Fred Dobson.

This new concept (Fig. 1) had serious implications on how the Atlantic Ocean operated as part of the global climate system. Millions of school children had been taught by geography teachers for years that Europe was milder than eastern North America because of the heat that the Gulf Stream carried from the



1. (a) Deep circulation (0 to 4°C) in the eastern North Atlantic after Worthington (1976). Note the complete separation of the f`low into two gyres off the Tail of the Banks. (b) Dynamic topography in the region of the Tail of the Grand Banks (Clarke et al.*, 1980). Note the splitting of the Gulf Stream into two components, one flowing to the north, the other to the east.*

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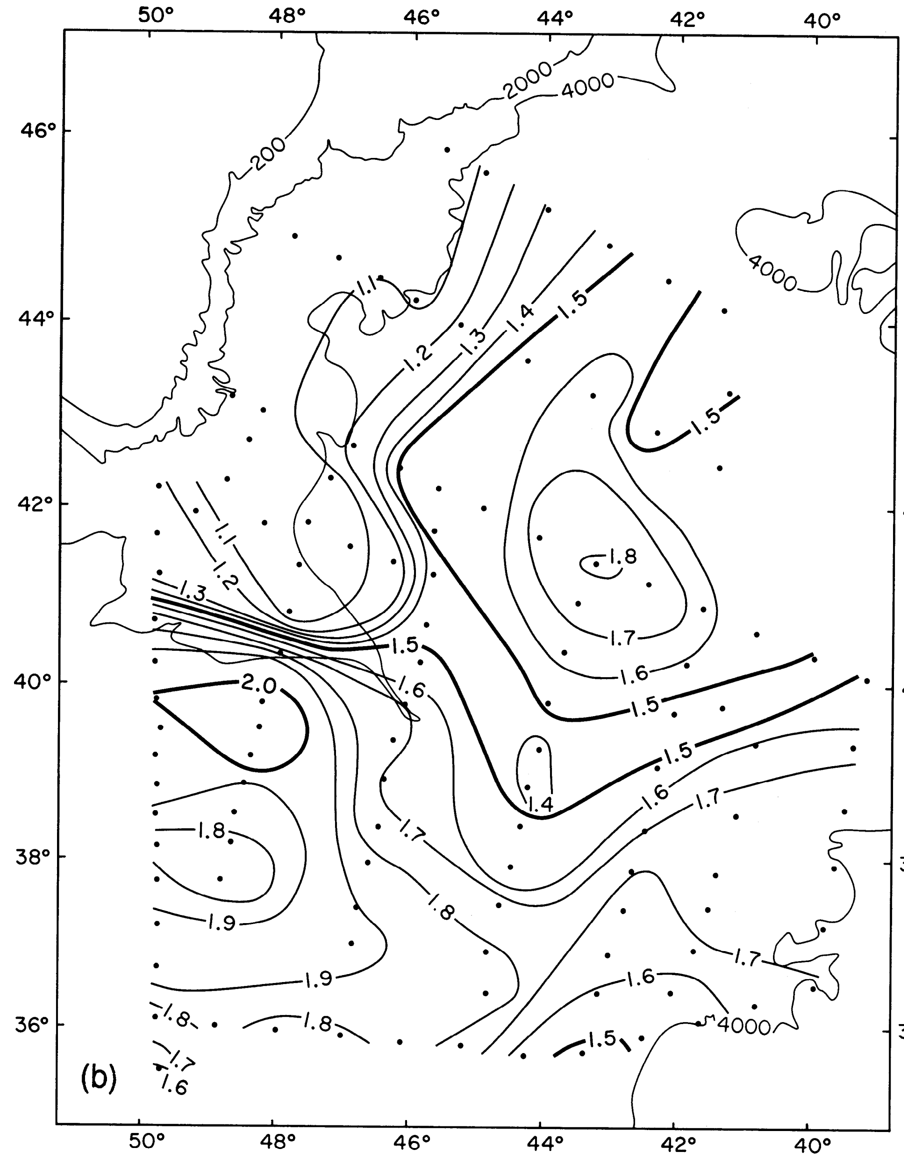

Gulf of Mexico northeastward across the Atlantic. If Worthington's new model was correct, then the waters that warm Europe would have to arise in the temperate rather than the tropical latitudes or else be transferred between the Gulf Stream and the North Atlantic Current by some smaller scale process such as mixing. The difficulties went beyond the question of where the heat in the upper waters of the North Atlantic Current came from. In the Nordic seas north of Iceland, water is cooled to great density during the winter. Because this water is of greater density than the waters to the south, it flows over the ridges joining Greenland to Iceland to the Faeroe Islands to the Shetland Islands and then flows equatorward as a well-identified bottom current along the lower continental slope of Greenland and North America. This deep water flowing south has to be replaced by other waters flowing north. Before Worthington, this was assumed to be done by Gulf Stream waters. Oceanographers had to show that his model was incorrect or develop new ideas of how the ocean balanced its water flows and transferred its heat northwards.

Steele *et al.* (1962) and Volkmann (1962) both reported on measurements of key transport values in the North Atlantic by blending velocity estimates obtained by the new technique of tracking neutrally-buoyant floats with classical hydrographic sections. The first article reports on measurements south of Iceland where floats were placed in the deep waters exiting the Norwegian Sea across the Iceland-Faeroe ridge and flowing westward south of Iceland. The second article deals with the southward flow along the lower continental slope south of Cape Cod. These two articles still present two of the few estimates of the deep water transport equatorward in the North Atlantic.

Modelling, too, was just beginning. Eriksson (1962) used some of the radionuclide data sets that were just beginning to become available and created a simple box model of the ocean from which he estimated mixing rates and residence times. Much of what we believe today about the rates of exchange of the abyssal waters of the ocean is based on data sets and box models that are outgrowths of work such as this.

The published papers of 1962 represented work that was completed several years earlier. From the abstracts of the spring 1962 AGU (American Geophysical Union) meeting it would appear that the interests of a large percentage of physical oceanographers were pointed to the equatorial regions where the properties of the newly rediscovered Equatorial Undercurrent were being explored. There is also a report (Wennekens, 1962) on an instrument that measured sound speed and temperature continuously with depth as it was lowered through the water. This is an early movement toward today's CTD although engineers soon decided that it was easier to measure conductivity than sound speed to the accuracy necessary for hydrographic measurements. Robinson (1962) discussed the possibility of using objective analysis on a computer to determine the seasonal variation of the upper ocean temperature field of the North Pacific from bathythermograph (BT) data. Finally, Bryan (1962) reported on a calculation of the heat transport across various latitudes in each of the oceans based on the heat fluxes across the sea surface and hydrographic sections.

In 1987, 25 years later, the world oceanographic community is in the third year of an experiment (TOGA) to understand the upper layers of the tropical oceans and their connections with the global atmospheric dynamics as well as in the midst of the scientific planning

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for a global oceanic experiment (WOCE) designed to collect the data and develop the models that will give us a measure of all the important components of the ocean circulation and their interactions with the atmosphere. In each of these experiments, we will be relying heavily on those techniques such as neutrally buoyant floats, CTD packages, and objective analysis of large-scale data sets by computers that were just being developed 25 years ago. In addition, these large scale experiments are being designed on the basis of concepts that arose from regional experiments run by various institutions and groups of institutions over the years.

Many regional experiments have involved BIO. One of the first areas in which BIO's physical oceanographers became active was offshore of the Tail of the Banks. On the basis of two major oceanographic voyages in 1963 and 1964, Mann (1967) offered an alternative circulation pattern in this region, which had a significant portion of the Gulf Stream waters move around the Banks and join the North Atlantic Current. A final three-vessel, three-institution (BIO, WHOI, and the Fisheries Laboratory in Lowestoft, UK) project in 1972 used a combination of deep-sea moorings, hydrographic stations including nutrients and oxygen content analysis (Fig. lb), and extensive XBT surveys to establish that the circulation pattern proposed by Mann (1967) was the most probable (Clarke ***et al.,*** 1980).

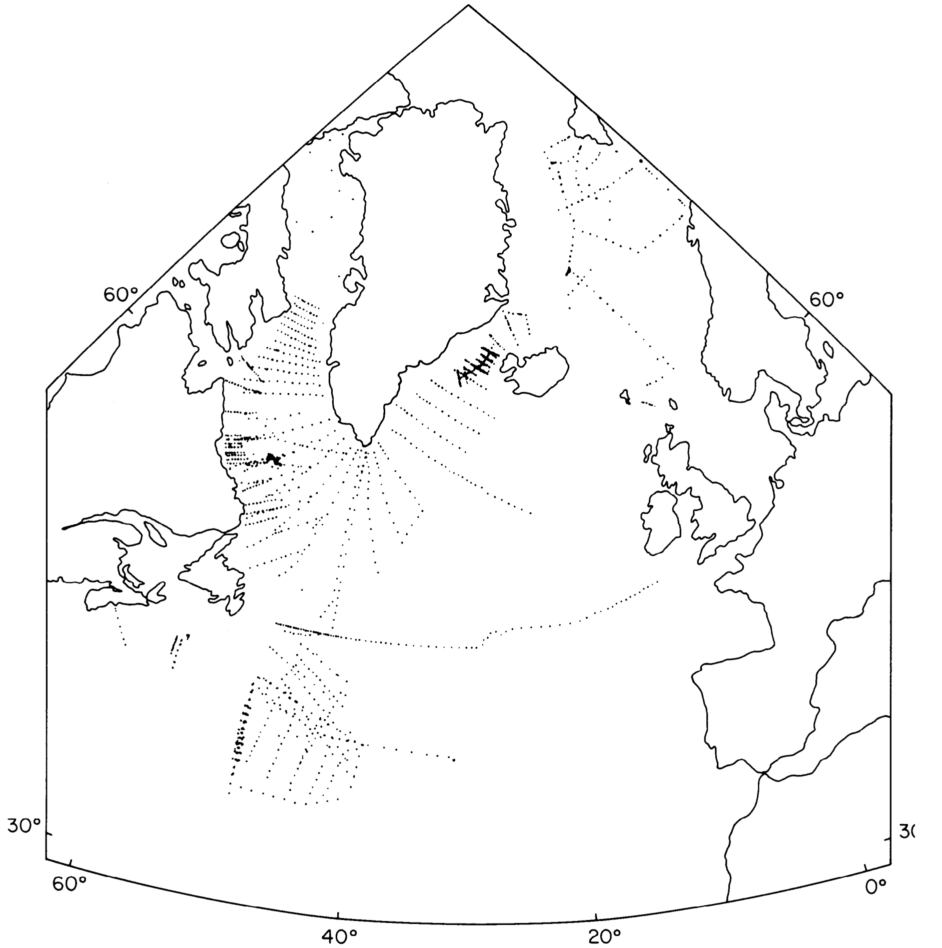
Much of the deep waters found throughout the world oceans at depths below 2 km sinks to these depths by surface cooling in the high latitudes of the North Atlantic. In the late sixties, BIO conducted an extensive series of winter observations of temperature and salinity all around Greenland from Davis Strait to Denmark Strait (Lazier, 1973). While this voyage failed to find direct evidence of intermediate and deep water renewal by deep convection from the surface, the data set consisting of a series of sections radiating out from Greenland all the way from Davis Strait around Cape Farewell to Denmark Strait has been used by several theoreticians to develop objective analysis schemes to recover absolute velocity fields from hydrographic and tracer data.

During this winter cruise, an attempt was made by WHOI to measure the velocity of the deep water spilling over a submarine sill across the Denmark Strait into the deep North Atlantic. This attempt largely failed when the unexpectedly strong currents pulled the mooring buoyancy packages below their collapse depth. Five years later, BIO successfully maintained a mooring array in Denmark Strait for a one month period as Canada's contribution to the multinational ICES (International Council for the Exploration of the Sea) co-ordinated Overflow '72 project. These moorings provide us with the best estimates of the volume of deep water entering the North Atlantic and its temperature and salinity characteristics. The latter aspect of this measurement is particularly important since it showed that the greatest volume of water overflowing Denmark Strait was not the very dense bottom water that is formed in the Norwegian Sea but rather the less dense intermediate water that is formed just offshore of the East Greenland current, which flows southward over the East Greenland Shelf and serves as the outflow of cold low salinity waters from the Arctic Ocean. The Overflow '72 moorings will be used to plan the mooring array required in the nineties to monitor the inflow of deep water into the North Atlantic for WOCE.

Since this epic winter cruise around Greenland, the Labrador Sea has certainly become BIO's sea. In 1976, a new BIO winter expedition to the Labrador Sea observed deep convection to depths of nearly 2 km, thus, demonstrating conclusively that the Labrador Sea Water, an intermediate water mass found over most of the northwestern North Atlantic, is created by deep convection driven by atmospheric cooling of the surface layers of the ocean (Clarke and Gascard, 1983). The newly formed Labrador Sea Water was cooler and less salty although of the same density as the waters seen in the Labrador Sea some 10 years earlier. An analysis by Lazier (1980) of the oceanographic data collected by the US Coast Guard from the Ocean Weather station ***Bravo*** in the central Labrador Sea showed that, during the late sixties, low salinity surface water appeared and suppressed deep convection because of its lower density. Eventually, deep convection did occur during the extremely severe winter of 1972 carrying the low salinity signal to deeper layers. It is this low salinity surface layer that resulted in the very low salinity cold Labrador Sea Water that was observed forming in 1976.

Before these observations, oceanographers had tended to implicitly assume that unique, named, water masses such as the Labrador Sea Water retained their temperature/salinity characteristics over long periods of time. After all, stations observed by *Challenger* more than 100 years ago showed basically the same water masses as modern stations. The idea that an intermediate water mass such as the Labrador Sea Water could change significantly over only a decade was an important new constraint in the sampling strategy for oceanography. Discussions at the ICES Oceanic Hydrography Working Group revealed that the appearance of low salinity water occurred everywhere in the subpolar North Atlantic over the sixties and seventies. The timing of its appearance at various locations around the gyre gives some valuable information concerning the speed of the gyre circulation and the rate at which water is exchanged vertically to denser levels. This signal was even detected in the overflows of deep water through Denmark Strait into the North Atlantic (Fig. 2).

A successful climate program not only requires an understanding of the state of the ocean but also a means to estimate the momentum, heat, and moisture fluxes between the ocean and atmosphere that serve to drive their circulations. In 1962, oceanographers and meteorologists were estimating these fluxes with empirical formulae that related them to bulk properties of the media, such as wind velocity, air and sea temperature, and so on. In 1963, M.I. Budyko published his famous "Atlas of the Heat Balance of the Earth", which used the bulk formulae to produce a detailed global budget, constrained only by the requirement that it balance over



2. Hydrographic/tracer stations occupied by BIO in the North Atlantic on large scale climate related projects since 1966.

the year to zero. Budyko's budget is still used in regions where more accurate estimates of the fluxes are unavailable (e.g., the Southern Oceans).

Meanwhile the theory of turbulence had progressed enough by 1962 for a number of groups to consider making direct measurements of the momentum, heat, and moisture fluxes. At the time, the Russians had laid the groundwork (Monin and Oboukhov, 1960; Gurvich, 1961) and were the furthest ahead, but the Germans (e.g., Roll, 1963) were active as were two groups in Canada: one at UBC (Pond *et al.*, 1963) and one at BIO (Doe, 1963).

From 1960 to 1980, a strong coupling grew up between the two Canadian groups. Doe, and after him Smith, developed a thrust anemometer system usable in open sea conditions. Mounting it on a stabilized spar buoy, BIO obtained the first wind stress and heat flux measurements in gale force winds (Smith, 1980), still widely quoted today. A smaller mast on the shores of Sable Island produced the most comprehensive set of moisture flux measurements published to date (Anderson and Smith, 1981).

Meanwhile, a combination of a severe drought in the Sahel and the fear of a "Greenhouse Effect" from man-made atmospheric CO_2 led the WMO, ICSU, IOC, and SCOR to establish a World Climate Research Programme (WCRP) with the goal of understanding our climate well enough to model and predict it. BIO has been involved from the beginning in the planning for WCRP. An important step towards a better understanding of climate is to design key experiments aimed at quantifying various parts of the climate system. At this time, there is still considerable disagreement between oceanographers and meteorologists over the proportions of heat carried poleward by the atmosphere and ocean across various circles of latitude.

BIO took the lead to co-ordinate a feasibility study to determine whether it would be possible to measure the meridional heat transport of an ocean to an accuracy sufficient to constrain climate modelling (10 Watts/m averaged over the North Atlantic; Dobson *et al.*, 1982). This study examined three possible techniques: area integration of the surface fluxes; a budget of incoming solar radiation and of atmospheric and oceanic heat transport and storage with the meridional oceanic transport as a residual; and direct oceanographic determination of the flux across a line of latitude. All failed the test for one reason or another, leaving the WCRP with some important outstanding process studies that are urgently required. Some of these studies, which are aimed at the improvement of the bulk formulae, are presently in progress at BIO. The HEXOS program (Humidity Exchange Over the Sea; Smith and Katsaros, 1983) has provided the first

Kelly Bentham

Roger Cassivi and George Fowler check the electronic components of an ice forcast buoy used to monitor via satellite the annual freeze-up of the Gulf of St. Lawrence.

open-sea measurements of the moisture fluxes in high sea states. Dobson and Smith (1985) re-evaluated the accuracy with which incoming solar radiation to the sea surface can be corrected for the effect of cloud cover as described by standard WMO cloud codes.

The WCRP has decided that an ability to realistically model the global oceanic circulation and water mass distributions is important if climate models are to be able to predict climate variations over time scales of decades and longer. Such oceanic models will be especially important when considering the climatic consequences of increasing CO_2 or other similar man caused changes. For this reason, the WCRP has defined the World Ocean Circulation Experiment (WOCE), a combined observational and modelling effort on the global scale, which will form the basis for modelling the fully coupled atmosphere-ocean system in the nineties and beyond. BIO scientists are playing important roles in the planning of this experiment and hope to play an equally important role in its execution.

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Charts and Publications

CHART PRODUCTION

The Scotia-Fundy Region of the Canadian Hydrographic Service has a cartographic staff of 27 and responsibility for 424 nautical charts covering Canada's east coast from Georges Bank to Prince of Wales Strait in the Arctic.

The charts produced can be divided into three types. A New Chart is the first chart to show an area at that scale or to cover an area different from any existing chart. These charts are now constructed to the metric contour style in bilingual form using new formats. A New Edition is a new issue of an existing chart showing new navigational information and including amendments previously issued in Notices to Mariners. New navigational information may include new Loran C lattices from a recent extension in coverage, new shipping terminals, or a new International Boundary such as the one through Georges Bank. A Reprint is a new print of a current edition that incorporates amendments previously issued in Notices to Mariners.

CHS (Atlantic) completed another successful year of chart production in 1985. In addition to those New Charts and New Editions listed below, 85 chart amendments and 6 paste-on patches were issued through Notices to Mariners from the review of some 10,000 chart related items.

Hydrographers target a horizontal survey control station for aerial photography to establish shoreline reference points.

New Charts

4844 Cape Pine to/a Renews Harbour
4845 Renews Harbour to/a Motion Bay
5335 Riviere George
5373 Approches a/Approaches to Riviere George
5376 Approches a/Approaches to Riviere Koksoak

New Charts (by Contract)

7511 Resolute Passage
7512 Strathcona Sound and/et Adams Sound
7568 Lancaster Sound and/et Admiralty Inlet
7569 Barrow Strait and/et Wellington Channel

Special Charts

M-302 75th Naval Anniversary Commemorative Chart
10041 Strait of Belle Isle to/a Davis Strait Fisheries and Oceans Statistical Chart

New Editions

4306 Strait of Canso and/et Southern Approaches/Les approches sud
4315 Sydney Harbour
4316 Halifax Harbour
4356 Liscomb and Marie Joseph Harbours
4391 La Have River
4588 St. John's Harbour
4614 Argentia Harbour
5153 Napatalik to Iglosiatik Island
7212 Bylot Island and Adjacent Channels
7935 Crozier Strait and/et Pullen Strait
7950 Jones Sound, Norwegian Bay, and Queen's Channel

New Editions (Loran C) (by Con tract)

4020 Strait of Belle Isle
4321 Cape Canso to Liscomb Island
4335 Strait of Canso and Approaches
4363 Cape Smoky to St. Paul Island
4367 Flint Island to Cape Smoky
4374 Red Point to Guyon Island
4375 Guyon Island to Flint Island
4403 East Point to Cape Bear
4404 Cape George to Pictou
4405 Pictou Island to Tryon Shoals
4406 Tryon Shoals to Cape Egmont
4462 St. George's Bay
4463 Cheticamp to Cape Mabou
4464 Cheticamp to Cape St. Lawrence
4574 Approaches to St. John's

PUBLICATIONS

We present below an alphabetical listing by author of BIO publications for 1985, produced by the Atlantic Oceanographic Laboratory, Marine Ecology Laboratory, Atlantic Geoscience Centre, Marine Fish Division, and Atlantic Region, Canadian Hydrographic Service. Articles published in scientific and hydrographic journals, books, conference proceedings, and various series of technical reports are included. For further information on any publication listed here please contact Library Services, Bedford Institute of Oceanography, P.O. Box 1006 Dartmouth, Nova Scotia, Canada B2Y 4A2.

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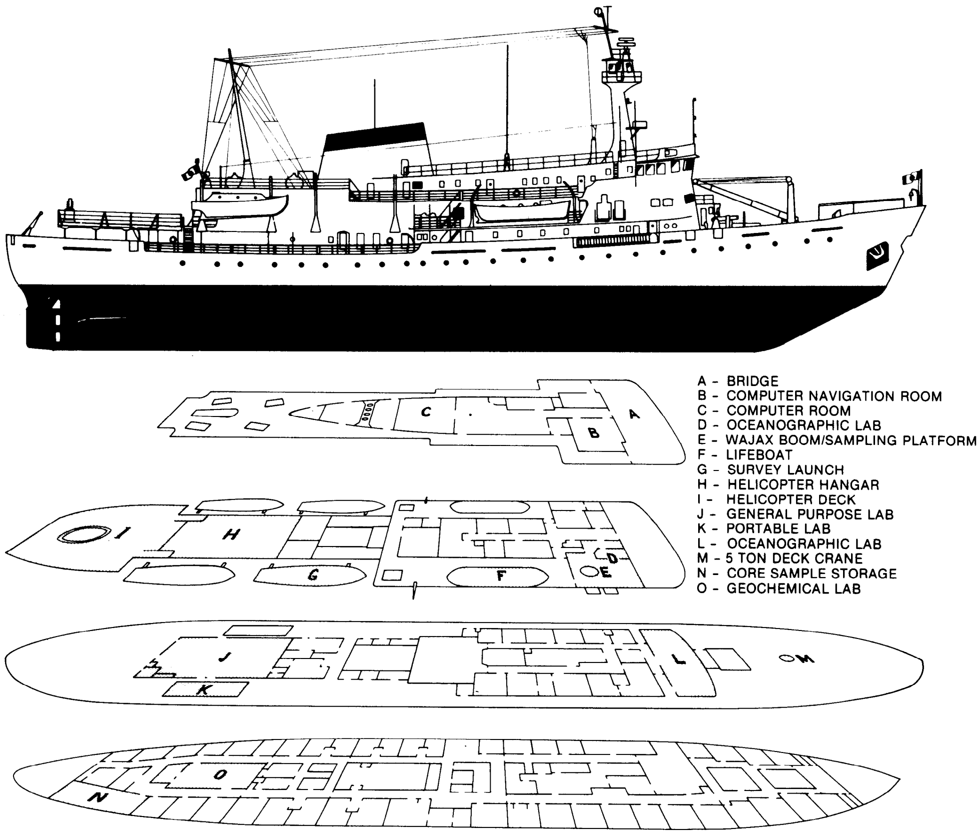
Voyages

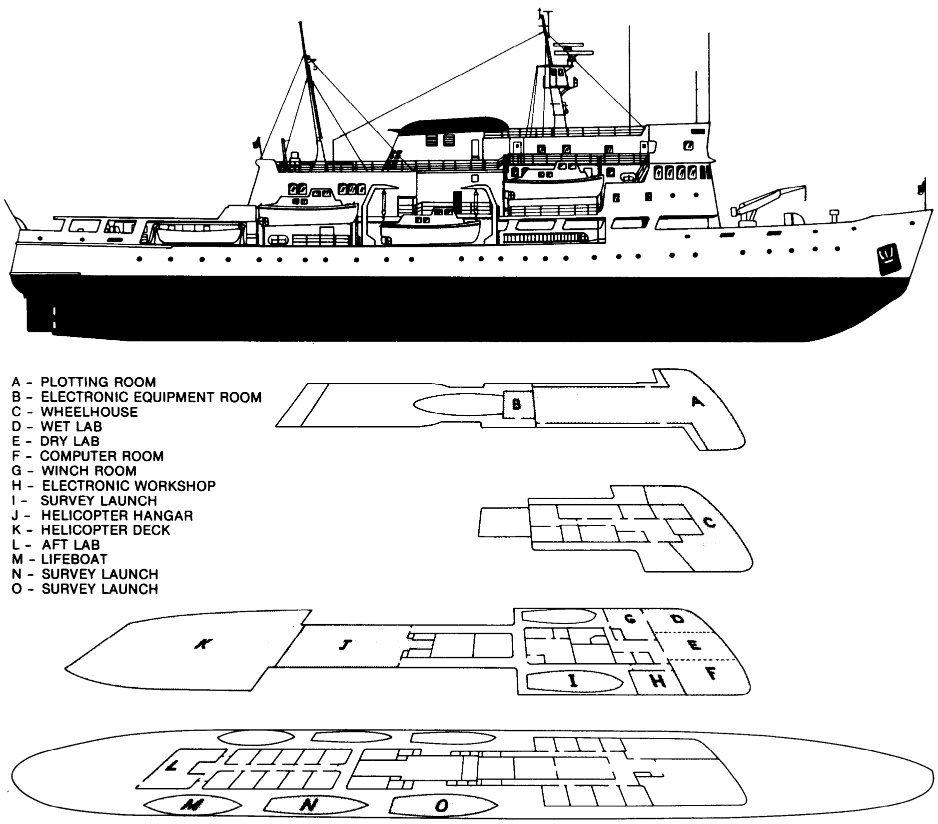


C.S.S. HUDSON

- The C.S.S. *Hudson* is a diesel-electric driven ship designed and used for multi-disciplinary oceanographic research. The ship is owned by the federal Department of Fisheries and Oceans, and it is operated by DFO's Scotia-Fundy Region.
- Principal Statistics - Lloyds Ice Class I hull . . . built in 1963 . . . 90.4 m overall length . . . 15.3 m overall beam . . . 6.3 m maximum draft . . . 4870 tonne displacement . . . 3721 gross registered tons . . . 17 knot full speed . . . 13 knot cruising speed in Sea State 3 . . . 80 day endurance and 23,000 n. mile range at cruising speed … scientific complement of 26 . . . 205 m^2 of space in four laboratories . . . two HP 1000 computer systems . . . heliport and hangar . . . twin screws and bow thruster for position holding . . . four survey launches.
- 224 days at sea and 28,838 n. miles steamed in 1985.

VOYAGE YEAR - NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	VOYAGE OBJECTIVES
85-001	Mar. 18 to 29	D. Piper, AGC	Laurentian Fan Fogo Seamounts	Investigate stability of seabed, gravel waves and evolution of Pleistocene valley in Laurentian Fan and Fogo Seamounts
85-005	Mar. 3 1 to Apr. 24	G. Fader, AGC	Grand Banks and Avalon Channel	Map surficial bedrock geology and carry out NORDCO rockcore drill and acoustic positioning equipment tests
85-010	Apr. 30 to May 27	L. Mayer, Dalhousie University	Kane Fracture	Future drill site survey; rock drill experiment
85-14	May 29 to Jun. 27	N. Oakey, AOL	Mid-Atlantic Ridge	Ocean Mixing
85-018	Jun. 30 to Jul. 14	J. Lazier, AOL	Hamilton Bank	Labrador Current Studies
85-020	Jul. 22 to Aug. 13	W. Harrison, MEL	Gulf of Maine/Gulf Stream	Biological, optical, physical data from tidal frontal zones and from Sargasso Sea water
85-025	Aug. 19 to Sep. 1	I. Reid, AGC	Southern Flemish Cap	Study the deep crustal structure across transition zone between continental and oceanic crust via OBS refraction seismic methods
85-027	Sep. 23 to Oct. 27	B. MacLean, AGC	Davis Strait, Baffin Bay, and Hudson Strait areas	Surficial samples in Baffin Bay for paleoecological studies, surficial and shallow bedrock mapping and sampling using rock core drills and high resolution seismic techniques.

85-031	Sep. 3 to 22	K. Drinkwater, MEL	Hudson Strait	Particle size spectra
85-034	Oct. 30 to Nov. 12	R. Louden, Dalhousie University	Labrador Sea	Heat flow measurements, seismic profiles
85-044	Nov. 14 to 21	K. Manchester, AGC	Flemish Pass	Sample bedrock on Hudson Prong area using NORDCO rock core drill; collect piston cores in pass and high resolution seismic reflection data



C.S.S. BAFFIN

- The C.S.S. *Baffin* is a diesel driven ship designed for hydrographic surveying but also used for general oceanography. The ship is owned by the federal Department of Fisheries and Oceans, and it is operated by DFO's Scotia-Fundy Region.
- Principal Statistics - Lloyds Ice Class I hull . . . built in 1956 . . . 87 m overall length . . . 15 m moulded beam . . . 5.7 m maximum draft . . . 4986 tonne displacement . . . 15.5 knot full speed . . . 10 knot cruising speed in Sea State 3 . . . 76 day endurance and 18,000 n. mile range at cruising speed . . . complement of 29 hydrographic staff . . . drafting, plotting, and laboratory spaces provided . . . two HP1000 computer systems . . . heliport and hangar . . . twin screws and bow thruster for position holding . . . six survey launches
- 211 days at sea and 32,140 n. miles steamed in 1985

VOYAGE YEAR - NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	VOYAGE OBJECTIVES
85-003	Apr. 1 to 8	R. Gershey, Dalhousie University	Scotian Shelf	Trace metal and organic characteristics of water masses
85-006	Apr. 8 to 13	A. Koslow, Dalhousie University	Southwest Nova Scotia	Haddock ichthyoplankton drift, condition of larval cod and haddock
85-007	Apr. 22 to 29	C. Amos, AGC	Sable Island, Banquereau Bank	Deployment and recovery of current meters, R.A. tracer detection of sediment movement and high resolution seismic surveys
85-009	May 2 to 30 Jun. 3 to Jul. 5 Jul. 8 to 26	G. Henderson, CHS	St. Pierre Bank	Standard navigational charting
85-023	Aug. 6 to Sept. 30	M. Swim, CHS	Labrador, Northeast Baffin, Cameron Island	Standard navigational charting
85-029	Oct. 1 to 13	C. Ross, AOL	Baffin Bay	Baffin Bay circulation
85-035	Oct. 28 to Nov. 29	M. Swim, CHS	Grand Manan Channel	Standard navigational charting

Home

C.S.S. DAWSON

Heinz Wiele

- The C.S.S. *Dawson* is a diesel driven ship designed and used for multidisciplinary oceanographic research, hydrographic surveying, and handling of moorings in deep and shallow water. The ship is owned by the federal Department of Fisheries and Oceans, and it is operated by DFO's Scotia-Fundy Region.
- Principal Statistics - built in 1967 . . . 64.5 m overall length . . . 12 m moulded beam . . . 4.9 m maximum draft . . . 1940 tonne displacement . . . 1311 gross registered tons . . . 14 knot full speed . . . 10 knot cruising speed in Sea State 3 . . . 45 day endurance and 11,000 n. mile range at cruising speed . . . scientific complement of 13 . . . 87.3 m^2 of space in four laboratories . . . computer suite provided . . . twin screws and bow thruster for position holding . . . one survey launch.
- 204 days at sea and 24,607 n. miles steamed in 1985

VOYAGE YEAR - NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	VOYAGE OBJECTIVES
85-004	Apr. 2 to 18	R. Hendry, AOL	Gulf Stream	Recovery of current meter moorings
85-008	Apr. 22 to May 6	S. Smith, AOL	Grand Banks/Labrador Shelf	Track iceberg drift
85-012	May 8 to 21	K. Frank, MEL	Brown's Bank	Measure fisheries production processes
85-013	May 23 to 29	P. Smith, AOL	Cape Sable	Brown's Bank studies
85-015	Jun. 1 to 14	D. Sameoto, MEL	Scotian Shelf, Banquereau Bank	Distribution of chlorophyll and zooplankton
85-017	Jun. 19 to Jul. 15	P. Yeats, AOL	Scotian Shelf	Metal distribution
85-019	Jul. 9 to 14	R. Boyd, Dalhousie University	Sable Island Bank	Map and evaluate sediment properties
85-022	Jul. 19 to Aug. 12	R. Haedrich, Memorial University	Baie D'Espoir/Fortune	Study pelagic food chains and benthic/pelagic couplings; heat flow and sedimentary history
85-024	Aug. 16 to 29	H. Sandstrom, AOL	Grand Banks	Current surges
85-026	Sep. 3 to 22	W. Harrison, MEL	Avalon Channel	Distribution and metabolic activity of plankton and bacteria
85-028	Sept. 16 to Oct. 1	A. Herman, AOL	Scotian Shelf	Zooplankton survey
85-032	Oct. 15 to 25	D. McKeown, AOL	Scotian Shelf	Equipment trials
85-036	Nov. 5 to 8	D. Piper, AGC	Bras d'Or Lakes	Late Quaternary acoustic stratigraphy for Bras d'Or Lakes, history of deep water (carbon isotopic studies), surficial and bedrock geology
85-037	Oct. 18 to Nov. 4	C. Amos, Phase I R. Sparks, Phase II, AGC	Sable Island areas	High resolution seismic surveys, sidescan sonar, surficial samples, radioactive tracer survey to determine sediment transport
85-039	Nov. 12 to 19	G. Bugden, AOL	Gulf of St. Lawrence	Ice forecasting
85-040	Nov. 22 to Dec. 5	T. Foote, AOL	Scotian Shelf	Mesoscale studies
85-041	Dec. 9 to 16	J. Smith, AOL	Point Lepreau, Bay of Fundy	Environmental monitoring

Home

PANDORA II

- The *Pandora II*, a converted offshore supply boat, is chartered by the Department of Fisheries and Oceans from NorthLake Shipping Ltd. and used specifically as a *Pisces IV* submersible support vehicle.
- Principal Statistics - built in 1974 . . . 58.2 m overall length . . . 4.6 m beam . . . 1377 gross registered tons . . . 13 knot full speed . . . 10.5 knot cruising speed . . . 100 day endurance at cruising speed . . . A-frame aft for handling submersibles . . . submersible tracking facilities . . . complete mechanical, electronic, and battery workshops for submersibles.


Heinz Wiele

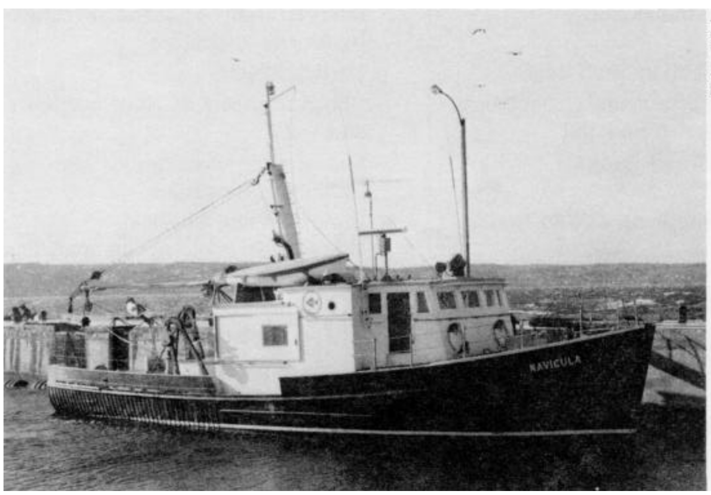
VOYAGE YEAR - NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	VOYAGE OBJECTIVES
85-050	May 10 to 19	D. Forbes, AGC	Scotian Shelf	Study various bottom types on outer Halifax Harbour
85-053	Jun. 7 to 10	B. Hargrave, MEL	Scotian Shelf edge	Behaviour of particulate matter near seabed
85-054	May 20 to 26	C. Amos, AGC	Sable Island and Banquereau	Evaluate seismic and sidescan interpretations of surficial features by on-site inspection
85-055	Jun. 12 to 22	K. Kranck, AOL	Scotian Shelf edge	Particle studies
85-056	Jun. 24 to 29	R. Haedrich, Memorial University	Eastern shore, Southeast Newfoundland	Photo transects of fjord bottom and walls
85-057	Jun. 30 to Jul. 13	G. Fader, AGC	Grand Banks	Submersible observations and sampling of seafloor
85-058	Jul. 14 to 21	K. Frank, MEL	Southeast Grand Banks	Biological and physical characteristics of capelin spawning beds
85-059	Jul. 21 to Aug. 2	D. Piper, AGC	Laurentian Fan	Ground truth Sea MARC I data on Laurentian Fan slump areas
85-062	Aug. 31 to Sep. 23	J. Syvitski, AGC	Baffin Island fjords	Study, map and ground truth the surficial geology features
85-063	Sep. 23 to Oct. 5	E. Levy/C. Ross, AOL	Baffin Island	Study of natural seepage at Scott Inlet; recover current meter moorings
85-064	Oct. 14 to 20	C.F.M. Lewis, AGC	Grand Banks and Laurentian Channel	Ground truth surficial geology of area previously mapped
85-065	Oct. 25 to Nov. 3	B. Hargrave, MEL	Emerald Basin, Continental Slope	Measure flux to/from sediment; impact of oil-based drilling mud

Roger Belanger

C.S.S. *MAXWELL*

- The C.S.S. *Maxwell* is a diesel-driven ship designed and used for inshore hydrographic surveying. The ship is owned by the federal Department of Fisheries and Oceans, and it is operated by DFO's Scotia-Fundy Region.
- Principal Statistics - built in 1962 . . . 35 m overall length . . . 7.6 m moulded beam . . . 2.1 m maximum draft . . . 270 tonne displacement . . . 262 gross registered tons . . . 12.2 knot full speed . . . 10 knot cruising speed in Sea State 2 . . . 10 day endurance and 2400 n. mile range at cruising speed . . . scientific complement of 7 . . . drafting and plotting facilities . . . two survey launches
- 180 days at sea and 2,513 n. miles steamed in 1985

VOYAGE YEAR - NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	VOYAGE OBJECTIVES
85-011	May 1 to Oct. 18	J. Goodyear, CHS	Passamaquoddy	Standard navigational charting
85-033	Oct. 25 to Nov. 8	M. Eaton, CHS	Bedford Basin	Global Positioning System and electronic chart testing



Heinz Wiele

C.S.S. *NAVICULA*

- The C.S.S. *Navicula* is a wooden-hulled fishing vessel owned and operated by the federal Department of Fisheries and Oceans and used for research in biological oceanography. It is operated by DFO's Scotia-Fundy Region.
- Principal Statistics - built in 1968 . . . 19.8 m overall length . . . 5.5 m moulded beam . . . 110 ton displacement . . . 78 gross registered tons
- 168 days at sea and 3,445 n. miles steamed in 1985

VOYAGE YEAR – NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	VOYAGE OBJECTIVES
85-016	May 3 to Jul. 13	T. Lambert	Southwest Nova Scotia/ Georges Bank	Early life history of cod and haddock
85-042	Jul. 29 to Oct. 24	J. Ferguson, CHS	Northumberland Strait	Navigational chart revisions
95-043	Jul. 15 to 24	K. Tay, EPS	Port Hawkesbury	Dump site survey

LADY HAMMOND


Roger Belanger

- The *Lady Hammond*, a converted fishing trawler, is chartered by the Department of Fisheries and Oceans from Northlake Shipping Ltd. and used specifically for fisheries research. The ship is operated by DFO's Scotia-Fundy Region: its main user is the Marine Fish Division, which has components at BIO and in St. Andrews, N.B. Except as otherwise noted below and in the remainder of this chapter, "officers in charge" are affiliated with the Atlantic Fisheries Service's Scotia-Fundy Region. Staff of other regions (Quebec, Gulf, or Newfoundland) are identified separately.
- Principal Statistics - built in 1972 . . . 54 m overall length . . . 11 m overall beam . . . 5.5 m maximum draft . . . 306 gross registered tons . . . 13.5 knot maximum speed . . . 12 knot cruising speed.

VOYAGE YEAR - NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	VOYAGE OBJECTIVES
H130	Jan. 28 to Feb. 1 and Feb. 4 to 22	J. Reid	Scotian Shelf	Gear trials
H131	Feb. 26 to Mar. 8	W.D. Smith	NAFO 4X, 5Z	Spawning cod tagging study
H132	Mar. 11 to 29	P. Hurley	Scotian Shelf	Ichthyoplankton survey
H133	Apr. 1 to 19	P. Hurley	NAFO 4X	Ichthyoplankton survey
H134	Apr. 22 to May 3	B. Hickey	Western Scotian Shelf	Selectivity of square versus diamond mesh codends
H135	May 6 to 17	P. Hurley	NAFO 4X	Ichthyoplankton survey
H136	May 20 to 31	B. Hickey	Scotian Shelf	Selectivity of square versus diamond mesh codends
H137	Jun. 3 to 14	P. Hurley	NAFO 4X	Ichthyoplankton survey
H138	Jun. 17 to 27	R.I. Perry	NAFO 4X and Canadian section of Georges Bank	Juvenile haddock survey
H139	Jul. 8 to 26	Pringle/Harding	NASFO 4X, 5Ze	Distribution of lobster larvae
H140	Aug. 6 to 30	P. Rubec, Gulf	NAFO 4RST	Redfish abundance survey
H141	Sep. 6 to 16 Sep. 5 to 25	L. Currie, Gulf	NAFO 4T	Southern Gulf groundfish survey and comparative fishing with *E. E. Prince*
H142	Sep. 30 to Oct. 11	M.J. Trembley	Bay of Fundy, southwestern Nova Scotia and Georges Bank	Distribution of scallop larvae
H143	Oct. 14 to 18	G. McClelland	NAFO 4VWX	American plaice parasite study
H144	Oct. 21 to 31	P. Fanning	Scotian Shelf	Comparative fishing with *Alfred* ***Needler***
H145	Nov. 6 to 14	J. Reid	NAFO 5Y	Distribution of herring larvae
H146	Nov. 18 to 29	G. McClelland	NAFO 4VWX	American plaice parasite study
H147	Dec. 4 to 13	J. McGlade	NAFO 4VWX and Subarea 5	Stock structure and abundance of pollock including study of eggs and larvae in spawning areas
H143	Oct. 14 to 18	G. McClelland	NAFO 4VWX	American plaice parasite study
H144	Oct. 21 to 31	P. Fanning	Scotian Shelf	Comparative fishing with ***Alfred*** *Needler*
H145	Nov. 6 to 14	J. Reid	NAFO 5Y	Distribution of herring larvae
H146	Nov. 18 to 29	G. McClelland	NAFO 4VWX	American plaice parasite study
H147	Dec. 4 to 13	J. McGlade	NAFO 4VWX and Subarea 5	Stock structure and abundance of pollock including study of eggs and larvae in spawning areas

E.E. PRINCE

Roger Belanger

- The *E.E. Prince* is a steel stern trawler used for fisheries research, and experimental and exploratory fishing. The ship is owned by the federal Department of Fisheries and Oceans, and it is operated by DFO's Scotia-Fundy Region.
- Principal Statistics - built in 1966 . . . 39.9 m overall length . . . 8.2 m overall beam . . . 3.6 m maximum draft . . . 421 ton displacement . . . 406 gross registered tons.

VOYAGE YEAR - NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	VOYAGE OBJECTIVES
P317	Jan. 18 to Feb. 21	U. Buerkle	NAFO 4WA	Winter Herring acoustics survey, Chedabucto Bay
P317A	Mar. 4 to 18	A. Wilson, MEL	NAFO 4X, 5Y	Seasonal benthic survey
P318	Mar. 22 to 29	L. Dickie, MEL	NAFO 4X	Acoustic survey using ECOLOG
P319	Apr. 2 to 11	A. Wilson, MEL	NAFO 4X, 5Y	Seasonal benthic survey
P320	Apr. 15 to 22	M. Etter	NAFO 4Vn	Shrimp survey
P321	May 5 to 8	R. Dufour, Quebec	NAFO 4T	Snow crab tagging study
P322	May 13 to 24	M. Lundy	NAFO 4W, 4X	Sea scallop survey
P323	May 31 to Jun. 14	R. Tizzard, Nfld.	NAFO 3L	Cod behavioural study
P324	Jun. 19 to Jul. 8	B. Mercille, Quebec	NAFO 4T, 4Vn	Mackerel egg and larval survey
P325	Jul. 22 to Aug. 1	W.D. Smith	NAFO 4X	Haddock and cod tagging study
P326	Aug. 6 to 28	G. Robert	NAFO 5Ze	Deep-sea scallop survey
P327	Sep. 4 to 26	G. Chouinard, Gulf	NAFO 4T	Groundfish abundance survey comparative fishing with ***Lady*** *Hammond*
P328	Oct. 7 to 15	M. Etter	NAFO 4V	Shrimp survey
P329	Oct. 21 to Nov. 15	M. Power	NAFO 4X, 52	Larval herring survey

Roger Belanger

M. V. ALFRED NEEDLER

- l The *M. V. Alfred Needler* is a diesel-driven ship owned by the federal Department of Fisheries and Oceans, and used for fisheries research. It is operated by DFO's Scotia-Fundy Region.
- l Principal Statistics - built in 1982 . . . 50.3 m overall length . . . 10.9 m beam . . . 925.03 gross registered tons . . . complement of 10 scientific staff . . . equipped with up-to-date communication systems, electronics, navigational aids, research equipment, and fishing gear.

VOYAGE YEAR - NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	VOYAGE OBJECTIVES
NO39	Jan. 3 to 22	J.H. Young	Halifax to Miami	Distribution of larval and juvenile squid
NO40	Feb. 4 to 25	B. Short, Nfld.	NAFO 3M, 3N	Grand Bank salmon survey
NO41	Feb. 28 to Mar. 8	J.S. Scott	NAFO 4X, 4W	Groundfish abundance survey
NO42	Mar. 11 to Apr. 4	D.L. Lyon	NAFO 4X, 5Z	Spawning haddock tagging study

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N043	Apr. 10 to 27	W.N. Batten, Nfld.	NAFO 3N0	Groundfish abundance survey
N044	May 7 to I7	L.M. Dickie, MEL	NAFO 4X	Acoustic survey and benthic sampling
N045	May 20 to Jun. 4	P. Ouellet, Quebec	NAFO 4s	Larval shrimp distribution
N046	Jun. 10 to 14	G. McClelland	NAFO 4VWX	American plaice parasite study
N047	Jun. 17 to 27	J. Neilson	NAFO 4X and Canadian portion of Georges Bank	Juvenile haddock survey
N048/49	Jul. 3 to 29	S. J. Smith/ P. Koeller	Scotian Shelf, Bay of Fundy	Groundfish abundance survey
N050	Jul. 29 to Aug. 16	C. Fitzpatrick, Nfld.	NAFO 3L, 3K	Annual oceanographic cruise
N051	Sep. 7 to 18	T. Rowe11	NAFO 4X to Gulf Stream	Larval and juvenile squid survey
N052	Sep. 23 to 25	R.G. Halliday	NAFO 4X	Survey of deep sea ichthyofauna
N053	Oct. *7* to *17*	K. Zwanenburg	NAFO 4Vs	Redfish abundance survey
N054	Oct. 21 to Nov. 1	S. Gavaris/ P. Fanning	Scotian Shelf	Comparative fishing experiment with *Lady Hammond*
N055	Nov. 8 to 30	R. Shotton, MEL	NAFO 4Vn	Herring acoustic survey

CO-OPERATIVE VOYAGES

During 1985, the Marine Fish Division participated in a co-operative voyage aboard the USSR's research vessel *Tava* (abbreviated as T below)

VOYAGE YEAR - NUMBER	VOYAGE DATES	OFFICER IN CHARGE	AREA OF OPERATION	VOYAGE OBJECTIVES
T01	Oct. 18 to 28	J. Neilson, MFD	NAFO 4VWX	Canada-USSR cooperative research on juvenile silver hake, including annual abundance survey

Organization

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BIO is a research institute of the Government of Canada operated by the Department of Fisheries and Oceans (DFO), both on its own behalf and for the other federal departments that maintain laboratories and groups at the Institute. Research, facilities, and services are co-ordinated by a series of special and general committees.

BIO also houses the office of the Northwest Atlantic Fisheries Organization (Executive Secretary - Captain J.C.E. Cardoso); the analytical chemistry laboratories of the Department of the Environment's (DOE) Atlantic Region Environmental Protection Service (Chief - Dr. H.S. Samant); and the Canada Oil and Gas Lands Administration Laboratory of the Department of Energy, Mines and Resources (DEMR). In leased accommodation at BIO are the following marine-science related private companies: ASA Consulting Ltd., Brooke Ocean Technology, Seakem Oceanography, Seastar Instruments Ltd., and Seimac Ltd.

Presented below are the major groups at BIO and their managers as at July 1987. Telephone numbers are included: note that Nova Scotia's area code is 902 and the BIO exchange is 426. An * denotes DFO Halifax location.

DEPARTMENT OF FISHERIES AND OCEANS

Regional Director Science
S.B. MacPhee 3492
Marine Assessment and Liaison Division
H.B. Nicholls, Head 3246

Biological Sciences Branch
J.E. Stewart, Director* 3130
Marine Fish Division
W.D. Bowen, Chief 8390
Invertebrates, Plants, and Environmental Ecology Division
M.M. Sinclair, Chief* 6138
Biological Oceanography Division
T.C. Platt, Chief 3793
Enhancement, Culture and Anadramous Fisheries Division
N.E. MacEachern, Chief* 3573
Fish Aquaculture and Applied Physiology
R.H. Cook, Chief
(St. Andrews, N.B.) . . . . (506) 5239-8857

Physical and Chemical Sciences Branch
J.A. Elliott, Director 7456
Marine Chemistry Division
J.M. Bewers, Head 2371
Coastal Oceanography Division
C.S. Mason, Head 3857
Metrology Division
D.L. McKeown, Head 3489
Ocean Circulation Division
R.A. Clarke, Head 2502

Hydrography Branch
Canadian Hydrographic Service (Atlantic)
A.J. Kerr, Regional Director 3497
T.B. Smith, Assistant Director 2432
Field Surveys Division
T.B. Smith, Head 2432
Chart Production
S.L. Weston, Superintendent 7286
Hydrographic Development
R.G. Burke, Head 3657
Navigation Group
R.M. Eaton, Head 2572
Data Management and Planning
R.C. Lewis, Manager 2411
Tidal Section
S.T. Grant, Head 3846

Management Services Branch
E.J. Maher, A/Director* 7433
Marine Services
J.H. Parsons, Head 7292
Engineering and Technical Services
D.F. Dinn, Manager 3700
BIO Library Services
J.E. Sutherland, Head 3675
BIO Administrative Services
J. Broussard, Chief 7037

Comptroller's Branch
G.C. Bowdrige, A/Comptroller . . . 6166
Accounting and Treasury Operations
S. Lucas, Chief* 3552
Financial Planning and Analysis
L.Y. Seto, Chief 7060

Operational and Work Planning Division
R.A. Huggins, Chief* 2271

DEPARTMENT OF ENERGY, MINES AND RESOURCES

Atlantic Geoscience Centre
(Geological Survey of Canada)
M.J. Keen, Director 2367
D.I. Ross, Assistant Director 3448
Eastern Petroleum Geology
M.E. Best, Head 2730
Environmental Marine Geology
D.J.W. Piper, Head 7730
Regional Reconnaissance
C.E. Keen, Head 3413
Program Support
K.S. Manchester, Head 3411
Administration
C. Racine, Head 2111

DEPARTMENT OF ENVIRONMENT

Seabird Research Unit
(Canadian Wildlife Service)
E.H. J. Hiscock, Administrative
Coordinator 3274

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Projects

WE present below a listing of the projects and individual investigations (1, 2, 3, etc.) being undertaken by the major component laboratories of the Bedford Institute of Oceanography. For more information on these projects and those of other components at the BIO, feel free to write to the: Regional Director of Science, Scotia-Fundy Region, Department of Fisheries and Oceans, c/o Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, Nova Scotia B2Y 4A2,

SURFACE AND MIXED-LAYER PHYSICAL OCEANOGRAPHY

1. Humidity- exchange over the sea (HEXOS) programme *(S.D. Smith, R.J. Anderson)*
2. Studies of the growth of wind waves in the open sea *(F. W. Dobson)*
3. Wave climate studies *(W. Perrie, B. Toulany)*
4. Oil trajectory analysis *(D. J. Lawrence)*
5. Iceberg drift track modelling *(S.D. Smith)*
6. Microstructure studies in the ocean *(N. S. Oakey)*
7. Near-surface velocity measurements *(N. S. Oakey)*
8. Investigations of air-sea fluxes of heat and momentum on large space and time scales using newly calibrated bulk formulae *(F. W. Dobson, S.D. Smith)*
9. Labrador coast ice *(S. Prinsenberg, I. Peterson)*
10. Gulf of St. Lawrence ice studies *(G. Bugden)*
11. Marginal ice zone experiment (MIZEX): Wind stress and heat flux in the ice margin *(R. J. Anderson, S.D. Smith)*
13. Wind sea dynamics *(W. Perrie, B. Toulany)*
14. Current measurements near the ocean surface *(P. C. Smith, D. J. Lawrence, J.A. Elliott, D.L. McKeown)*
15. The spin-down and mixing of Mediterranean salt lenses (N.S. *Oakey, B. R. Ruddick)*
16. Modelling of ice and icebergs flowing along the Labrador and Baffin Island coasts *(M. Ikeda)*
17. Large-scale circulation in the Labrador Sea and Baffin Bay *(M. Ikeda)*
18. Labrador ice studies - Field program *(I. Peterson)*
19. Labrador ice margin study *(C. Tang, M. Ikeda)*

LARGE-SCALE DEEP-SEA PHYSICAL OCEANOGRAPHY

1. Labrador sea water formation *(R.A. Clarke, N.S. Oakey, J.-C. Gascard (France))*
2. Modelling the Labrador Sea (C. *Quon, R.A. Clarke)*
3. Labrador Current variability *(R.A. Clarke, V. Larichev (U. S. S. R.))*
4. Age determinations in Baffin Bay bottom water *(E.P. Jones, J.N. Smith, KM. Ellis)*
5. Moored measurements of Gulf Stream variability: A statistical and mapping experiment *(R. M. Hendry)*
6. Newfoundland Basin experiment *(R.A. Clarke, R.M. Hendry)*
7. Problems in geophysical fluid dynamics *(C. Quon)*
8. Norwegian/Greenland Sea experiment *(R. A. Clarke, J. A. Swift (Scripps), J. Reid (Scripps), N. Oakey, P. Jones, R. Weiss (Scripps))*
9. Baseline hydrography: North Atlantic at *48°N (R.M. Hendry)*
10. Studies of the North Atlantic Current and the seaward flow of Labrador Current waters *(J. R.N. Lazier, D. Wright)*
11. Ship of opportunity expendable bathythermography programme for the study of heat storage in the North Atlantic Ocean *(F. Dobson)*
12. Thermodynamics of ocean structure and circulation *(E. B. Bennett)*

CSS Hudson *in Anarctica during HUDSON 70.*

CONTINENTAL SHELF AND PASSAGE WATER DYNAMICS

1. Circulation off southwest Nova Scotia: The Cape Sable experiment *(P.C. Smith, D. LeFaivre (DFO Quebec Region), K. Tee, R. Trites)*
2. The shelf break experiment: A study of low-frequency dynamics and mixing at the edge of the Scotian Shelf *(P.C. Smith, B. D. Petrie)*
3. Flow through the Strait of Belle Isle *(B.D. Petrie, C. Garrett (Dalhousie University), B. Toulany)*
4. Shelf dynamics - Avalon Channel experiment *(B. D. Petrie)*
5. Current surges and mixing on the continental shelf induced by large amplitude internal waves *(H. Sandstrom, J.A. Elliott)*
6. Batfish internal waves *(A.S. Bennett)*
7. Theoretical investigations into circulation and mixing on Georges Bank: Dynamics of tidal rectification over submarine topography *(J. W. Loder, D.G. Wright)*
8. Numerical models of residual circulation and mixing in the Gulf of Maine *(D.A. Greenberg, J. W. Loder, P. C. Smith, D. G. Wright)*
9. Theoretical investigations into circulation and mixing on Georges Bank: Mixing and circulation on Georges Bank *(J. W. Loder, D. G. Wright)*
10. Circulation and dispersion on Browns Bank: The physical oceanographic component of the Fisheries Ecology Program *(P. C. Smith)*
11. Storm response in the coastal ocean: The oceanographic component of the Canadian Atlantic Storms Program *(P.C. Smith, W. Perrie, F. W. Dobson, D.A. Greenberg, D. J. Lawrence)*
12. Dynamical origins of low-frequency motions over the Labrador/Newfoundland Shelf *(D. Wright, J. Lazier, B. Petrie)*

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CONTINENTAL SHELF AND PASSAGE WATER-MASS AND TRANSPORT STUDIES

1. Analyses of the physical oceanographic data from the Labrador Current *(J. R. N. Lazier)*
2. Flemish Cap experiment *(C.K. Ross)*
3. Long-term monitoring of the Labrador Current at Hamilton Bank *(J. R.N. Lazier)*
4. Long-term temperature monitoring *(D. Dobson)*
5. Data management and archival *(D. N. Gregory)*
6. Development of a remote sensing facility in the Atlantic Oceanographic Laboratory *(C.S. Mason, B. Topliss, L. Payzant)*
7. Oceanography of the Newfoundland continental shelf *(B. D. Petrie, D. Green berg)*
8. Eastern Arctic physical oceanography *(C. K. Ross)*
9. Water transport through and in the Northwest Passage *(S. J. Prinsenberg, E. B. Bennett)*
10. Heat and salt budget studies for the Grand Banks region *(J. W. Loder, K. F. Drink water, B. D. Petrie)*
11. Horizontal and vertical exchange on the Southeast Shoal of the Grand Bank *(J. W. Loder, C.K. Ross)*

PHYSICAL OCEANOGRAPHY OF ESTUARIES AND EMBAYMENTS

1. Saguenay Fjord study *(G.H. Seibert)*
2. Seasonal and interannual variability in the Gulf of St. Lawrence *(G.L. Bugden)*
3. Laurentian Channel current measurements *(G. L. Bugden)*
4. The Gulf of St. Lawrence - Numerical modelling studies *(K. T. Tee)*
5. Tidal and residual currents - 3-D modelling studies *(K. T. Tee, D. Lefaivre)*
6. Bay of Fundy tidal power - Studies in physical oceanography *(D.A. Greenberg)*
7. Physical dynamics of particulate matter *(K. Kranck)*
8. Bottom and surface drifters *(D. Gregory)*
9. Suspended sediment modelling *(D.A. Greenberg, C.L. Amos (AGC))*
10. Winter processes in the Gulf of St. Lawrence *(G. Bugden)*
11. Modelling historial tides *(D. Greenberg)*
12. Storm surges *(D. Greenberg, T.S. Murty (DFO Pacific Region))*
13. Circulation and air/sea fluxes of Hudson Bay and James Bay *(S. Prinsenberg)*
14. Foxe Basin mooring observation program to study tidal current, mean circulation, and water mass formation and transport *(S. Prinsenberg)*
15. Tidally induced residual current - Studies of mean current - tidal current interaction *(C. Tang, K.T. Tee)*

SENSOR DEVELOPMENT

1. Anemometers for drifting buoys *(J. -G. Dessureault, D. Belliveau)*
2. CTDs and associated sensors *(A.S. Bennett)*
3. Thermistor chains on drifting buoys *(G.A. Fowler, J.A. Elliott)*
4. Towed biological sensors *(A. W. Herman, M. Mitchell, S. W. Young, E.F. Phillips, D. Knox)*
5. The dynamics of primary and secondary production on the Scotian Shelf *(A. W. Herman, D. Sameoto, T. Platt)*
6. Vertical profiling biological sensors *(A. W. Herman, M.R. Mitchell, S. W. Young, E.F. Phillips, D. R. Harvey)*
7. Zooplankton grazing and phytoplankton production dynamics *(A. W. Herman, A.R. Longhurst, D. Sameoto, T. Platt)*
8. Real-time data acquisition *(A. S. Bennett)*
9. CTD sensor time constant measurements *(A. S. Bennett)*
10. Moored biological sensors *(A. W. Herman, M.R. Mitchell, S. W. Young, E.F. Phillips)*
11. Satellite estimations of primary productivity *(B. J. Topliss)*
12. Optical properties of Canadian waters *(B. J. Topliss)*
13. Biological Arctic instrumentation *(A. Herman, D. Knox)*
14. Automatic winch control for towed plankton samplers *(M. Mitchell, J.-G. Dessureault, A. Herman, S. Young, D. Harvey)*

SURVEY AND POSITIONING SYSTEM DEVELOPMENT

1. Bottom referenced acoustic positioning systems *(D. L. McKeown)*
2. Ship referenced acoustic positioning systems *(D. L. McKeown)*
3. Multifrequency acoustic scanning of water column *(N. A. Cochrane)*
4. Doppler current profiler *(J. Whitman)*
5. Development of a Lagrangian surface drifter *(D. L. McKeown, G. Fowler)*
6. Bottom-mounted acoustic current profiler *(N. Cochrane, J. Whitman, D. Belliveau)*

OCEANOGRAPHIC INSTRUMENT DEPLOYMENT

1. Mooring systems development *(G.A. Fowler, A. J. Hartling, R. Reiniger, J. Hamilton)*
2. Handling and operational techniques for instrument/cable systems *(J. -G. Dessureault, R. F. Reiniger)*
3. *In-situ* sampling of suspended particulate matter *(G.A. Fowler, B. Beanlands, W. Whiteway)*
4. Techniques to recover or refuel the submarine DOLPHIN underway *(J.-G. Dessureault, R. Vine)*

Mary Lewis familiarizes herself with a survival suit prior to sailing.'

NEARSHORE AND ESTUARINE GEOCHEMISTRY

1. Estuarine and coastal trace metal geochemistry *(P. Yeats, D.H. Loring, J. A. Dalziel)*
2. Sediment geochronology and geochemistry in the Saguenay Fjord *(J.N. Smith)*
3. Organic carbon transport in major world rivers: The St. Lawrence, Canada *(R. Pocklington, F. C. Tan)*
4. Physical-chemical controls of particulate heavy metals in a turbid tidal estuary *(D. H. Loring)*
5. Organic carbon sinks in shelf and slope sediments *(R. Pocklington, R. Martin, G. Gassmann)*
6. Arctic and west coast fjords *(J. Smith)*
7. Climatological variability recorded in marine sediments *(J. Smith)*
8. Isotope geochemistry of major world estuaries *(F. C. Tan)*
9. Review of chemical oceanography in the Gulf of St. Lawrence *(J.M. Bewers, D.H. Loring, R. Pocklington, J.N. Smith, P.M. Strain, F. C. Tan, P. A. Yeats)*
10. Radioecological investigations of plutonium in an Arctic marine environment *(J.N. Smith, K.M. Ellis, A. Aarkrog)*
11. Trace metal geochemistry in estuarine mixing zones *(P. Yeats, J.M. Bewers, J. Dalziel)*

DEEP OCEAN MARINE CHEMISTRY

1. The carbonate system and nutrients in Arctic regions *(E.P. Jones)*
2. Distribution of sea ice meltwater in the Arctic *(F. C. Tan)*
3. Trace metal geochemistry in the North Atlantic *(P. A. Yeats)*
4. Natural marine organic constituents *(R. Pocklington)*
5. Paleoclimatic studies - Paleoclimatological studies of Lake Melville sediment cores *(F.C. Tan, G. Vilks (AGC))*
6. Comparison of vertical distribution of trace metals in the North Atlantic and North Pacific oceans *(P.A. Yeats)*
7. Radionuclide measurements in the Arctic *(J. Smith)*
8. Carbon isotope studies on particulate and dissolved organic carbon in deep-Sea and coastal environments *(F.C. Tan, P. Strain)*

TOXIC, CHEMICAL, ENVIRONMENTAL, EMERGENCY, AND OTHER APPLIED STUDIES

1. Petroleum hydrocarbon components *(E.M. Levy)*
2. Petroleum residues in the eastern Canadian Arctic *(E.M. Levy)*
3. Point Lepreau environmental monitoring program *(J. N. Smith)*
4. Canadian marine analytical chemistry standards program *(M. Bewers, P. Yeats, D. Loring)*
5. International activities *(J.M. Bewers, P.A. Yeats, D.H. Loring)*

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6. Joint Canada/Federal Republic of Germany caisson experiments *(D. H. Loring, R. Rantala, F. Prosi)*
7. Marine emergencies *(E.M. Levy)*
8. Heavy metal contamination in a Greenland fjord *(D. Loring)*
9. ICES intercalibration for trace metals in sediments *(D. Loring)*
10. Enhanced degradation of petroleum in the marine environment *(E.M. Levy, K. Lee)*
11. Elements in the marine environment *(P.A. Yeats)*
12. Heavy metal contamination of sediments and suspended matter on the Greenland Shelf *(D.H. Loring)*
13. Fish ageing from $^{210}Pb/^{226}Ra$ measurements in otoliths *(J. N. Smith)*
14. Growth rates of the sea scallop *(Placopecten magellanicus)* using the oxygen isotope record *(F.C. Tan, D. Roddick)*

PRIMARY PRODUCTION PROCESSES

1. Bio-optical properties of the pelagic ocean *(T. Platt)*
2. Physiology and biochemistry of photosynthesis, respiration, and growth in marine phytoplankton *(J. C. Smith, T. Platt)*
3. Respiration, nutrient uptake, and regeneration in natural plankton populations *(W. G. Harrison, J. C. Smith, T. Platt)*
4. Physical oceanography of selected features in connection with marine ecological studies *(E.P. W. Horne)*
5. Physiology of marine microorganisms *(WK. W. Li)*
6. Picoplankton in the marine ecosystem *(D. V. Subba Rao)*
7. Biological oceanography of the Grand Banks *(E.P. W. Horne and others)*

SECONDARY PRODUCTION PROCESSES

1. Carbon and nitrogen utilization by zooplankton and factors controlling secondary production *(R. J. Conover)*
2. Ecology of microzooplankton in the Bedford Basin, Nova Scotia *(M.A. Paranjape)*
3. Development of profiling equipment (BIONESS) and LHPR for plankton and microplankton *(D.D. Sameoto)*
4. Secondary production and the dynamic distribution of micronekton and zooplankton on the Scotian Shelf *(D.D. Sameoto, A. W. Herman, N. Cochrane)*
5. Nature and significance of vertical variability in zooplankton profiles *(A.R. Longhurst)*
6. Nutrition and biochemistry in marine zooplankton *(E. J. H. Head)*
7. BIOSTAT program: Zooplankton and micronekton *(D. D. Sameoto)*
8. Feeding studies on zooplankton grown in an algal chemostat *(E. J. H. Head, R. J. Conover)*

ATLANTIC CONSHELF ECOLOGY

1. Scotian Shelf resources and the Shelf ichthyoplankton program: Data acquisition over large spatial and long temporal scales *(R. J. Conover)*
2. Seasonal cycles of abundance and distribution of microzooplankton on the Scotian Shelf *(M.A. Paranjape)*
3. Comparison of methods used for calculation of secondary production from zooplankton population data *(R. J. Conover)*
4. Comparative studies of functional structure of pelagic ecosystems *(A.R. Longhurst)*

EASTERN ARCTIC ECOLOGICAL STUDIES

1. Shore-based studies of under-ice distribution of zooplankton, their reproduction and growth, and the relative importance of epontic and pelagic primary production in their preparation *(R. J. Conover)*
2. Summertime shipboard studies in the eastern Canadian Arctic *(E. J.H. Head)*
3. Feeding dynamics of 'zooplankton and micronekton of the eastern Arctic *(D.D. Sameoto)*
4. Distribution and abundance of microzooplankton in the Arctic *(M.A. Paranjape)*
5. Ecophysiological aspects of marine microbial processes *(W.K. W. Li)*
6. Field and laboratory studies of diapause in copepods *(N. H. F. Watson)*

ECOLOGY OF FISHERIES PRODUCTION

1. Acoustic analysis of fish populations and development of survey methods *(L.M. Dickie and others)*
2. Genetics of production parameters *(L. M. Dickie, A. Mallet, K. Freeman, and others)*
3. Metabolism and growth of fishes *(S.R. Kerr, K. Waiwood)*
4. Mathematical analysis of fish production systems *(S.R. Kerr, W. Silvert, L. M. Dickie)*
5. Size-structure spectrum of fish production *(S.R. Kerr and others)*
6. Plankton growth rates in relation to size and temperature *(R. W. Sheldon, A. Orr)*
7. Bioenergetics of Marine mammals *(P. F. Brodie)*
8. Marine mammal - fisheries interaction *(P. F. Brodie)*
9. Modelling Bay of Fundy ecosystems *(D. Gordon, P. Keizer, P. Schwinghamer, and others)*

ENVIRONMENTAL VARIABILITY EFFECTS

1. Residual current patterns on the Canadian Atlantic Continental Shelf as revealed by drift bottles and seabed drifters *(R. W. Trites)*
2. Water-mass analyses for NAFO areas *(R. W. Trites, K.F. Drinkwater, L. Petrie)*
3. Larval transport and diffusion studies *(R. W. Trites, T. Rowell)*
4. Environmental variability - Correlations and response scales *(R. W. Trites, K. Drinkwater, L. Petrie)*
5. Climatic variability in the NAFO areas *(R. Trites, L. Petrie, K. Drinkwater)*
6. Baffin Island fjords *(R. W. Trites)*

FISHERIES RECRUITMENT VARIABILITY

1. Steady state model and transient features of the circulation of St. Georges Bay *(K. F. Drinkwater)*
2. Nutrition and growth of micro-, macro-, and ichthyoplankton *(R. W. Sheldon and A. Orr)*
3. Vertical movement of plankton, suspended matter, and dissolved nutrients in the water column of coastal embayments *(G.C.H. Harding and others)*
4. Characterization of water masses by particle spectra as a means of predicting larval fish survival *(R. W. Sheldon)*
5. Coupling of pelagic and benthic production systems *(P. Schwinghamer, S.R. Kerr)*
6. Trophic relations in nearshore kelp communities *(K. H. Mann)*
7. Mixing and the temperature-salinity characteristics of the water in the southeastern Magdalen Shallows *(K. F. Drinkwater)*
8. Fish reproductive strategies *(T. Lambert)*
9. Recruitment of larval lobsters along southwest Nova Scotian coast, Bay of Fundy, and Gulf of Maine *(G.C.H. Harding and others)*
10. Fine-scale measurements of larval survival *(K. T. Frank, J. McRuer)*
11. Dispersal strategies of marine fish larvae *(K.T. Frank, J. McRuer, D. Reimer)*
12. Broad-scale spatial coherence of reproductive success among discrete stocks of capelin *(K. T. Frank and others)*
13. Southwest Nova Scotia fisheries ecology - benthic production processes *(P. Schwinghamer, D.L. Peer, J. Grant)*

SUBLETHAL CONTAMINATION AND EFFECTS

1. MFO induction by PCBs and PCB replacements *(R. F. Addison)*
2. Organochlorines in seals *(R.F. Addison, P. Brodie)*
3. Fate, metabolism, effects of petroleum hydrocarbons in marine environments *(J. H. Vandermeulen)*
4. Organochlorine dynamics in the marine pelagic ecosystem *(G. C. H. Harding, R. F. Addison)*
5. Hazard assessment of "new" environmental contaminants *(R. F. Addison)*
6. "Calibration" of the MFO system in winter flounder as an effects monitoring tool *(R. F. Addison)*
7. Development of methods for studies of atmospheric transport of organochlorines *(R. F. Addison)*

DEEP OCEAN ECOLOGY

1. Structure and function of deep ocean benthic communities *(P. Sch winghamer)*
2. Mobility of radionuclides and trace metals in sediments *(P.E. Kepkay, B. T. Hargrave)*
3. Activity of scavenging amphipods in transfer of material in the deep ocean *(B. T. Hargrave)*
4. Vertical fluxes under the Arctic ice cap *(D. C. Gordon, G. C.H. Harding, B. T. Hargrave)*
5. Microbial metabolism at interfaces *(P.E. Kepkay and P. Schwinghamer)*

GRAND BANKS ECOLOGY

1. Biological oceanography *(E.P. W. Horne and others)*
2. Grand Banks ecology: Ecosystem modelling *(W. Silvert, P. Keizer)*
3. Impact of Hudson Bay runoff *(K. Drinkwater and others)*

Home

STOCK ASSESSMENTS AND ASSOCIATED RESEARCH PROJECTS OR SERVICES
1. Herring *(T.D. Iles, R.L. Stephenson)*
2. Haddock *(P. Fanning, S. Gavaris, R. Mahon, R. O'Boyle, K. Waiwood, K. Zwanenburg)*
3. Cod *(S. Campana, J. Hunt, S. Gavaris, A. Sinclair, S. Smith)*
4. Pollock *(C. Annand, J. McGlade)*
5. Silver hake *(P. Fanning, D. Waldron)*
6. Redfish *(K. Zwanenburg)*
7. Flatfish *(J. Neilson)*
8. Argentine assessment and continental shelf margin studies *(R. Halliday)*
9. Underutilized species *(C. Annand)*
10. Seals *(D. Bowen, W. Stobo)*
11. Fisheries management studies *(R. Halliday, J. McGlade, R.- O'Boyle, A. Sinclair, D. Waldron, G. White)*
12. Stock assessment methodology *(G. White)*
13. National sampling program *(J. Hunt, K. Zwanenburg)*
14. International observer program *(D. Waldron)*
15. Groundfish surveys program *(S. Gavaris)*
16. Groundfish age determination *(J. Hunt)*
17. Computing support and special projects *(R. Branton, B. Charlton, B. Freeman, J. Gale, J. McMillan)*

OTHER MARINE-FISH RELATED RESEARCH PROJECTS
1. Ichthyoplankton studies: Data analysis from Scotian Shelf Ichthyoplankton Program (SSIP) and southwest Nova Scotia Fisheries Ecology Program (FEP) *(P. Hurley)*
2. Otolith studies *(S. Campana)*
3. Statistical consulting and special projects: Evaluation of groundfish survey design, comparative fishing analysis *(P. Fanning, S. Smith)*
4. Groundfish and herring tagging studies *(W. T. Stobo)*
5. Groundfish distribution and community structure *(R. Mahon, J.S. Scott)*
6. Social organization, movement patterns, and mating strategies of grey and harbour seals on Sable Island *(J. Godsell)*
7. Acoustics research and surveys *(U. Buerkle)*
8. Parasitology of Scotian Shelf fishes *(J. S. Scott)*
9. Oceanographic processes influencing fish distribution and survival *(I. Perry)*
10. Juvenile fish ecology and surveys *(P. Koeller, J. Neilson, I. Perry, J.S. Scott, K. Waiwood)*
11. 4X herring purse-seine fishery analysis *(P. Mace, G. White)*
12. Groundfish survey technology *(P. J. G. Carrothers)*
13. Ecophysiology of cod and haddock *(K. Waiwood)*

HYDROGRAPHIC FIELD SURVEYS
1. Coastal and harbour surveys:
   Passamaquoddy Bay, N.B. *(J. Goodyear)*
   St. Marys Bay, *N.S. (J. Goodyear)*
   Seal Cove, Grand Manan, N.B. *(J. Goodyear)*
   Grand Manan Channel, N.B. *(M. G. Swim)*
   Baffin Island (NE Coast) *(M.G. Swim)*
   Cameron Island, (N.W.T.) *(M.G. Swim)*
2. St. Pierre Bank and Laurentian Channel *(G. W. Henderson)*
3. Eastern Arctic surveys - Wellington Channel, Austin Channel, Resolute Passage, Resolute Bay, N.W.T., Goose Bay Narrows, Labrador *(E.J. Comeau)*
4. Revisory surveys - Port Mouton, Louisbourg, St. Patricks Channel, N.S., Gulf of St. Lawrence - north side of Prince Edward Island *(J. Ferguson)*
5. Sweep survey of Miramichi River and Shippegan Gully, N.B. *(G. Rockwell)*
6. Contract route survey of Foxe Channel, N.W.T. *(K. Malone)*
7. Contract survey of Roche Bay, N.W.T. *(K. Malone)*

F.C.G. Smith *surveying in Lunenburg Harbour,*

TIDES, CURRENTS, AND WATER LEVELS
1. Ongoing support to CHS field surveys and chart production *(S. T. Grant. C. O'Reilly, L. MacDonald, C.P. McGinn, G. B. Lutwick, F. Carmichael)*
2. Operation of the permanent tides and water levels gauging network *(S. T. Grant, C.P. McGinn, G.B. Lutwick, F. Carmichael, L. MacDonald)*
3. Review and update of tide tables and sailing directions *(S. T. Grant, C. O'Reilly)*
4. Contract studies *(S. T. Grant)*
   Placing tide staffs and gauges in the Miramichi *(Discovery Consultants Ltd.)*
   Propagation measurements in Baffin Bay, Lancaster Sound and Nares Strait *(Dobrocky Seatech Ltd.)*
   Numerical tidal model of Hudson Strait/Ungava Bay *(Martek Ltd.)*

NAUTICAL CHART PRODUCTION
1. Production of
   - 5 New Charts
   - 4 New Charts *(by contract)*
   - 11 Standard New Editions
   - 15 New Editions for Loran-C *(by contract)*
   - 2 special charts *(T.B. Smith, S. Weston)*

NAVIGATION
1. Loran-C calibrations in the Atlantic for large-scale charts *(R.M. Eaton)*
2. Loran-C error accuracy enhancement for Atlantic Canada *(N. Stuifbergen)*
3. Testing and developing the electronic chart *(R.M. Eaton)*
4. Upgrading and maintaining BIONAV *(H. Boudreau)*
5. Navstar's evaluation *(R.M. Eaton)*

HYDIiOGRAPHIC DEVELOPMENT
1. Data-logger and navigation-system evaluations *(S. Forbes, H. Varma. T. Berkeley)*
2. DOLPHIN trials *(R.G. Burke, M. Lamplugh, H. Varma, T. Berkeley)*
3. Shipboard computer replacement *(S. Forbes, H. Varma)*
4. Enhancing automated field surveys *(K. White, S. Forbes, H. Varma)*
5. Enhancing computer-assisted chart production *(S. Forbes, K. White, H. Varma)*
6. Sweep vessel program equipment procurement and integration *(R. G. Burke, T. Berkeley)*

PREPARATION OF SAILING DIRECTIONS
1. Publication of Sailing Directions, Nova Scotia (SE Coast) and Bay of Fundy, Tenth Edition *(R. Pietrzak)*
2. Revisions to Sailing Directions, Newfoundland *(R. Pietrzak)*

HYDROGRAPHIC RESEARCH AND DEVELOPMENT
1. ARCS - Development of an Autonomous Remotely Controlled Submersible for use in the Arctic under ice cover *(under con tract to International Submarine Engineering Ltd.)*

COASTAL GEOLOGY PROGRAM
1. Consulting advice on physical environmental problems in the coastal zone *(R.B. Taylor)*
2. Morphology, sedimentology, and dynamics of Newfoundland coast *(D.L. Forbes)*
3. Coastal environments and processes in the Canadian Arctic Archipelago *(R. B. Taylor)*
4. Sediment dynamics and depositional processes in the coastal zone *(D.L. Forbes)*
5. Beaufort Sea coast *(P.R. Hill)*
6. Permafrost processes in Arctic beaches *(R. B. Taylor)*

GEOLOGY OF COASTAL INLETS
1. The physical behaviour of suspended particulate matter in natural aqueous environments *(J. P.M. Syvitski)*
2. Sedimentology of fjords *(J. P.M. Syvitski)*

Home

3. Sediment dynamics at Head of the Bay of Fundy *(C.L. Amos)*
4. The recent paleoclimatic and paleoecologic records in fjord sediments *(C.T. Schafer)*
5. Transfer of sediments from the land mass to the continental shelf (SEDFLUX) *(J. P. M. Syvitski)*

GEOLOGY OF THE SOUTHEASTERN CANADIAN MARGIN

1. Bedrock and surficial geology, Grand Banks and Scotian Shelf *(G.B. Fader)*
2. Ice scouring of continental shelves ***(C. F. M. Lewis)***
3. Stability and transport of sediments on continental shelves *(C.L. Amos)*
4. Quaternary geologic processes on continental slopes *(D. J. W. Piper)*
5. Facies models of modern turbidites *(D. J. W. Piper)*
6. Engineering geology of the Atlantic shelf *(R. Parrott)*
7. Marine geotechnical study of the Canadian eastern and Arctic continental shelves and slopes *(K. Moran)*
8. Open File map series *(G. B. Fader)*
9. Nearshore sediments and non-fuel minerals ***(G. B. Fader)***

EASTERN ARCTIC AND SUBARCTIC GEOLOGY

1. Eastern Baffin Island shelf bedrock and surficial geology mapping program *(B. C. MacLean)*
2. Surficial geology, geomorphology, and glaciology of the Labrador Sea *(H. W. Josenhans)*
3. Quaternary methods in marine paleontology *(G. Viks)*
4. Near-surface geology of the Arctic island channels *(B. C. MacLean)*
5. Quantitative Quaternary paleoecology, eastern Canada *(P. J. Mudie)*
6. Temporal and spatial variation of deep ocean currents in the western Labrador Sea *(C.T. Schafer)*
7. Ice island sampling and investigation of sediments *(P. J. Mudie)*

WESTERN ARCTIC GEOLOGY

1. Surficial geology and geomorphology, Beaufort Sea *(S.M. Blasco)*
2. Beaufort Sea boundary dispute *(P.R. Hill)*

GEOCHEMISTRY

1. Environmental geology of the deep ocean *(D. E. Buckley)*
2. Diagenesis and geochemical cycling *(R. Cranston)*

REGIONAL GEOPHYSICAL SURVEYS

1. East coast potential fields *(R.F. Macnab)*
2. Evaluation of KSS-30 gravimeter ***(B. D. Loncarevic)***
3. An earth science atlas of the continental margins of eastern Canada ***(S. P. Srivastava)***
4. Potential fields data-base operation ***(K. G. Shih)***
5. Satellite altimetry applications for margin gravity *(J. M. Woodside)*
6. Seismicity studies of the eastern Canadian margins *(I. Reid)*
7. Ocean Drilling Program site survey: Labrador Sea *(S. P. Srivastava)*
8. Regional geophysics of the Mesozoic-Cenozoiceras of the Newfoundland margins *(A. Edwards)*

INVESTIGATIONS OF DEEP GEOLOGICAL STRUCTURES

1. Comparative studies of the continental margins of the Labrador Sea and the North Atlantic *(S. P. Srivastava)*
2. Seismic studies of continental margins of eastern Canada and related areas *(I. Reid)*
3. Seismic systems development *(B. Nichols)*
4. Arctic Ocean seismic refraction and related geophysical measurements *(H. R. Jackson)*
5. Seismic refraction along the Canadian Polar margin *(H.R. Jackson)*
6. Gulf of St. Lawrence - Gravity ***(B. D. Loncarevic)***
7. Regional geologic and plate tectonic history of the Canadian Appalachians *(G. Stockmal)*
8. Marine deep seismic reflection studies, offshore eastern Canada *(C.E. Keen)*
9. Ocean Drilling Program Leg 105 in the Labrador Sea and Baffin Bay ***(S. P. Srivastava)***

THEORETICAL GEOPHYSICAL MODELLING

1. Rift processes and the development of passive continental margins (C. *E. Keen)*

BASIN ANALYSIS AND PETROLEUM GEOLOGY

1. Regional subsurface geology of the Mesozoic and Cenozoic rocks of the Atlantic continental margin *(J. A. Wade)*
2. Geological interpretation of geophysical data as an aid in basin synthesis and hydrocarbon inventory *(A. C. Grant)*
3. Compilation of geoscientific data in the Upper Paleozoic basins of southeastern Canada *(R. D. Howie)*
4. Stratigraphy and sedimentology of the Mesozoic and Tertiary rocks of the Atlantic continental margin *(L. F. Jansa)*
5. Reconnaissance field study of the Mesozoic sequences outcropping on the Iberian Peninsula *(L. F. Jansa)*
6. Sedimentary basin evolution of the continental margin of Newfoundland, Labrador, and Baffin Bay *(K. D. McAlpine)*
7. Sedimentology of east coast formations *(D. J. Cant)*
8. Lithospheric stress in Canada (with special emphasis on sedimentary basins) ***(J. S. Bell)***
9. Lithologic evolution in the offshore basins of eastern Canada *(A. Fricker)*
10. Labrador Shelf Basin Atlas *(J.S. Bell)*

HYDROCARBON RESOURCE APPRAISAL

1. Hydrocarbon inventory of the sedimentary basins of eastern Canada *(M.E. Best)*
2. Rank and petrographic studies of coal and organic matter dispersed in sediments *(P. A. Hacquebard)*
3. Maturation studies *(K.D. McAlpine)*
4. Interpretation of geophysical data from the Scotian margin and adjacent areas as an aid to basin synthesis and estimation of hydrocarbon potential *(B. C. MacLean)*

BIOSTRATIGRAPHY

1. Identification and biostratigraphic interpretation of referred fossils *(M. S. Barss)*
2. Palynological zonation of the Carboniferous and Permian rocks of the Atlantic Provinces, Gulf of St. Lawrence, and northern Canada *(M.S. Barss)*
3. Biostratigraphy of the Canadian Atlantic Shelf and adjacent areas *(R.A. Fensome)*
4. Taxonomy and ecology of palynomorphs *(R.A. Fensome)*
5. DSDP Late Cretaceous-Cenozoic dinoflagellates *(G. L. Williams)*
6. Biostratigraphic zonation (Foraminifera, Ostracoda) of the Mesozoic and Cenozoic rocks of the Atlantic Shelf *(P. Ascoli)*
7. Quaternary biostratigraphic methods for marine sediments *(G. Vilks)*
8. Quantitative stratigraphy in paleo-oceanography and petroleum basin analysis *(F. M. Gradstein)*

GEOLOGICAL DATA BASES

1. Geological Survey representative on steering committee for the Kremp palynologic computer research project *(M. S. Barss)*
2. Information base for offshore east coast wells *(G. L. Williams)*
3. Data inventory *(I.A. Hardy)*
4. Coastal information system development *(D. Forbes)*

GEOLOGICAL TECHNOLOGY DEVELOPMENT

1. Sediment dynamics monitor: RALPH *(D. E. Heffler)*
2. Development of vibrocorer/drill for geotechnical, geological, and engineering studies *(K. S. Manchester)*
3. Development and implementation of cable handling and maintenance procedures ***(K. S. Manchester)***
4. Seabed II *(K.S. Manchester)*
5. Digital single channel seismic data *(W. Kay)*
6. CIGAL - Computer integrated geophysical acquisition and logging ***(B. D. Loncarevic)***
7. Long Coring Facility development (LCF) *(K.S. Manchester,* ***W.*** *MacKinnon)*

SPECIAL GEOLOGICAL PROJECTS

1. Ocean Drilling Program planning *(M. J. Keen)*
2. Boundary disputes: St. Pierre et Miquelon *(D. I. Ross)*
3. Hudson Bay bedrock and surficial geology *(W.H. Josenhans, A.C. Grant)*

Exerpts from the BIO Log: 1962-1987

Home

IN this edition of the BIO log, selected highlights during each of the twenty-five years from October 1962 through October 1987 are presented. The selection was made by H.B. Nicholls.

1962

- The Bedford Institute of Oceanography was officially opened on October 25, 1962 by Hon. Paul Martineau, Minister of Mines and Technical Surveys, and Dr. J.L. Kask, Chairman of the Fisheries Research Board of Canada; there were over three hundred invited guests, including the Hon. R.L. Stanfield, Premier of Nova Scotia. Several months earlier, Dr. W.N. English was appointed the first Director of the Institute.

- Hydrographic survey and research vessels *Baffin, Kapuskasing, Acadia* and *Maxwell* of BIO, supplemented with the charter ships *Arctic Sealer* and *North Star VI* tallied 660 days at sea and steamed 68,000 miles, primarily on hydrographic surveys in the Atlantic and Arctic regions.

- Two oceanographic research programs were ongoing: deep ocean circulation studies in areas from Nova Scotia to the Azores; and Gulf of St. Lawrence studies of energy exchange at the air-sea boundary and the heat budget.

1963

- The Secretariat of the International Commission for the Northwest Atlantic Fisheries (ICNAF) moved into BIO (its successor, NAFO, is still housed at the Institute).

- The research vessel *Atlantis II* of the Woods Hole Oceanographic Institution visited BIO, being one of the first foreign research vessels to do so.

- The Scientific Committee on Oceanic Research (SCOR) met at BIO on April 10.

1964

- CSS *Hudson* was officially commissioned at BIO on February 14 by the Hon. W.M. Benidickson, Minister of Mines and Technical Surveys.

- The first of many multidisciplinary hydrographic/geophysics off-shore surveys was undertaken, using CSS *Baffin*.

- A geophysical Data Logger (GEODAL) was developed. The system produced about 600,000 gravimeter and magnetometer readings in its use on three cruises.

- A quantative study of the temperature and salinity characteristics of the Gulf of St. Lawrence in both summer and winter was completed.

1965

- CSS *Hudson* undertook geophysical surveys of the Mid-Atlantic Ridge.

- Dr. W.L. Ford became Director of BIO.

- The old Atlantic Oceanographic Group was expanded to become an independent marine research laboratory within the Institute; its studies were to focus on those physical and biological processes underlying marine production (this laboratory, which was part of the Fisheries Research Board of Canada, was subsequently renamed Marine Ecology Laboratory).

1966

- Applied Oceanography and Ocean Circulation groups were established.

- The Engineering Services group was divided into two to form Metrology (responsible for "research, design and development in the field of specialized oceanographic instrumentation directly related to the overall program") and Engineering Services (responsible for "general engineering support functions").

From left to right: W.M. Cameron, Honourable Paul Benidickson, and Deputy Minister Van Steenburgh on board CSS Hudson *on commissioning day.*

Dr. W. Ford "taking a BT" from CSS Hudson.

- An atlas and report presenting a new concept of major water mass transport in the region between the Grand Banks and the Azores was completed.

- The first modern detailed charting of the Grand Banks was undertaken by the Canadian Hydrographic Service at BIO.

1967

- A stable platform for air-sea interaction studies was placed on location some 2 miles offshore and near the approaches to Halifax Harbour.

- Members of the Science Council of Canada including the Chairman, Dr. O.M. Solandt, visited BIO.

- The Frozen Sea Research Group (responsibility for which was transferred from BIO to the Institute of Ocean Sciences, Sidney, B.C. in 1970) continued studies on the physics of the growth and decay of polar sea ice and related processes in the seawater beneath.

- A variable depth echosounder transducer was designed, and subsequently tested on CSS *Hudson*.

1968

- Preliminary scientific programs were developed for an oceanographic expedition around North and South America on CSS *Hudson* (HUDSON 70).

- On February 1 the Atlantic Oceanographic Laboratory (AOL) came into being as a separate laboratory within the Institute. It centralized all Marine Sciences Branch functions at the Institute.

- CSS *Dawson* was delivered to BIO from the shipbuilder (G.T. Davie Shipyard, Lauzon, Quebec).

- A remotely controlled, submarine rock-coring drill, capable of operating at a depth of 1200 ft, was developed to the stage where it could be used as a geological tool.

1969

- An automated system was developed to continuously measure and record chlorophyll II concentrations throughout the water column.

- On November 19, CSS *Hudson* departed the Institute for South Georgia, with a call at Rio de Janeiro, beginning the first leg of the HUDSON 70 expedition.

- CSS *Acadia* undertook her final cruise and was subsequently moored alongside the Institute for a number of years prior to being moved to her present location at the Maritime Museum of the Atlantic in Halifax, Nova Scotia.

1970

- On February 4 the Liberian tanker ***Arrow*** ran aground in Chedabucto Bay, Nova Scotia, resulting in the spill of her cargo of Bunker C residual fuel oil. Many BIO staff were involved in spill response activities.

- On October 16, CSS *Hudson* returned to the Institute after HUDSON 70, becoming the first ship ever to circumnavigate the Americas.

- The development BATFISH, a towed underwater vehicle, reached the stage where a local firm was granted a license to manufacture this oceanographic research device.

1971

- A prototype radio-controlled launch, developed at the Institute, was tested during cruises to Antigua and the Mid-Atlantic Ridge.

- During both this year and in 1970, the Institute sent CSS ***Dawson*** to the Gulf Stream at 50W to develop techniques of setting current meter moorings, up to 2000 metres in length, in the strong currents of this region.

- A major geophysical reconnaissance cruise was undertaken in Baffin Bay/Davis Strait to: study the variations in crustal structure across the water bodies; map the ocean-continental boundary; and study the major features on the surrounding continental shelves.

1972

- The Atlantic Geoscience Centre (AGC) of the Geological Survey of Canada was established at the Institute. It amalgamated the former Marine Geology and Marine Geophysics sections of the Atlantic Oceanographic Laboratory plus GSC staff already at the Institute involved in the analysis of mandatory core samples from offshore drilling i.e. Eastern Petroleum Geology Section of the Crustal Geology Division; Dr. B.D. Loncarevic was appointed first director of AGC.

Heinz Wiele

BATFISH about to be deployed into the Labrador Sea.

Roger Belanger

CSS Baffin *arrives at Georgetown, Guyana.*

Home

An instrumented tower at the water's edge of Sable Island, part of the air-sea interaction study.

- BIO participated in an international three-ship experiment (involving CSS *Hudson, Chain* of the Woods Hole Oceanographic Institution and *Cirolana* of Lowestoft, U.K.) to study the Gulf Stream off the Tail of the Grand Bank.

1973

- Work was initiated on the St. Georges Bay (Nova Scotia) larval fish studies program.

- Institute staff were involved in the examination of the sunken barge, *Irving Whale* (containing 4500 tons of Bunker C crude oil) between Prince Edward Island and the Magdalen Islands in 60 meters of water.

- CSS *Hudson* participated in "Overflow '73" (Denmark Strait Overflow) expedition along with 12 other ships from six countries.

- A major multidisciplinary study was undertaken in Canso Strait and Chedabucto Bay, Nova Scotia on the impact of industrial development and other activities on the marine environment.

1974

- During the period June through September Institute staff participated in the GARP Atlantic Tropical Experiment (GATE).

- CSS *Baffin* undertook a hydrographic production/training survey cruise off Guyana, South America.

- A computerized acoustic fish counting system was developed which combined automatic processing of echo returns with data analysis to provide estimates of the numbers and sizes of different fish. This was the forerunner of the successful ECOLOG system.

1975

- The Institute cooperated with Woods Hole Oceanographic Institution in the Joint USA-USSR POLYMODE experiment by laying additional deep-sea moorings in the Gulf Stream.

- A deep tow seismic reflection system, jointly developed with Huntec (70') Ltd, was employed on four cruises of CSS *Hudson*.

- A remotely controlled bottom crawling vehicle SEA ROVER was constructed to carry an acoustic transducer for measuring the levels of Bunker C oil in the tanks of the *Irving Whale,* which sank in the Gulf of St. Lawrence several years earlier.

- The submersible *Pisces IV* was borrowed from the Institute of Ocean Sciences, Patrica Bay, Sidney, B.C. for use in studies of St. Margarets Bay, N.S.

1976

- A BIO field program on Sable Island resulted in the first direct measurement of gas flux between the sea and air. On the Scotian Shelf a program to study shelf break dynamics began.

- The first staff of the Marine Fish Division (of the former Resource Branch, Maritimes Region, Fisheries Management) relocated at BIO. The primary role of this group was the assessment of the stocks of fin fish and grey and harbour seals in the Atlantic area.

- As part of *Hudson's* 1976 Arctic cruise members of AGC completed bedrock and geophysical mapping of Baffin Island Shelf south of Cape Dyer.

1977

- Scientists on board CSS *Hudson* investigated an oil slick at Scott Inlet, Baffin Island; subsequent work showed the slick to be the result of a natural seepage.

- Also during the year, CSS *Baffin* worked off Peru as part of a CIDA sponsored Peruvian fishery project.

- A second generation multi-net zooplankton and micronekton sampler BIONESS was developed.

1978

- In March, 1978 BIO scientists visited the site of the *Amoco Cadiz* oil spill in Brittany, France.

- During the year Dr. W.L. Ford retired as Director-General, Ocean and Aquatic Sciences, Atlantic, BIO; he was succeeded by Dr. C.R. Mann.

- BIO's integrated navigation system BIONAV was developed.

1979

- BIO Scientists were involved in the response to the *Kurdistan* oil-spill incident; this British tanker broke up in Cabot Strait in March, spilling 7000 tons of Bunker-C oil.

Mike Lewis erects a parcoll tent in the Canadian Arctic on LOREX Expedition.

• A major research program to study the fundamental ecology of the Bay of Fundy got underway.

• BIO scientists were involved in the international LOREX and FRAM Arctic Expeditions, and the Institute's first major biological cruise to the Canadian Arctic was undertaken on CSS *Hudson.*

• During this year, Dr. C.R. Mann was succeeded by Dr. A.R. Longhurst as Director-General.

1980

• CSS *Dawson,* with the British ship RRS *Discovery,* worked south of Bermuda on the Lesser Antilles Deep Lithosphere Experiment (LADLE).

• The Huntsman Award for excellence in marine research, conceived by BIO, was awarded for the first time. The recipients were: Dan MacKenzie, U.K., geophysicist; Ramon Margalef, Spain, marine ecologist; and Henry Stommel, U.S.A., physical oceanographer.

• BIO established a Marine Advisory and Industrial Liaison office (BIOMAIL for short) during the year; also the Institute's first industrial tenant, Huntec '70 Ltd., which had been working on a cooperative project with the Atlantic Geoscience Centre for several years, moved into BIO (to be followed soon after by several other firms).

1981

• CSS *Hudson* returned to BIO after nine month's absence and a circumnavigation of North America, during which she undertook a hydrographic survey for a shipping corridor in the Beaufort Sea.

• BIO oceanographers participated in the international "Warm-Core Rings Experiment".

• BIO hosted a symposium "The Dynamics of Turbid Coastal Waters". Over 150 people from many different countries participated.

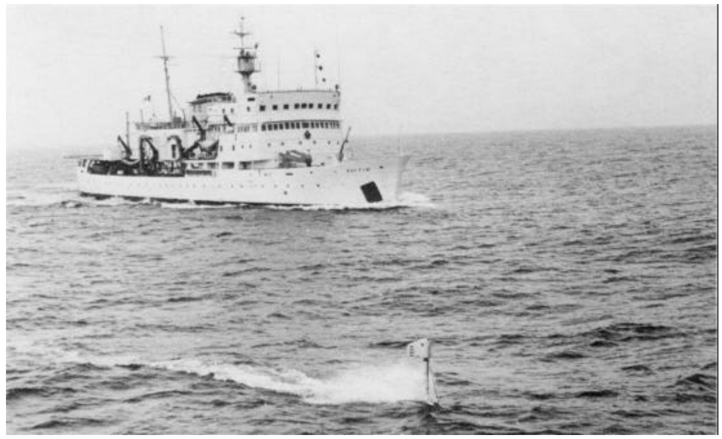
1982

• In February CSS *Hudson* departed BIO on the first leg of a mid-winter expedition to study the region between Iceland and Spitsbergen in the Norwegian-Greenland Sea.

• The first hydrographic charts produced at BIO since the earlier decentralization of the cartography function from Ottawa were released. These charts covered the Bras D'Or Lakes and St. John River.


Roger Belanger

Dr. W. Ying (left) and Dr. D. Bradford discuss rates of coastal recession during the Dynamics of Coastal Water Symposium.



DOLPHIN with mothership CSS Baffin, *in sea trials off the coast of Nova Scotia.*

• A new research trawler to be based at BIO, the R/V *Alfred Needler,* arrived at BIO in September to begin work on Atlantic fisheries problems.

• The first non-military use of the NAVSTAR global positioning system was achieved by BIO on cruises of CSS *Hudson.*

1983

• BIO scientists participated in CESAR (Canadian Expedition to study the Alpha Ridge) in the Arctic Ocean.

• CSS *Hudson* completed a sidescan survey of the epicentre of the 1929 Grand Banks earthquake on the continental slope south of Newfoundland.

• The semi-submersible vehicle DOLPHIN (Deep Ocean Logging Profiler Hydrographic Instrumentation and Navigation), which was developed under contract for the Institute, underwent its acceptance trials at BIO.

• In September BIO scientists participated in MIZEX '83, an international, interdisciplinary study of the marginal ice zone in Fram Strait between Greenland and Svalbard.

• Work started on a cooperative fishery ecology program for Browns Bank involving several BIO units and Dalhousie University.

• A major report was published on the pre-operationa1 phase of BIO's Point Lepreau nuclear power station monitoring program.

1984

• BIO staff participated at hearings of the Gulf of Maine boundary dispute before the International Court at the Hague; prior to this Institute staff had been involved in preparing a range of technical documentation and providing advice to the Department of External Affairs pertaining to this case.

• A new project to model the possible effects of oil spills on the Grand Banks ecosystem was initiated.

• Geological and geochemical research in evaluating the feasibility of the seabed disposal of high level radioactive waste continued.

• A image analysis system for remote sensing and other applications was installed at the Institute.

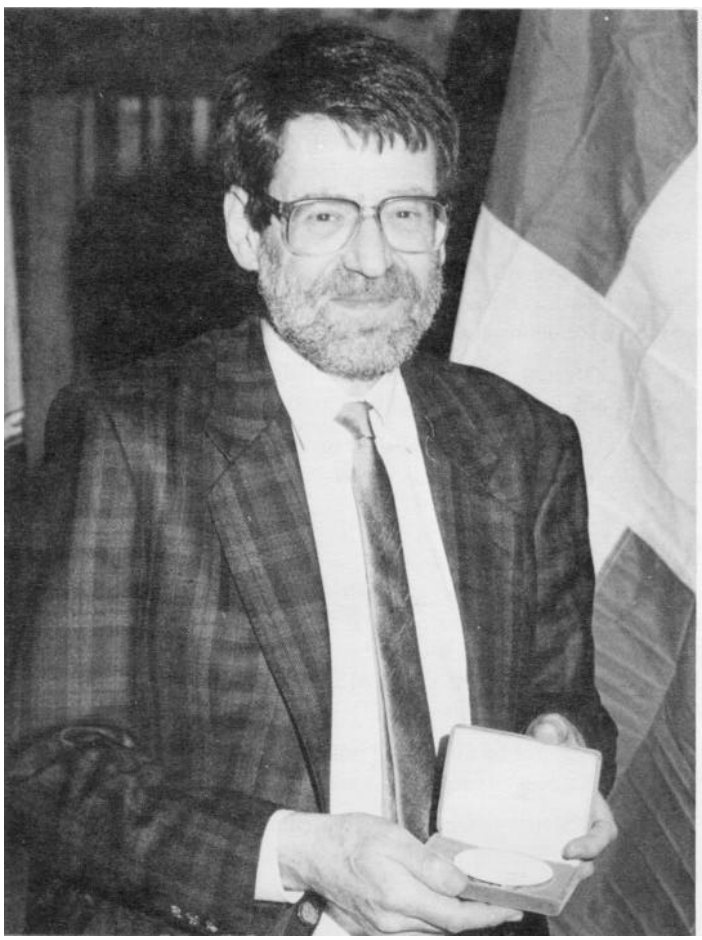
Home

A satellite image taken by a NOAA satellite showing summer sea temperatures on the Scotian Shelf and in the Gulf of St. Lawrence.

1985

- The Atlantic Oceanographic Laboratory at BIO was a major participant in the pilot experiment of the Humidity Exchange Over the Sea (HEXOS) program that was carried out in the North Sea off the coast of the Netherlands.

- During March the CSS *Baffin* worked the front in the ice fields off Labrador with scientists from BIO, the Smithsonian Institution (USA) and the Northwest Atlantic Fisheries Centre. Researchers collected data on a range of topics from seals to phytoplankton physiology.



Heinz Wiele

- For the first time, BIO scientists had direct access to a Cray "super-computer" through the DOE/AES facility in Dorval Quebec.

1986

- The new 35 metre acoustic sweep vessel for BIO, F.C.G. *Smith*, was accepted by DFO from the shipbuilders, Georgetown Shipyard of Prince Edward Island.

- A joint research venture between BIO scientists and ELF/Aquitaine of Paris, France was established to investigate sublethal effects of petroleum exposure in juvenile Atlantic salmon.

- A major experimental study of the physical and chemical characteristics of the ocean east of the Grand Banks was carried out by AOL using CSS *Hudson.*

- An oil spill impact assessment workshop was held at BIO with participation from several government agencies, local environmental consulting firms and Dalhousie University. Discussion centred on the usefulness of a holistic ecosystem model (developed at BIO) for predicting potential impacts from oil spills on the Grand Banks.

- The first units of a new computer system for BIO ships were installed. Based on the Digital Equipment MicroVAX II computer, the system provides increased reliability and enhanced shipboard data acquisition and analysis capabilities in support of oceanographic and hydrographic programs at BIO.

1987

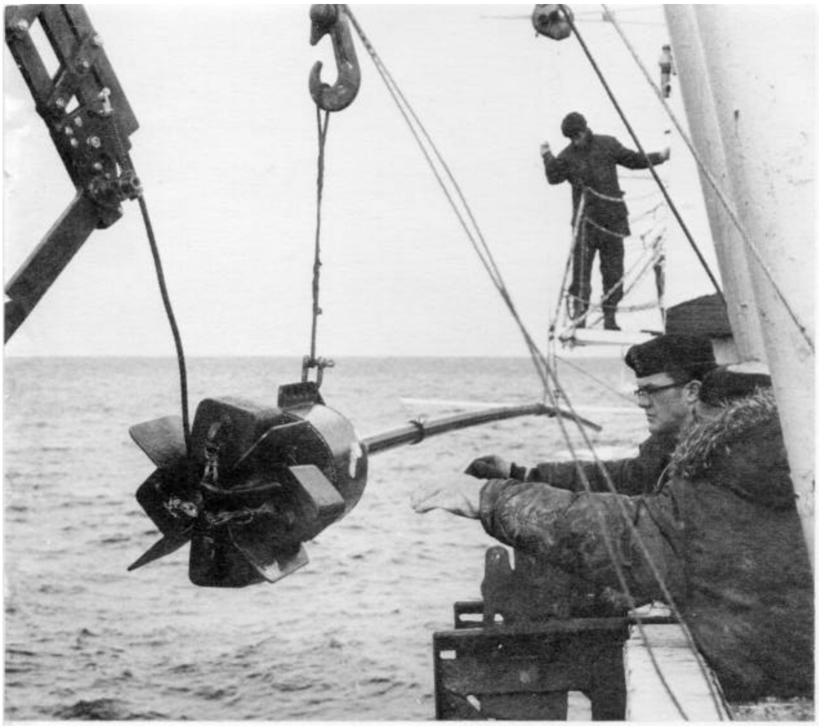
- The Canadian Hydrographic Service at BIO tested the efficiency and feasibility of transmitting and receiving mapping information via the ANIK-D Satellite Network.

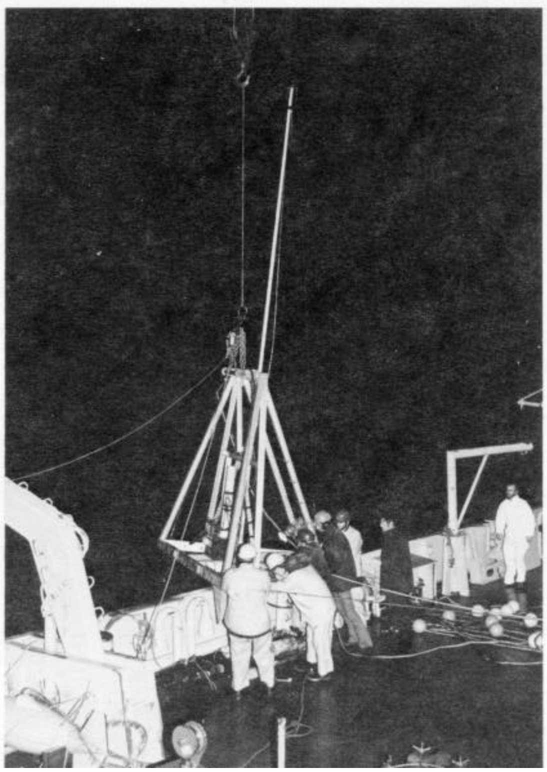
- AGC successfully completed tests of the "Long Coring Facility" which enables the recovery of cores up to 20 metres in length from areas where previous cores of only half the length were recovered.

- AIMS-l, the first field prototype of the Arctic Ice Monitoring System, manufactured jointly by AOL and Seimac Ltd., completed winter field tests at the approaches to Halifax Harbour, and was deployed in the Northwest Passage in August.

- Dr. A.R. Longhurst, Regional Director General, was succeeded by S.B. MacPhee as DFO Regional Director of Science.

Dr. Tom Fenchel, a professor of ecology and zoology at the University of Aarhus, Denmark, was the recipient of the 1986 A. G. Huntsman silver medal for excellence in the marine sciences. His early studies led to the first descriptions of the highly specialized foodwebs that occur within the interstitial space of all sediments, and his methods first applied to the microbenthic community have since been extended to more recent studies of pelagic communities. His findings and conclusions have significantly increased our understanding of the structure and function of marine microbial communities in marine sediments and the water column.





A look back. . .


FIRST CIRCUMNAVIGATION OF THE AMERICAS
1969
1970
PREMIÈRE CROISIÈRE AUTOUR DES AMÉRIQUES

Fisheries and Oceans | Pêches et Océans

Energy, Mines and Resources | Énergie, Mines et Ressources

Environment | Environnement